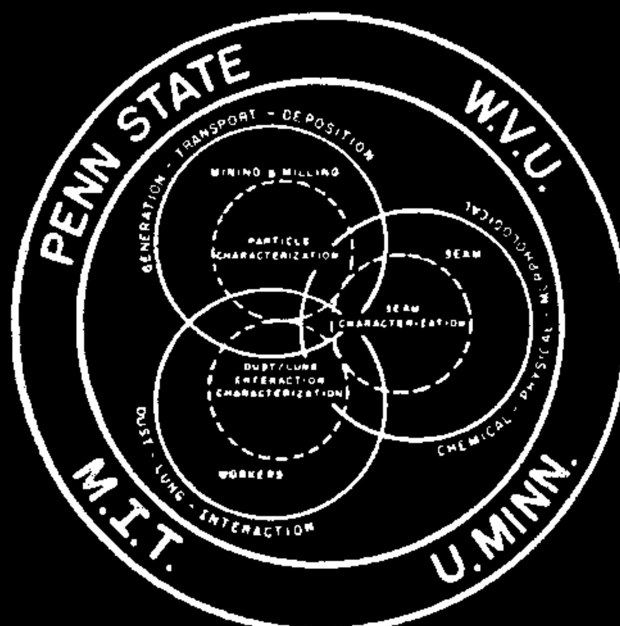
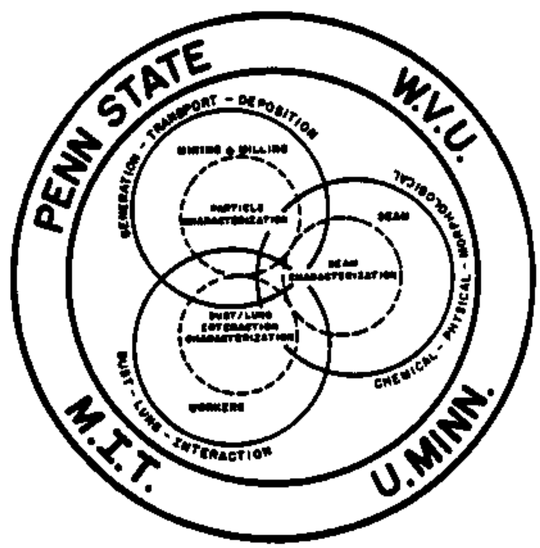
RESPIRABLE DUST IN THE MINERAL INDUSTRIES: HEALTH EFFECTS, CHARACTERIZATION AND CONTROL



Edited by
ROBERT L. FRANTZ
and
RAJA V. RAMANI

RESPIRABLE DUST IN THE MINERAL INDUSTRIES: HEALTH EFFECTS, CHARACTERIZATION AND CONTROL



Edited by
ROBERT L. FRANTZ
and
RAJA V. RAMANI

The Pennsylvania State University
University Park, Pennsylvania
1988

ISBN 0-936712-76-7

Printed in the United States of America

CONTENTS

Foreward vii

Planning Committee ix

KEYNOTE

Welcome Address 3
Bryce Jordan

Keynote Address 4
Honorable Nick J. Rahall, II

GENERAL

MSHA's Revised Quartz Enforcement Program 9
Thomas F. Tomb, Paul S. Parobeck and Andrew J. Gero

A Working Hypothesis on How Silica and Silica Surface May Cause Silicosis and CWP 15
T.P. Meloy

Wetting Characteristics of Particles and Their Significance In Dust Abatement 19
S. Chander, B.R. Mohal and F.F. Aplan

Electron Spin Resonance Detection of Reactive Free Radicals in Fresh Coal Dust and Quartz Dust and Its Implication to Pneumoconiosis and Silicosis 24
N.S. Dalal, M.M Suryan, B. Jafari, X. Shi, V. Vallyathan and F.H.Y. Green

MEASUREMENT

Numerical Technique for Calculating the Equivalent Aerodynamic Diameter of Particles 33
Virgil A. Marple, Zhang Ahiqun and Benjamin Y.H. Liu

MINIRAM Performance in the Coal Mining Environment 41
John A. Organiscak, Kenneth L. Williams and Thomas Ozanich

Measurements of Respirable Dust Concentrations by Using Various Samplers in Underground Coal Mines 51
C.Y. Hwang

Theoretical and Experimental Studies on Dust Transport in Mine Airways: A Comparative Analysis 60
R.V. Ramani and R. Bhaskar

Determining the Size Distribution of Coal Diesel Aerosol Mixtures with the Microorifice Uniform Deposit Impactor 71
Kenneth L. Rubow and Virgil A. Marple

GENERIZATION & CHARACTERIZATION I

Fracture Mode and Loading Rate Influences on the Formation of Respirable Size Fragments on New Fracture Surfaces 81
R. Karl Zipf, Jr. and Z.T. Bieniawski

Correlation of Fragment Size Distribution and Fracture Surface in Coal Cutting Under Various Conditions 88
A. Wahab Khair and W.M. Devilder

Statistical Analysis of the Elemental Characteristics of Airborne Coal Mine Dust 111
Changwoo Lee and Jan M. Mutmansky

Variation in Mineral and Elemental Composition of Respirable Coal Mine Dusts by Worker Location and Coal Seam 124
R.A. Andre, T. Simonyi and R.L. Grayson

HEALTH EFFECTS – CELLULAR RESPONSES

The Effects of Coal Mine Dust Particles on the Metabolism of Arachidonic Acid by Alveolar Macrophages 135
Laurence M. Demers, Matthew Rose, and Gerald L. Bartlett

Effects of Coal Dusts and Alveolar Macrophages on Growth of Lung Fibroblasts 142
Gerald L. Bartlett and Ann B. Pedersen

Measurement of Superoxide Release From Single Pulmonary Alveolar Macrophages Exposed to Dusts . . 150
E.V. Cilento, K.A. Digregorio and R.C. Lantz

The Effect of Lecithin Surfactant and Phospholipase Enzyme Treatment on Some Cytotoxic Properties of Respirable Quartz and Kaolin Dusts 154
W.E. Wallace, M.J. Keane, C.A. Hill, V. Vallyathan, F. Saus, V. Castranova and D. Bates

HEALTH EFFECTS – INHALATION STUDIES

Effects of Silica Inhalation on Pulmonary Alveolar Macrophages (PMA) and Microsomal Cytochrome P450 Activities 169
W. Pailes, J. Rabovsky, D. Judy, J. Tucker, V. Castranova and R.C. Lantz

Development of Alterations in the Lung Induced by Inhaled Silica: A Morphometric Study 177
R. Clark Lantz, Charles Stanley and David E. Hinton

Noninvasive Magnetopneumographic Studies of Lung Dust Retention and Clearance in Coal Miners . . . 181
Allan P. Freedman and Stephen E. Robinson

Pulmonary Injury in Laboratory Animals Induced by Huai-Nan Coal Mine Respiratory Dust 187
B.H. Chen, Z.H. Men, Y Huang, H.Q. Mao and S.Y. Wang

CHARACTERIZATION I

Standard Respirable Dusts 193
T.F. Dumm and R. Hogg

Contents

Detection of Organic Free Radicals in Coal Dust-Exposed Lung Tissue and Correlations with Their Histopathological Parameters 223
B. Jafari, N.S. Dalal, A.V. Vallyathan and F.Y.H. Green

Mineral Fiber Toxicity: Further Evidences for an Involvement of the Surface Chemistry 226
Denis Nadeau, Louise Fouquette-Couture, Jaleh Khorami and Daniel Paradis

A Hypothesis on the Possible Contribution of Coal Cleats to CWP 240
Thomas P. Meloy

GENERIZATION & CHARACTERIZATION II

Reducing Employee Silica Dust Exposures – A Case Study 245
William J. Francart, Joseph M. Denka and W. Carol Ensminger

Investigation of Quartz Dust Sources and Control Mechanisms on Surface Coal Mine Operations 252
Robert A. Zimmer, Stan R. Luecka and Stephen J. Page

Assessment of Respirable Dust Control for Rotary Blasthole Drills at Surface Coal Mines 258
Raymond Gadomski and Debora L. Chiz

Dust Sampling Roof Bolting Operations 264
Robert Ondrey, Richard Stoltz, David Atchison and Everett Gerbec

CHARACTERIZATION II

Size Distribution of the Airborne Dust in Longwall Coal Faces 271
H.S. Chiang, S.S. Peng and Y. Luo

Longwall Respirable Dust Simulator 285
Robert A. Haney

A Procedure for Extensive Characterization of Coal Mine Dust Collected Using a Modified Personal Sampler 290
T.F. Dumm and R. Hogg

Deposition of Respirable Dust in an Airway 298
Welby G. Courtney, Lung Cheng and Edward F. Divers

CONTROL I

The Campbell Flooded Bed Scrubber System, a Quiet Revolution 307
John A.L. Campbell

Evaluation of a New Half-curtain Technique for Continuous Miner Faces 313
Natesa I. Jayaraman, Edward F. Divers, R. Link Derick and Charles Babbitt

Dust Control for Personnel Downwind of the Miner 322
Charles A. Babbitt and Natesa I. Jayaraman

Remote Brattice Face Ventilation Systems 328
John E. Urosek, Charles S. Battistoni and George G. Hazuza

CONTROL II

Adhesive Foam Dust Control for Mine Production Face and Materials Handling 339
Kenneth J. Charlton

Dust Control on Longwall Shearers Using Water-Jet-Assisted Cutting 343
C.D. Taylor, P.D. Kovscek and E.D Thimons

The Relationship Between Respirable Dust and Ventilation in Underground Auger Mining 349
Dale D. Durrett and Natesa I. Jayaraman

Get Away from the Dust with Clean Air from an Overhead Air Supply Island (OASIS) 360
Jon C. Volkwein, Mark R. Engel and Thomas D. Raether

Simulations of Dust Dispersion for a Coal Mine Face Using a Scale Model 364
T.H. Ueng, S.D. Thompson and Y.J. Wang

APPENDIX

Registration List 373

Author Index 378

FOREWORD

This volume contains the proceedings of the International Symposium on Respirable Dust in the Mineral Industries held at The Pennsylvania State University, University Park, Pennsylvania, on October 14-16, 1986. A previous symposium was held at Morgantown, West Virginia, in 1984. These dust symposia have a common objective which they share with scientists, engineers and medical personnel working in the field of respirable dust: to contribute to the eradication of the Black Lung disease in the Nation's coal miners.

The research and development programs of the past decade have highlighted the need to more fully understand dust particle generation; the dust-lung interaction; and the influence of geological settings on the factors for improved dust control in the mineral industries. In recent years, the increased interaction between mining engineers, physicists, chemists, particle technologists and medical personnel has advanced the knowledge on the diverse aspects of the respirable dust problems in the mineral industries. The technical sessions of the symposium have focused on the latest scientific, bio-medical, engineering and management findings on the complex task of planning, designing and executing programs for respirable dust control. Specifically, the symposium papers have presented the research results on generation, characterization, measurement, control and health effects of respirable dust.

The dust symposia also have an important educational component. The Generic Mineral Technology Center for Respirable Dust, one of the symposium organizers, is a consortium of four universities, The Pennsylvania State University, West Virginia University, University of Minnesota and Massachusetts Institute of Technology. The Center was established in 1983 by the U.S. Bureau of Mines under the Mineral Institutes program. During the symposium, the findings of the interactions between many of the research projects in the Center were highlighted. The educational component was reinforced by the fact that the other sponsors of the symposium were the United States Bureau of Mines (USBM), Mine Safety and Health Administration (MSHA), National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental Industrial Hygienists (ACGIH). The Generic Center's efforts recognize the importance of an integrated and concerted fundamental respirable dust research program which is both compatible and complementary to the existing and ongoing research and development activities in the USBM, NIOSH and MSHA. This close interaction between academic institutions, governmental agencies and professional societies is necessary and beneficial to the rapid dissemination of research results.

In addition to the ten technical sessions, the symposium activities included a welcome address by Dr. Bryce Jordon, President of The Pennsylvania State University, and a Keynote address by the Honorable Nick J. Rahall, II, Member of the U.S. House of Representatives, 4th District, West Virginia.

A symposium of this kind depends for its success on the contributions of large numbers of people. Mr Chuck Herd, Co-ordinator, the Keller Conference Center, provided excellent administrative support for the symposium organizers. Special recognition is extended to Debra Sipe, Kelly Henry and Nancy Rishel for assistance and follow-up with the details of the symposium activities. Thanks are due the planning committee, the welcome and keynote speakers, the session chairpersons, the paper presenters, and the other authors. The members of the Planning Committee join us in recording their appreciation to all the participants, the vital link of the respirable dust symposia.

Robert L. Frantz
Raja V. Ramani
The Pennsylvania State University

Robert L. Frantz, Associate Dean of Continuing Education and Industry Programs and Professor of Mining Engineering at The Pennsylvania State University, received his B.S. in 1948 from Virginia Polytechnic Institute. In 1950 he earned a M.S. from The Pennsylvania State University. Both degrees were in mining engineering. In 1948 he joined the Warner Collieries Co., subsequently moving to J.W. Woomer & Associates in 1953. Three years later he became an engineer in the Planning and Development Department of Pocahontas Fuel Co. From 1957 to 1964 he was with Ohio State University's Mining Engineering Division. In 1964 he joined the John T. Boyd Co., leaving there in 1974 as president to go to Penn State. Frantz's research experience and interests include health, safety and productivity aspects of mining, design of innovative mining systems, and performance evaluation of new and novel equipment and systems. At Penn State, he is also co-director with Raja V. Ramani of the Generic Technology Center for Respirable Dust, and The Standard Oil Center for Scientific Excellence in Mining Technology. Frantz is a Distinguished Member of the Society of Mining Engineers, Inc., Class of 1987.

Raja V. Ramani is professor of mining engineering and chairman of the Mineral Engineering Management Section at The Pennsylvania State University. He is a graduate of the Indian School of Mines, Dhanbad, India, in mining engineering. He holds M.S. and Ph.D. degrees from The Pennsylvania State University. Prior to coming to the U.S. in 1966, he gained six years of engineering and managerial experience in underground coal mines. Ramani has authored over 75 research papers on such subjects as environment, health and safety considerations, and computer usage in underground and surface mining. He was editor of the proceedings of the 14th and 19th APCOM and Longwall-Shortwall Mining: State-of-the-Art, all published by SME-AIME in 1977 and 1981, respectively. Ramani was the chairman of the Mineral Engineering Division of the American Society for Engineering Education (ASEE) and currently is the chairman of the International Council for the Applications of Computers and Operations Research in the Mineral Industries (APCOM). He is the 1987 Chairman of the Coal Division of the Society of Mining Engineers, Inc.

PLANNING COMMITTEE

Richard A. Bajura,
West Virginia University
Gerald L. Bartlett,
The Pennsylvania State University
Z.T. Bieniawski,
The Pennsylvania State University
Christopher J. Bise,
The Pennsylvania State University
John A. Breslin,
U.S. Bureau of Mines
John A. Campbell,
Kerr McGee Coal Corporation
James A. Clem,
Peabody Coal Company
Dennis, E. Cole,
Kitt Energy Corporation
Joseph O. Cook,
Pennsylvania Mines Corporation
James L. Corsaro,
Eastern Associated Coal Corporation
Nar S. Dalal,
West Virginia University
Harrison J. Daniel,
U.S. Bureau of Mines
Donald Eget,
Rochester & Pittsburgh Coal Company
John Elliott,
Massachusetts Institute of Technology
Robin Ferguson,
National Mine Service Company
Robert L. Frantz,
The Pennsylvania State University
James B. Girod,
U.S. Steel Mining Company
Robert E. Glenn,
National Institute for Occupational Safety & Health
Robert L. Grayson,
West Virginia University
David A. Hall,
Pennsylvania Department of Health
Robert Haney,
Mine Safety & Health Administration
Richard Hogg,
The Pennsylvania State University
Murray Jacobson,
Mine Safety & Health Administration
William D. Kelley,
American Conference of Governmental Industrial Hygienists
Lorin Kerr,
United Mine Workers of America
Wahab A. Khair,
West Virginia University
Fred N. Kissell,
U.S. Bureau of Mines
Jerome Kleinerman,
Mount Sinai School of Medicine
Richard J. Kline,
Island Creek Coal Co.
Douglas Lester,
Westmoreland Coal Company
Pedro Lilienfield,
GCA Corporation
Peter T. Luckie,
The Pennsylvania State University
Virgil A. Marple,
University of Minnesota
Michael McCawley,
National Institute for Occupational Safety and Health
C. Wesley McDonald,
Consolidation Coal Company
Thomas Meloy,
West Virginia University
Ronald A. Munson,
U.S. Bureau of Mines
Jan M. Mutmansky,
The Pennsylvania State University
Syd S. Peng,
West Virginia University
Raja V. Ramani,
The Pennsylvania State University
Donald Reid,
Pennsylvania Department of Health
Wallace W. Roepke,
U.S. Bureau of Mines
Steven K. Ruggieri,
Foster Miller, Inc.
Madan M. Singh,
Engineers International, Inc.
Kandiah Sivarajah,
Pennsylvania Department of Health
William H. Sutherland,
Mine Safety and Health Administration
Pramod C. Thakur,
CONOCO, Inc.
Joseph J. Trautlein,
The Pennsylvania State University
William E. Wallace, Jr.,
The National Institute for Occupational Safety and Health
Y.J. Wang,
West Virginia University
James L. Weeks,
United Mine Workers of America
Robert Wheeler,
National Institute of Occupational Safety and Health
Lee Zinn,
Mine Safety Appliances Company

RESPIRABLE DUST IN THE MINERAL INDUSTRIES: HEALTH EFFECTS, CHARACTERIZATION AND CONTROL

Proceedings of the International Symposium on Respirable Dust in the Mineral Industries
October 14–16, 1986
The Pennsylvania State University
University Park, Pennsylvania 16802, USA

Sponsored by

The Generic Technology Center for Respirable Dust
The Pennsylvania State University
West Virginia University
University of Minnesota
Massachusetts Institute of Technology
United States Bureau of Mines (USBM)
Mine Safety and Health Administration (MSHA)
National Institute for Occupational Safety and Health (NIOSH)
American Conference of Governmental Industrial Hygienists (ACGIH)

KEYNOTE

Welcome Address

BRYCE JORDAN
President, The Pennsylvania State University

It is with great pleasure that I join you this morning for the opening of the International Symposium on Respirable Dust. I am delighted to welcome you to Penn State and to have this opportunity to learn about the very important subject that you will be addressing over the next few days.

I should like to extend a special welcome to the Honorable Nick J. Rahall II, Member of Congress from the 4th District in West Virginia. Congressman Rahall has a great interest in the welfare of the domestic mining industry and he has been very supportive of research regarding miners' health and safety. We are very pleased that he is with us this morning.

We hear a great deal these days about the information society in which we live as well as the tremendous growth in service industries. Yet mining remains one of the nation's most basic industries, providing many of the natural resources upon which all other industries depend. Although domestic nonfuel raw materials in the United States constitute only about one percent of the gross national product (GNP), processed materials of mineral origin are valued at nearly ten percent of the GNP. Coal, accounting for over half of the fuel supply to U.S. electric utilities, is crucial to our nation's economic survival in the event of a recurring energy crisis.

The vitality of the U.S. mining industry must be ensured. As with many other industries, the mineral industry in the United States is under pressure from foreign competitors. These competitors have advantages in quality, mining conditions, and geographic location. The American mining industry faces a double challenge: to remain technologically and economically competitive in the world marketplace and to maintain and improve health and safety standards in what continues to be one of the most dangerous industries in the nation.

The unique health, safety, and environmental problems of the mining industry have been addressed through industry-specific laws and the establishment of agencies for research and regulation. The U.S. Bureau of Mines and the National Institute for Occupational Safety and Health are to be commended for pioneering research and development contributions in the area of miner health, safety and productivity. Yet there remains an urgent need for ongoing research regarding these issues. Consider, for example, that black lung, the nation's most severe industrial disease, affects not only victims but also their families — a total of a half million people — at an annual cost exceeding two billion dollars.

New and potential developments in the control of respirable dust, the focus of this symposium, are of critical importance to the mineral industry and its workers. I should like to thank the conference co-sponsors — The Generic Technology Center for Respirable Dust, the U.S. Bureau of Mines, the Mine Safety and Health Administration, The National Institute for Occupational Safety and Health, and the American Conference of Governmental Industrial Hygienists as co-sponsors of this symposium — for their interest in this important research area.

Penn State is pleased to be part of the Generic Technology Center for Respirable Dust along with West Virginia University, The University of Minnesota, and the Massachusetts Institute of Technology. As Pennsylvania's Land Grant Institution, Penn State has a tradition of working on problems that are of direct interest to business and industry. Serving the coal industry in Pennsylvania and in the nation through the efforts of the Center is an important part of the University's mission.

Penn State brings to the Center's efforts a strong record in funded research. In 1984, the most recent year for which data are available, Penn State ranked fourth among colleges and universities in the nation in industry-sponsored research and twentieth in federally-supported research and development. The Generic Technology Center affords an exciting opportunity to build upon that record through cooperative efforts among scientific, engineering, and medical researchers at Penn State.

This symposium also is an excellent forum for cooperative exchange regarding the engineering, scientific, medical, and biological aspects of respirable dust in the mineral industries. It is encouraging to see the interest of academic, government, and industry researchers in sharing information about this critical problem.

In closing, I would like to extend you a warm welcome to Penn State on behalf of the entire university community. We hope that while you are here you will take the time to visit some of the university's places of interest and to enjoy the beautiful autumn season in the State College area. You may find the Earth and Mineral Sciences Museum in Steidle Building — just a short walk from here — to be of particular interest.

Best wishes for a most successful symposium.

Keynote Speech

HONORABLE NICK J. RAHALL, II

Chairman, Subcommittee on Mining and Natural Resources, Committee on Interior and Insular Affairs, U.S. House of Representatives

It is indeed a pleasure and honor to deliver the keynote address to this distinguished gathering of experts on respirable dust. There can be no question as to the importance of your mission.

After centuries of coal mining, there is still a lack of precise knowledge concerning the effects of coal-mine dust. Indeed, official and wide-spread recognition of its existence in this country came only relatively recently, although this was not the case in Europe. The term "black lung" was perhaps used for the first time by Thomas Stratton in an 1837 paper describing the lungs of a Scotsman who had worked in the mines for 50 years although references to "miners' asthma" in Great Britain were made as far back as 1822. In 1880, the author Emile Zola in a novel about French coal miners, *Germinal*, further brought to the public's attention the crippling effects of black lung, and it was generally acknowledged in Europe that coal mine dust was the cause of this affliction.

Unfortunately, in the U.S., for a variety of reasons this explicit linkage was not made until much later. In this country, it seems that a disaster has always been a necessary prerequisite to official recognition of the adverse conditions faced by the coal labor workforce.

For example, during the construction of the Hawk's Nest tunnel in the early 1930s near Gauley Bridge, West Virginia, 476 men died, many as a result of silicosis. This prompted a congressional investigation in 1936 after which Secretary of Labor Frances Perkins called the First National Silicosis Conference. Based on the findings of this body, many states subsequently added silicosis to their lists of occupational diseases, but due to highly restrictive qualifying requirements, few victims ever received benefits.

It took public outrage over the slaughter of 78 miners in a coal mine explosion at Farmington, West Virginia, in late 1968 to pave the way for the enactment of the landmark Federal Coal Mine Health and Safety Act of 1969. In Title IV of this Act, Congress legalized the term black lung and for the first time, mandated that an occupational disease occurring in a major industry be eradicated. Created by this law was the black lung benefits program as well as the framework to reduce dust levels in the mines. Subsequent amendments created the Black Lung Disability Trust Fund in an effort to place primary financial responsbility for the benefits program on industry rather than the federal treasury.

Yet today, despite the fact that over one-half million miners still suffer from the devastating effects of black lung and that since 1970, outlays for black lung benefits have exceeded $17 billion, we are still struggling to understand many of the fundamental relationships between the generation of coal dust in the mines, miners' lungs and treatments to both mitigate dust levels as well as the disease itself.

It is for this reason I greeted a joint proposal by West Virginia University (W.V.U.) and Penn State to establish the Generic Center with such enthusiasm in late 1982.

I believe history will show, at least from the American perspective, that the establishment in 1983 of the Generic Technology Center for Respirable Dust represents the most significant effort to address issues relating to black lung disease since enactment of the Federal Coal Mine Health and Safety Act of 1969 and its subsequent amendments.

The Generic Center for Respirable Dust is a fine example of how members of the academic community can identify a research need, take the concept to the Congress and with a good deal of hard work and perseverance, gain legislative approval — despite executive branch inertia.

I remember well the initial efforts in this matter. Ours was a difficult position as we were laboring under an Interior Department that was seeking to abolish funding for the Mineral Institute program as well as effect dramatic reductions in all areas of government supported mining-related research. And yet, we had the audacity to propose a new generic center. In this sense, the undertaking represented a political test of muscle.

In the final analysis, the Administration was no match for the likes of Representative John Murtha of Pennsylvania, who is a member of the Interior Subcommittee on House Appropriations, and Senator Robert C. Byrd of West Virginia, the ranking member on the Senate counterpart subcommittee, as well as a host of other members, including myself, on the authorizing Interior and Insular Affairs Committee.

Mandated by the fiscal year 1983 Interior Appropriation bill, on August 15, 1983, the Generic Mineral Technology Center for Respirable Dust was established by the U.S. Bureau of Mines at Penn State and W.V.U. in association with participating Mineral Institutes at M.I.T. and the University of Minnesota. This was to become the fifth generic center with the other four having been established the previous year also at the directive of the Congress in an effort to consolidate some of the research programs of the 31 Mineral Institutes.

For the first time, a multi-dimensional effort incorporating an integrated scientific-medical-engineering approach to the problems associated with black lung would be undertaken. The Generic Center would also complement other research being conducted in-house at the Bureau of Mines, NIOSH and MSHA, the United Mine Workers of America (U.M.W.A.), as well as in the academic community at large.

Since 1983, we have managed to provide adequate funding for the Generic Center as well as for the related Bureau of Mines programs. I have been impressed with the work being conducted by these entities and, as the chairman of the House subcommittee with jurisdiction, will continue to lend their efforts my full assistance for they represent a prudent investment for the future.

This symposium also represents a wise and necessary investment of time and resources. The task at hand for those of you gathered here today is not an easy one. It will be 20 or 30 years before the effects of the 1969 two-milligram dust standard are known. And, although the U.S. standard is probably the strictest in the world, its inherent safeness is not entirely certain. When Congress mandated this standard, it was based on the assumption of full and complete compliance, and even with that, the British research of the early 1960s which served as the basis of the two milligram standard has never been confirmed by a long-term study. The introduction and increased use of longwall mining techniques has also added a new dimension to the ability to keep dust levels at acceptable limits.

As such, dust control depends on reliable monitoring and improved suppression technologies. Continued research on the effectiveness of the standard itself is also of crucial importance. And for the sake of today's victims of this crippling disease, we must move forward with medical treatments. For there should be no doubt that worker exposure to dust is the most serious and costly health-related problem facing the mining industry.

All too often when we discuss matters relating to health and safety we tend to dwell on numbers, percentages and sanitized scientific terminology. In the Congress, for example, we bicker over financing many of these programs and, in fact, late in 1985 and earlier this year, negotiated endlessly over how much the industry-paid black lung excise tax should be increased. This is a risk public officials and academics alike face and I believe that in order to keep one's perspective, it is of the utmost importance to visit with the victims of black lung as I have done on many occasions.

In this vein, and as this is the opening session of this symposium on respirable dust, I would like to leave you with a quote from a speech made by Dr. Lorin Kerr to the U.M.W.A. at their 1968 convention with the hope you will keep it in the back of your mind during the activities of the next three days. Dr. Kerr, the director emeritus of occupational health at the U.M.W.A. and who is a member of the planning committee for this symposium, with these words placed into perspective what black lung means to its victim and they are words I often revisit during debates in the Congress relating to the federal black lung program:

"At work you are covered with dust. It's in your hair, your clothes and your skin. The rims of your eyes are coated with it. It gets between your teeth and you swallow it. You suck so much of it in your lungs that until you die you never stop spitting up coal dust. Some of you cough so hard that you wonder if you have a lung left. Slowly you notice you are getting short of breath when you walk up a hill. On the job, you stop more often to catch your breath. Finally, just walking across the room at home is an effort because it makes you short of breath."

Distinguished participants to this symposium, the eyes of the Nation's disabled coal miners are on you today. For their sake, and for the well-being of the current and future generations of coal miners, I wish you success in your most important endeavor.

GENERAL

MSHA's Revised Quartz Enforcement Program

THOMAS F. TOMB, PAUL S. PAROBECK, and ANDREW J. GERO
Pittsburgh Health Technology Center, Mine Safety and Health Administration

To control the health hazard associated with quartz in the U.S. coal mining industry, Federal regulations require that whenever the quartz content of the respirable dust in the coal mine environment exceeds five percent, the applicable respirable dust standard is reduced. This regulation, which is applicable for both surface and underground mining operations, has been in force since the promulgation of the Coal Mine Safety and Health Act in 1969. On December 1, 1985, the Mine Safety and Health Administration (MSHA) instituted a revised quartz policy relative to the enforcement of this regulatory requirement.

Under the previous enforcement policy, reduced dust standards were set based upon results of quartz analyses performed only on MSHA inspection samples and were determined from the results obtained from a single sample. The new (or revised) policy allows coal mine operators the opportunity to voluntarily submit samples for use in the standard setting process. The system also provides a mechanism for the reevaluation at approximate six month intervals of mining operations which are on a reduced standard.

This paper presents the background behind the development of the new program and discusses its operating mechanics. Information describing the mining community's participation in the program is also given.

Introduction

It has long been recognized that exposure to coal mine dust can lead to the development of the disease known as coal worker's pneumoconiosis (CWP); defined by Morgan and Seaton as "the accumulation of coal dust in the lungs and the tissues' reaction to its presence."[1]

In 1948 the Bureau of Mines recommended limits of dustiness for mining operations. The limit for dust containing more than five percent quartz was to be determined by multiplying the particle concentration by the percent quartz; the number determined was not to exceed five million particles per cubic foot of air. In setting this limit, recognition was given to the fact that the toxicity of coal mine dust is dependent on the quantity of quartz contained in the dust.

The increased hazard associated with exposure to coal mine dust containing quartz was further recognized by the U.S. Congress, when, as part of the Federal Coal Mine Health and Safety Act of 1969, it required that a formula be developed for determining the applicable respirable dust standard whenever the quartz content of the respirable dust was greater than five percent. Such a formula was developed and is included in Parts 70.101, 71.101, and 90.101 of Title 30, Code of Federal Regulations (CFR). These regulations state that: "When the respirable dust in the mine atmosphere of the active workings contains more than five percent quartz, the operator shall continuously maintain the average concentration of respirable dust . . . at or below a concentration of respirable dust . . . computed by dividing the percent of quartz into the number 10."

In 1978 a review of MSHA's quartz analysis data showed that approximately 40 percent of the underground respirable dust samples analyzed contained greater than five percent quartz; however, because of the analytical techniques used at that time, only 25 percent of the dust samples submitted for analysis were being analyzed. In 1981 a revised analytical technique was implemented.[2] The new technique provided the capability of analyzing nearly all samples submitted for quartz analysis. In December of 1984 there were approximately 1800 underground and 800 surface coal mining entities that were on a reduced standard because the quartz content of the respirable dust exceeded five percent. Figure 1 shows the percentage of samples, by type of underground mining operation, that had a quartz content greater than five percent. Also shown on this figure is the percentage of samples analyzed whose dust concentration exceeded the applicable dust standard established from the quartz percentage determined. One significant point that should be noted from these data is that 60 percent of the samples representative of the continuous mining and roof bolting operations are above the applicable standard established from the quartz content of those samples.

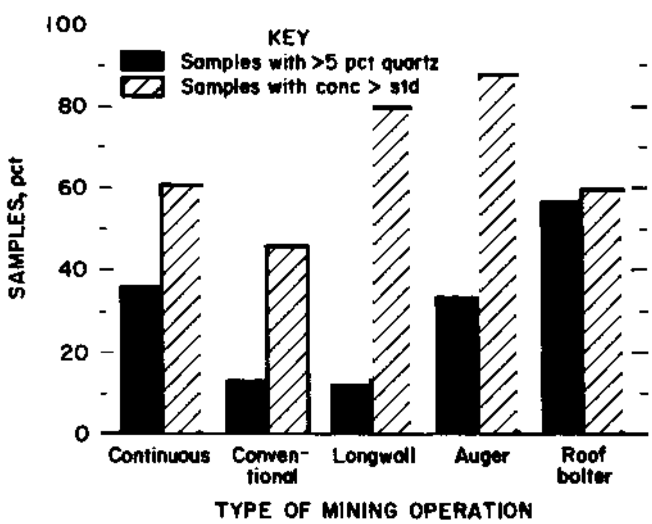


FIGURE 1. Analysis of quartz data from samples containing more than five percent quartz, 1984.

Because of the large number of mining entities on a reduced standard, the fact that many of the entities (more than half) are not sampled after the standard is reduced and mine operators were questioning adjustment of the standard based on the analysis of a single respirable dust sample, MSHA established a program to develop improved enforcement procedures that would enhance the health protection of the miner and the integrity of the protocol used to adjust the respirable dust standard when the quartz content of the dust exceeds five percent.

Quartz Enforcement Program Prior to December 1985

The main thrust of MSHA's respirable dust enforcement program is aimed at approving a mine operator's dust control plan. Selected respirable dust samples collected during the plan approval process are analyzed for quartz and, when necessary, the applicable respirable dust standard is adjusted. MSHA's policy calls for approving or reviewing a mine operator's dust control plan twice a year for underground mining operations and once a year for surface mining operations.

Those samples collected in underground coal mines during a plan approval that are typically analyzed for quartz content are the designated occupation (DO) samples (samples collected on the occupation on a mining operation that has the highest respirable dust exposure), all roof bolter (RB) samples and samples collected from areas of a mine where excessive respirable dust and/or quartz levels are suspected. Designated work position (DWP) samples collected at surface mining operations are the samples typically analyzed for quartz content; however, samples may be collected on other occupations or operations suspected of having excessive quartz and/or respirable dust levels.

TABLE I

Comparison of Occupational Quartz Determinations by Type of Mining

Type of Mining	DO* > All Occupations (%)	DO > All Occupations Except RB** (%)	RB > DO (%)
Continuous	41	68	61
Conventional	43	69	66
Longwall	57	NA	NA
Auger	50	50	100

* CO = Designated Occupation
** RB = Roof Bolter

Underground mine environments on a reduced standard based on the analysis of DO samples are sampled bimonthly by mine operators in accordance with the requirements of Title 30, CFR Part 70. Normally, 30 samples per year are collected in these environments. However, environments with standards which were adjusted based on the analysis of samples collected on the roof bolter or from some other nondesignated area of the mine were not sampled again until the dust control plan was reevaluated. In practice, the time span for resampling of these environments ranged from six months to two years. Consequently, the environments of the roof bolting operation, the underground mining operation that had the highest incidence of exposure to quartz and typically the lowest respirable dust standard, were never monitored for conformance with the reduced dust standard. A similar situation existed for surface coal mine environments. Only those occupations assigned as DWP's are required to be sampled by the mine operator (Title 30, CFR Part 71). Unless those occupations placed on a reduced dust standard are made DWP's by MSHA en- forcement personnel, no further sampling is conducted until the dust control plan is reevaluated. DWP's are sampled bimonthly by the mine operator. A minimum of six samples are collected per year.

Development of Revised Program

To achieve the goals of enhancing miner health protection through improved enforcement procedures and improving the integrity of adjusting the respirable dust standard when the quartz content of the dust exceeds five percent, two investigations were conducted. The first investigation evaluated MSHAs policy of adjusting the respirable dust standard for a mining operation based on the quartz percentage of the designated occupation, and the second centered on quantifying the day-to-day variability associated with the quartz percentage in the environments of underground mining operations.

The first investigation consisted of analyzing all samples collected by enforcement personnel during the approval of a mine operator's dust control plan, for quartz content. This consisted of samples collected on the DO, RB and three or more other occupations working on the mining operation whose dust control plan was being evaluated.

The percentage of quartz determined for the DO sample was then compared to the percentage of quartz determined for: all the other occupation samples on the mining operation, all occupations except the roof bolter. A comparison of these three determinations is shown on Table I. As the comparison shows, the quartz percentage of the DO sample is equal to or greater than the quartz percentage of all occupations approximately 45 percent of the time, is equal to or greater than all occupations except the roof bolter approximately 70 percent of the time and is less than that of the roof bolter sample approximately 63 percent of the time.

It was concluded from this investigation that: 1) adjusting the respirable dust standard based on the quartz determination of a sample collected on the DO would provide protection for the majority of the personnel on a mining operation, except for the roof bolter, and 2) that a separate standard needed to be established for the environment of the roof bolter occupation.

The second investigation consisted of analyzing mine operator dust samples, submitted in fulfillment of regulatory requirements (Title 30, CFR Part 70), for quartz content. The samples analyzed were designated occupation samples from mining operations that were on a reduced dust standard as of April 1983. Data were accumulated on 86 mining operations, which represented approximately ten percent of the operations on a reduced dust standard at that time. For each operation there were five or more samples which represented three or more bimonthly sampling periods. The number of analyses necessary to estimate the long-term average quartz percentage for a given operation was determined by calculating the average quartz percentage using the most recent groups of five, three, and two samples and then comparing these respective averages to the averages determined from all the samples obtained on a given operation. In addition, the last sample analyzed was compared to the overall average.

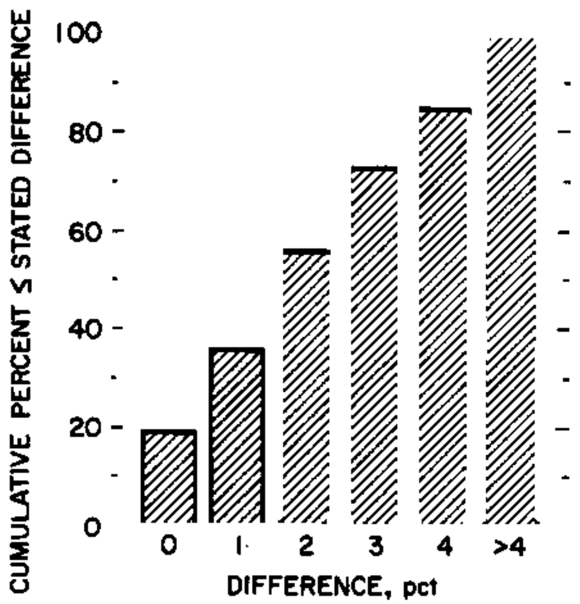


FIGURE 2. Difference between six-month average percentage and percentage of last sample.

Figure 2 shows the cumulative frequency distribution of the differences between the quartz percentage determined over the three bimonthly sampling periods and the quartz percentage of the last sample analyzed. As the data show, a quartz determination based on a single sample is equivalent to the long-term average approximately 20 percent of the time, and is only within three percent approximately 72 percent of the time, indicating that a quartz determination from a single sample is not a good estimator of the long-term average quartz level of an operation.

Figure 3 shows the cumulative frequency distribution obtained when the average of the last five samples is compared to the long-term average. As these data show, the average determined from the most recent five samples agrees closely with the long-term average, i.e., the five sample average is within one percent of the long term average 87 percent of the time and within two percent 92 percent of the time.

Figure 4 shows the distribution obtained using the average of the last three samples. As the data show, at a difference of two percent, the average of three samples provides nearly as good an estimator of the long-term average as using the average of five samples.

A comparison of the average of the last two samples to the average of the last three samples is shown in Figure 5. This comparison shows that these two averages are within two percent 96 percent of the time. Based on these data, it was concluded that a reasonable estimate of the long term (six months) average quartz percentage of an operation could be obtained from the average of three samples and that a high percentage of the time the average of the two most recent samples reasonably agreed with the average of the most recent three. These data were used to develop the sampling scheme used in the revised quartz program to adjust the dust standard of an operation.

Revised Quartz Program

In developing the revised quartz program, the following objectives were given primary consideration:

1. Accounting for the day-to-day variability associated with environmental quartz percentages.
2. Using samples collected by mine operators to establish the dust standard when the percent quartz in the mine environment exceeds five percent.
3. Providing for subsequent environmental monitoring of occupations, or environments placed on a reduced dust standard.
4. Reevaluating operations on a reduced dust standard biannually.

All of these objectives were met in the program developed and implementation of the program did not require the promulgation of new regulations or changes to existing regulations.

In the revised quartz program, samples collected during the approval of a mine operator's dust control plan are similarly submitted for quartz analysis, i.e., samples collected on the DO, RB, DWP as well as those collected from

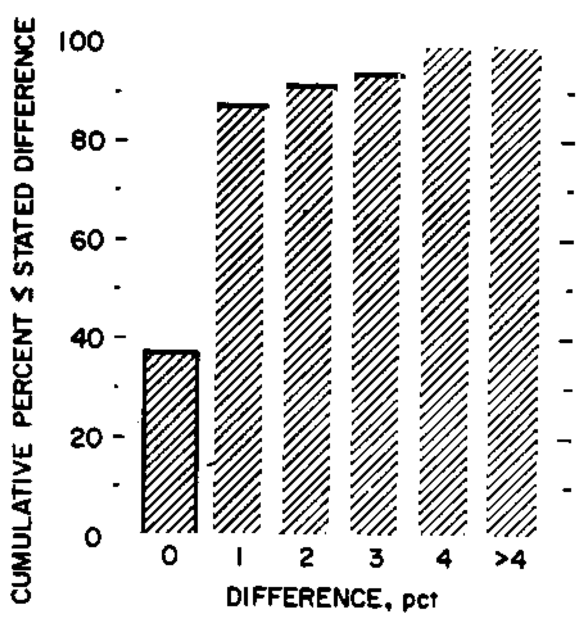


FIGURE 3. Difference between six-month average percentage and average percentage of last five samples.

areas where excessive respirable dust and/or quartz level are suspected. If any of the samples submitted for quartz analysis are found to contain more than five percent quartz, the mine operator is notified that he has the option of collecting a sample on the entity represented by that sample and submitting it to MSHA for analysis. If the analysis of the sample shows the quartz percentage to be within two percent (difference) of the MSHA sample, the quartz determinations from the two samples are averaged. If the average is greater than five percent, a new environmental dust standard is established based on the average quartz value. However, if the quartz determination of the operator's optional sample differs from the MSHA sample by more than two percent (difference), the operator is given the option of collecting another sample on the entity and submitting it for analysis. The quartz determinations from all three samples are then used to establish an average quartz percentage for the entity. If the average quartz percentage is greater than five percent, the standard for the entity is accordingly adjusted. In any instance where the mine operator does not elect to submit a sample for analysis or the samples submitted do not contain sufficient dust (greater than 0.5 milligrams) for analysis, the standard established for the entity is based on the quartz percentage determined from the MSHA sample or, if a first optional sample had been submitted, on the greater of the two (MSHA or operator). In the revised program, any entity, other than the DO, that is placed on a reduced dust standard can be required to be assigned "designated area" (DA)

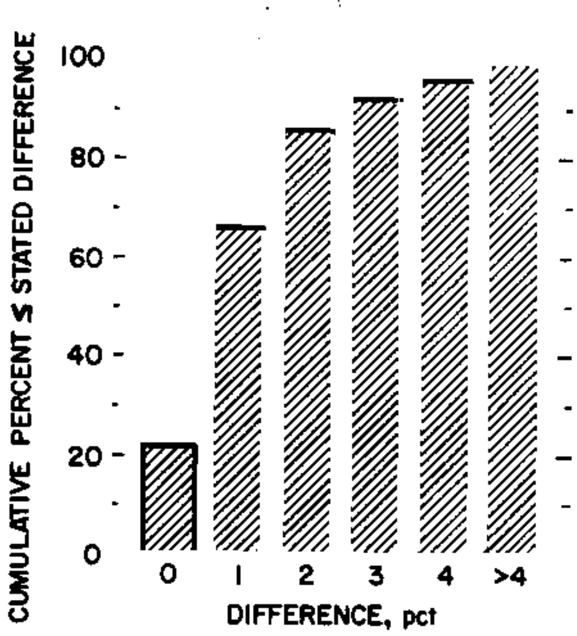


FIGURE 4. Difference between six-month average percentage average and average percentage of last three samples.

status. This requires the entity to be identified in the operator's Ventilation System and Methane and Dust Control Plan and to be sampled bimonthly by the mine operator. The mine operator is required to collect five samples bimonthly on the DO whether the dust standard has been adjusted or not. The samples may be collected on consecutive production shifts or on production shifts on consecutive days. Requiring all entities on a reduced standard (other than the DO) to be made designated areas is considered a major thrust at enhancing miner health protection because subsequent monitoring of the entity is then required by the mine operator.

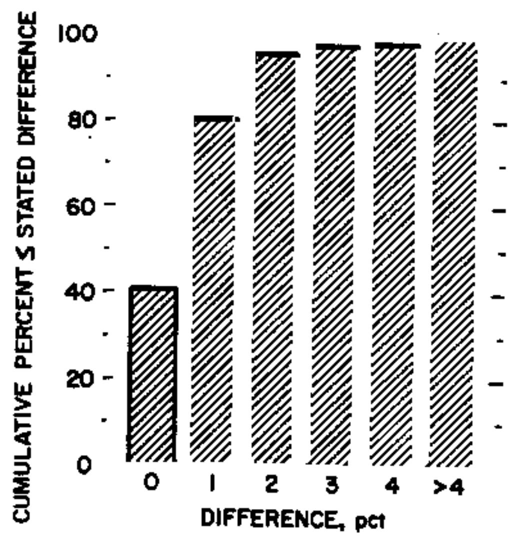


FIGURE 5. Difference between average percentage of last two samples and average percentage of last three samples.

Six months after an entity has been placed on a reduced dust standard, the data of samples submitted by mine operators in accordance with regulatory requirements (Title 30, CFR) are screened by a computer. Provided that the entity is in compliance with its applicable dust standard, the computer identifies the first sample submitted with sufficient dust for analysis. This sample is then analyzed for quartz content. If the quartz percentage determined from that sample is within two percent of the quartz percentage used to adjust the standard, the quartz percentage used to adjust the standard and the quartz percentage determined from the operator's sample are averaged and the standard revised accordingly. If the quartz percentage from the operator's sample is not within two percent, the operator is given the option of collecting and submitting a sample for analysis. The environmental dust standard for the operation is then determined by averaging the quartz percentage used to establish the existing standard, the quartz percentage determined from the computer selected sample and the quartz percentage of the optional sample submitted by the operator. If the operator does not elect to submit the optional sample or the sample is voided because of insufficient weight, the preestablished environmental standard remains in effect. The standard is not automatically reevaluated again until another six month period has lapsed.

Revised Quartz Program Status

Initiation of the revised quartz program commenced on December 1, 1985. At the time of commencement approximately 360 samples were being analyzed per month; 38 percent of these were DO samples, 10 percent DWP samples, 6 percent DA samples, 33 percent roof bolters, and the remainder nondesignated entities or work positions. Of the samples analyzed, approximately 30 percent of the DO samples, 50 percent of the roof bolter samples, and 50 percent of the DWP samples contained greater than five percent quartz. Based on these figures and the assumption that 100 percent of the mine operators would elect to submit a sample for analysis when given the option and that 45 percent of the time a third optional sample would be submitted by the operator, it was estimated that approximately 18,000 quartz analyses would be performed a year.

At the present time, approximately 500 samples per month are being analyzed. The percentage of samples being analyzed in the respective categories previously discussed is approximately the same, and the percentage of samples in each of the categories that have a quartz percentage greater than five percent is also approximately the same. However, mine operators are not electing to participate in the standard setting process at the level assumed (100%). Only 35 percent of the operators who have been notified that they have the option of submitting a sample for analysis have elected to submit one. Of the optional samples submitted by mine operators, approximately 25 percent could not be analyzed because of insufficient weight gain (< 0.5 milligrams).

Prior to commencement of the revised program, it was estimated that quartz determinations on two consecutive samples would be within two percent (difference) 55 percent of the time and the option to submit a third sample would occur approximately 45 percent of the time. However, at the present time only 31 percent of the operators' first optional samples are within two percent of the MSHA sample, permitting the option to submit a third sample 69 percent of the time.

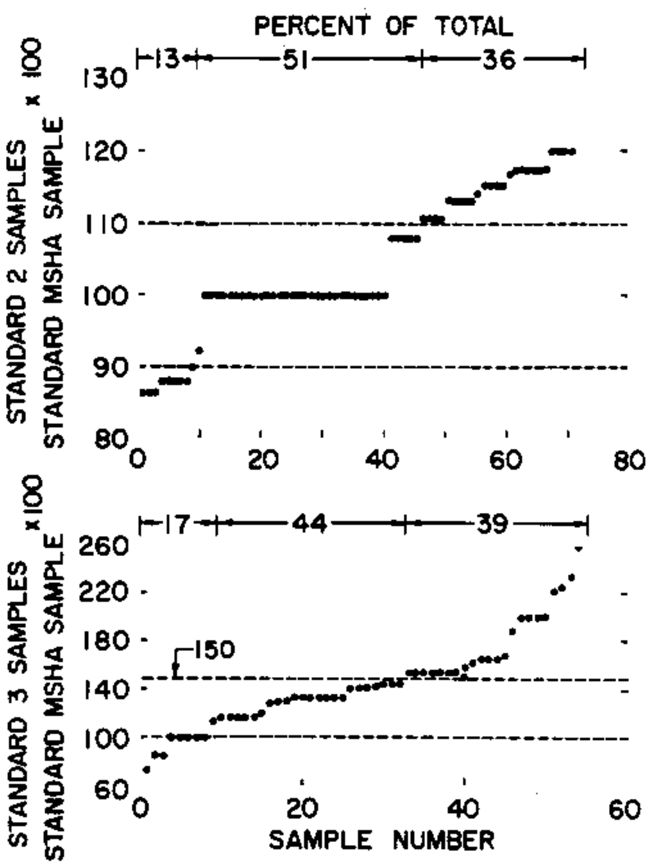


FIGURE 6. Comparison of dust standards established using an average quartz value and the quartz value from a single MSHA sample (data from revised quartz program.)

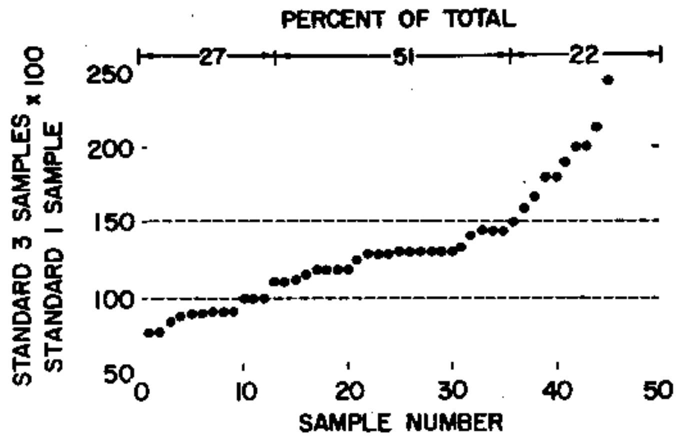


FIGURE 7. Comparison of dust standards established using an average quartz value from three samples and the quartz value from one sample (data from analyzing operator samples).

The effect of the revised program on the standard established for a given operation was also assessed. Figure 6 shows a comparison of dust standards established using the average quartz value determined from the analysis of two or three samples and the quartz value determined from the MSHA sample that was greater than five percent. As these data show, dust standards established from the average of two samples (one MSHA and one operator) are equal to or within ten percent of the standard determined from the MSHA sample alone 51 percent of the time and are 10 to 20 percent higher 36 percent of the time. When three samples are used (one MSHA and two operators) the standards established exceed those established using the one MSHA sample 83 percent of the time. Approximately one-half of these standards are more than 1.5 times those established from the one MSHA sample. Standards derived from the single MSHA sample exceeded the standard derived from using the average from three samples only 7.5 percent of the time. This percentage is not significantly different from that obtained from a similar analysis of operator data where standards based on quartz determinations from a single sample, with greater than five percent quartz, were compared to the average determined from three samples (the single sample determination being one of the three). A plot of these data is shown in Figure 7. As the data show, approximately 73 percent of the time the standard derived from the average quartz percentage is greater than that derived from the single sample; with approximately 27 percent of these exceeding 1.5 times those established from the single sample.

As previously discussed, one of the major objectives of the revised quartz program was to enhance miner health protection through subsequent monitoring of occupations or environments placed on a reduced dust standard, the occupation of primary concern being the roof bolter. To date, there have been 482 roof bolting operations placed on a reduced dust standard (approximately 45% of all roof bolter samples analyzed have greater than 5% quartz). At the present time 243, or 50 percent, of these operations have been established as a DA, thus requiring subsequent monitoring by the operator.

In May of 1986, computer screening of operator respirable dust samples from operations on a reduced dust standard commenced. Nine samples had been identified and analyzed by August. To date insufficient data have been gathered to comment on this aspect of the program.

Epilogue

MSHA's revised quartz enforcement program inherently contains the elements necessary to achieve the objectives of:

1. Taking into consideration the day-to-day variability associated with quartz percentages when establishing the respirable dust standard for a mine environment.
2. Using the analysis of operators' samples to establish the respirable dust standard of an environment.
3. Subsequent monitoring of personnel or operations placed on a reduced dust standard.
4. Reevaluation of operations on a reduced dust standard biannually.

However, a review of the revised program seven months after its implementation indicates that several of these objectives have not been fully realized. Mine operators have elected to submit optional dust samples for use in establishing an environmental dust standard only 35 percent of the time, and the percentage of roof bolting operations that have been placed on a reduced dust standard and assigned "designated area" status, is less than originally projected. Failure of mine operators to participate in establishing the standard has had no impact on individual health protection because standards established based on the analysis of a single sample are typically lower than those established from averaging the results from several samples. However, not assigning roof bolting operations on a reduced dust standard "designated area" status eliminates any requirement of the operator to subsequently sample the operation to confirm that the dust concentration is being maintained at the applicable standard.

References

1. **Morgan, W.K. and A. Seaton:** *Occupational Lung Diseases..* W.B. Sanders Company, Philadelphia, Pennsylvania (1975).
2. **Goldberg, S.A., T.F. Tomb, P.M. Kacsmar et al:** MSHA's Procedure for Determining Quartz Content of Respirable Coal Mine Dust. Mine Safety and Health Administration, *IR 1152* (1984).

A Working Hypothesis on How Silica and Silica Surface may Cause Silicosis and CWP

T.P. MELOY
Benedum Professor, Particle Analysis Center, West Virginia University, Morgantown

This paper presents an interim progress report on our recently begun research project on respirable dusts. We are reporting on a sophisticated, predictive, probably correct, testable hypothesis that postulates a mechanism by which some natively cytotoxic respirable size mineral particles, such as kaolin, are not harmful to the lungs, while other equally cytotoxic particles, such as quartz, are, even in small quantities, very harmful. In essence the hypothesis predicts that some mineral particles, not normally present in the earth's ambient dust, causes the lungs dust defense mechanisms to turn on the lung and harm it. However fruitful the hypothesis may be, it is a hypothesis and much work remains to be done before it can be accepted as a theory.

While I may make the presentation and be the PI, my co-PI, Dr. William Wallace of NIOSH, has and will continue to make at least as much contribution to the project as I. Our sophisticated hypothesis is deeply scientifically based and unfortunately, in spite of the multifacited aspects of this project, there is virtually nothing in the literature to guide our work. This means we must go back to the classical physics to develop the models for calculating the powerful electrical effects near particle edges, and we must measure the fundamental biological constants associated with pulmonary macrophage. While there are daily discussions on Boltzman distributions, Einstein's Brownian Motion paper, the Nernst Equation, and sophisticated semi- *in vivo* biological time constant measurements, we are aware that this is not an easy problem and we are not likely to have irrefutable closed solutions to these problems by next Monday morning.

Hypothesis

Let me now turn to our hypothesis. In order to occupy all the naturally occurring surface areas on the earth, man, during his long evolution from fish, had to evolve effective defenses against all the naturally occurring cytotoxic respirable mineral dusts. For example, clays, which are often the main component in naturally occurring respirable mineral dusts, are quite cytotoxic but do not harm the lung. However, for respirable mineral dusts that contain significant amounts of nonnaturally occurring but equally cytotoxic quartz and asbestos particles, the body has not had to evolve an effective defense mechanism, and thus respirable mineral dusts containing these particles may harm the lung. Our hypothesis is, therefore, that a few nonambient minerals such as quartz, cause the bodies dust defensive system to harm the body in a manner analogous to Lupus or MS, diseases of the immune system.

For respirable size mineral dusts that enter the alveoli of the lung, the body has evolved three main defense mechanisms: surfactant coating of the particles which acts as a protective sheath, ingestion and eventual removal of the particle from the lung by macrophage — phagocytosis, and when the afore mentioned mechanisms fail, walling off the affected area by scaring — fibrosis. In the case of the clays, the first two defense mechanisms work, while in the case of quartz, some types of coal particles and perhaps some other minerals, such as asbestos, the first two mechanisms fail and the body responds by initiating fibrosis, characteristic of silicosis, progressive massive fibrosis and asbestosis. It is believed that when a macrophage is killed, some type of chemical messenger is released, when present in sufficient quantities, initiates fibrosis.

To understand how the body responds to respirable mineral dust particles, consider the fate of two respirable size particles, 2 to 5 um, when they enter the lung's alveoli. Let one of the particles be kaolin, a typical clay, and the other a freshly broken, sharp edged, quartz particle. Immediately, both particles are wetted and then covered by a protective coating of the lung's surfactants, primarily lecithin. In time, the lung's free scavenger cells, pulmonary macrophages, ingest by a mechanism called phagocytosis both the clay and the quartz particles. After ingestion, both particles are exposed to the digestive, lytic enzymes of the macrophage. While the kaolin particle remains in the macrophage and is eventually removed from the lung, the quartz particle destroys the macrophage and remains in the lung.

Wallace *et al* [1] mimicked experimentally the events that take place in the lung by first coating respirable size kaolin and quartz particles with lecithin, digesting this coating with the lytic enzymes of the macrophage, and then testing the cytotoxicity of these treated kaolin and quartz particles. With one or two hours of enzyme exposure, most of the protective coating remains on the kaolin particle with some modification of the outer adsorbed layer. On the other hand, the lytic enzymes rapidly removed most of the coating from the quartz particles thus retoxifying them, and these stripped particles were again cytotoxic. (Both kaolin and quartz particles uncoated are equally cytotoxic, but when both particles are coated with the pulmonary surfactant lecithin, both are noncytotoxic.) As a test the lecithin coating, enzyme digestion, cytotoxic testing test has wider application.

The writer believes that a modification of the above described dust test may now be used for quantitatively testing the cytotoxicity of quartz bearing respirable mineral dusts and thus presumably the pathogenicity of said dusts. Furthermore, in the relatively near future, this test may well be shown to apply to a variety of other minerals and solids that cause pulmonary fibrosis. This test, a research tool now, may well become the standard laboratory test of monitoring and predicting the quantitative pathogenicity of respirable mineral dusts. Currently, Dr. Wallace is measuring longer digestion time behavior of the dusts in the test systems to investigate the possible role of such interactions in the pathogenisis of pneumoconiosis and to determine if the phenomenon might provide a basis for more predictive cytotoxic testing. Additional test parameters are also being investigated.

Since the body evolved a simple effective protective mechanism that covers a large variety of naturally occurring respirable size mineral particles such as clays, oxides, carbonates, hydroxides, halides, silicates, borates, sulfides, sulfates and phosphates, why is this mechanism not effective against the silica minerals: quartz, cristobalite and tridymite? What is so unusual about these silica minerals. Quartz, which is characteristic of these silica minerals, has four unusual properties: it is relatively inert chemically, piezoelectric, in physiological saline it has a very high surface charge, and it has extraordinarily sharp edges and corners. Quartz's chemical inertness means that it does not bind surface coatings strongly and thus they are easily removed by the microphage's lytic enzymes. Combined with quartz's extremely sharp edges and corners, the high surface charge means that at the sharp edges and corners very powerful electrical effects are present; so powerful in fact, that when an edge with these electrical effects is brought close to a cell's membrane, it will rip that membrane apart. Finally, quartz being piezoelectric can generate large voltages when impacted.

Clays, in contrast to quartz, are quite active chemically, binding surface coatings tightly, and do not have sharp edges and corners. However, clays, because of their layered structure which consists of alternate layers of positive and negative charges, also have very powerful electrical effects on their edges, which, when uncoated with a surfactant, are as cytotoxic as quartz.

Coal particles, which normally would be considered benign, sometimes have a quartz surface and thus would behave as if they were a quartz particle. Meloy[2] has postulated that the cleats in coal, which act as conduits for underground water, have their surfaces coated with quartz, and he has shown that the amount of respirable size quartz-coated coal dust particles present in an unregulated coal mine is sufficient to cause the characteristic fibrosis. However, these quartz-coated coal particles would have a quartz assay that would be very low compared to the number of quartz-coated particles present. Obviously, the number of quartz-coated coal particles present must be measured experimentally by a variety of approaches — something we are currently setting up to do.

One can speculate that the *in vitro* test described above may predict which type of mineral particles will be cytotoxic because the test itself mimics the action of the body defense so closely. Those particles that do not destroy macrophage will not test positive, will not be cytotoxic, and will not be fibrogenic. Those particles that do test positive, will probably also destroy macrophage, be cytotoxic, and initiate fibrosis. Therefore, there is the possibility that this proposed work will lead to a generalized mineral dust test.

Sub Programs

In a hypothesis as sophisticated and promising as the one presented above, there are number of related but independent programs that must be done before the hypothesis can be considered a viable theory. We must show that the "*in vitro*" mimicking of the macrophage's phagocytosis is as postulated, and we must also explore the envelope of the pulmonary surfactants and lytic enzymes. In addition, we must show that the powerful electrical effects exist for both the uncoated quartz and clay particles; that these electrical effects are strong enough to disrupt cell membranes, that experimentally modified (rounded) quartz particles are not cytotoxic, that experimentally quartz particles really have these unusually sharp edges and corners, that a significant amount of quartz-surfaced particles exist to initiate pulmonary fibrosis, and that cleat surfaces are silica coated.

Electrical Effects

Because there is no extant method for measuring the electrical affects near a sharp edge or corner, extending out 30 to 50 A, these effects must be calculated. Since the Chapman Gouy and similar models were developed for flat or gently curving surfaces and are not applicable near sharp edges and corners, an entirely new model to describe the electrical fields near these sharp features has been developed. Until actual SEM measurements are available characterizing the sharpness of quartz, we must calculate these electrical effects by making the fundamental calculation of the distribution of the ions and surface charges near the edges, using the Boltzman distribution and Nernst equation and then seeking to integrate the Poisson equation in a region near a tip or edge of known radius of curvature. In addition, since the respirable quartz particles are small and subject to Brownian motion that results in rather high peak velocities, we must calculate the effect of this motion on the electrical effects. Quartz being piezoelectric, will generate voltages when struck by molecules during its Brownian motion dance. Because these calculations go back to the basis of classical physics and involve noncontinuum fluid flow, they are not easy. While we are confident that we will get accurate answers, currently, we are trying to calculate the bounds on these electrical effects before getting the broader solutions.

In addition to the edge effects, we also must show that the molecules that comprise the surface membrane of cells can be disrupted by the electrical fields calculated above. This is done by showing that the neutral molecules with a charge separation in a unit membrane can be disorganized when closely approached by an electrical field of the strength and divergence calculated above. While there may be experimental methods of showing this to be true, the cost and time to do the experimental work is prohibitive.

Finally, in this program we must show that the uncoated layered clay particles have electrical effects also sufficiently powerful to disrupt cell membranes. Part of the work done above may be applicable to the clay edge problem. Once again, one is working with discontinuous charge distributions and non-Newtonion fluid flow. Experimental measurements do not appear to be feasible.

Macrophage — Mimicking

When a respirable particle deposits in a pulmonary alveolus, its first contact will be with the pulmonary surfactant lining the wet alveolar surface. The possibility that the major component in the surfactant could adsorb onto a respirable particle has been investigated by Wallace *et al.*[3] Following the surface adsorption on both the clay and quartz particles, the cytotoxicity of both coated particles is neutralized.[4] We presume that such coated particles in the lung are phagocytized by pulmonary macrophage and subjected to an enzymatic digestion process within the cell. These processes are being modeled by "*in vitro*" enzymatic digestion of lecithin treated dusts.[1,5] Currently, the results of these reported studies are being used as the basis for extension of the studies to longer digestion times, full surfactant and full enzyme use, and testing using macrophage in culture. The tests are designed to determine the time course of enzymatic digestion of protective surfactants from various dust (mineral) surfaces to determine if there are mineral-specific difference which might be significant to the initiation of pulmonary disease process. These studies are performed in concert with NIOSH projects on "Effective Silica Indices for Respirable Mineral Dusts, Evaluating Prophylactic Coatings for Silica Dusts," and the NIOSH – USBM Interagency Agreement on "Correlation of Free Silica and Active Silica Content of Respirable Coal Mine Dust Fractions Associated with Coal and Overburden Mineralogy."

Dust Test

Currently, we are doing our dust testing at NIOSH, but we are in the process of setting up the simple "*in vitro*" dust test in my laboratory at CCMER. Cytotoxicity of a variety of respirable size dust particles will be tested as a function of surfactant morphology, surface charge and surface coating. In addition, we plan to test raw respirable mineral dusts from coal and perhaps other mines as well as artificially generated dust samples. We anticipate having a full load of work for the dust test laboratory. We do not claim that our dust cytotoxic test is fully developed or even proven, but it is a powerful research tool, and, imperfect as it may be, it does mimic the *in vivo* defense of the body to respirable size mineral dust particles.

SEM — Shape Characterization

Key to the proposed hypothesis of the cytotoxicity of quartz particles is the sharpness of the corners and edges of quartz particles. Since once again there is nothing quantitative in the literature on the sharpness of quartz's edges, these parameters must be measured with an SEM. Fortunately, we hope we may soon purchase a new SEM with sufficient brightness and resolving power to measure the radius of curvature of these edges. From other work we believe that the sharpness will be on the order of 8 A. For an SEM to make this measurement it must not only have the brightness and resolving power, but it also must have two orthogonal angles of specimen tilt, a goniometer, so that the edge of the particle will be parallel to the beam. Current SEMs available to us do not have the needed resolving power, brightness, or extra angle of tilt. Probably a field emission SEM with a resolving power of 15 A will be required.

Should the SEM available to us not be able to resolve the sharpness of the corners and angles, then we will probably work with the National Electron Microscope Laboratory located in Berkeley, California. We are in contact with the Scientific Director and applying for the necessary time and status to use their facilities if needed. One of the problems in working with quartz is that high kvs smashes quartz, therefore high magnification with low kvs is required. It will probably be sufficient to show that the radius of curvature at an edge is less than 15 A. In any event, to calculate the electrical field effects at an edge or corner, it is necessary to postulate the sharpness of that corner.

Cleat Surfaces — A Possible Source of Cytotoxic Particles

The presence of respirable quartz-bearing mineral particles has been well documented in many coal mines, and MSHA regulations address the quartz content of mine dusts. Work is currently underway by NIOSH-USBU, and work is being included in the Respirable Dust Center Program by Dr. Seehra to determine the surface availability of quartz in mixed composition mine dusts. Prof. Ting[6] and I are preparing a study to determine if some quartz bearing dust originates from quartz deposited on organic coal substrates, a study which would compliment the above effort and the Shape and Surface Characteristics project.

Meloy[2] has demonstrated that if the cleat surfaces are mineralized with quartz, then in many mines there will be enough quartz coated coal particles to cause a fibrotic reaction. From locked particle theory,[7-10] it is predicted that only one coal particle in two to five hundred will show a quartz coating. Proposed, by Profs. Ting and Meloy, is an additional approach to look directly at the cleat surface to see if they are mineralized with silica.

Summary

What I have presented is an explanation of how quartz and clay particles are and are not cytotoxic depending on whether they are coated or not. This explanation depends solely on physical effects — electrical fields and mechanics from the classical physics — not on traditional biological explanations. In the long view all biological and even all chemical reactions are governed by physics. As Prof Philip Morrison of MIT once said, "We are cousin to the clouds and brother to the stones" and the law of physics that effect them also effect us.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

References

1. Wallace, W.E. et al: *Proceedings Coal Mine Dust*

Conf. Morgantown, WV (1984).

2. **Meloy, T.P.:** A Hypothesis on the Possible Contribution of Coal Cleats to CWP. *Proceedings Respirable Dust in the Mineral Industries Conference,* pp. 240-241. Univ. Park, PA (1986).

3. **Wallace, W.E. et al:** *J. Colloid Interface Science 52: 535 (1975).*

4. **Wallace, W.E. et al:** *J. Toxicol. Environ. Health 16:* 415 (1985).

5. **Wallace, W.E. et al:** *Proceedings Inhaled Particle Conference.* Cambridge, England (September 1985) (To be published).

6. **Ting, F.T.C.:** Origin and Spacing of Cleats in Coal. *Trans. AIME,* Vol. 99. J. Press., Vessel Tech. (1977).

7. **Meloy, T.P.:** Liberation Theory — Eight Useful Theorems. *Int. J. Miner. Proc. 13*:113-124 (1984).

8. **Meloy, T.P., U. Preti and G. Ferrara:** Volume and Mass Locking Profiles Derived — Theoretical and Practical Conclusions. *Int. J. Miner Proc.* (1986) (To be published).

9. **Meloy, T.P. and N.N. Clark:** Generalized Locking Profile of Angular Particles — Locked Particle Theory. *Part. Charact.*, pp. 63-67 (1986).

10. **Meloy, T.P. and N.N. Clark:** Locking Profile of Diamond Shaped Particles — of all Aspect Ratios. *Int. J. Miner Proc.* (1987) (To be published.).

Wetting Characteristics of Particles and Their Significance in Dust Abatement

S. CHANDER, B.R. MOHAL and F.F. APLAN

Mineral Processing Section, The Pennsylvania State University, University Park

Dust abatement by water sprays involves the subprocesses of 1) collision between dust particles and water droplets, 2) adhesion of particles to droplets, and 3) engulfment of particles by the droplets. A review of the fundamental aspects of these subprocesses shows that collisions between particles and droplets are determined by aerodynamics and the size and surface charge of the particles and of the droplets. However, the adhesion and engulfment subprocesses depend upon the wetting characteristics of the particles. Although wetting agents (also known as surfactants) have been used as dust suppressants in several investigations, conflicting results are available regarding their effectiveness. In this paper, we show that these results can be explained if the effects of coal rank on surfactant adsorption and wetting characteristics are taken into account.

The influence of several nonionic surfactants containing polyethoxy adducts on the wetting behavior of coal is presented. The wetting was determined by a modified Walker Test method, and contact angle measurements. The results show that the wettability of coal depends upon coal rank, structure of the hydrocarbon chain of the surfactant, and the number of ethoxy groups in the molecule.

Introduction

Due to the inherent nature of the mining process, a large number of particles are generated, a portion of which becomes airborne to create dust. Dust can be aesthetically and environmentally unacceptable and it can also be explosive. Fine particles in the respirable size range (< 5 um) are considered to cause lung diseases, namely, silicosis, pneumoconiosis, etc.[1] Several approaches to reduce dust in mine environments are practiced throughout the mining industry. These include decrease in generation of dust through improvements in mine machinery, ventilation (in which lower dust levels are achieved by dilution of contaminated air with clean air), and dust removal methods. Water sprays are most commonly used to remove dust particles. Recently, scrubbers are reported to have been installed on mining machines to remove dust,[2,3] which also make use of water sprays to reduce dust.

Wetting agents, also known as surfactants, are often used to increase the effectiveness of water sprays in capturing dust particles, particularly in the respirable dust range. This use of surfactants is not new. As early as 1924, a sulfonated hydrocarbon was found to be a very effective dust suppressant in both laboratory tests and underground trials.[4] Foams have been suggested as alternate to water sprays,[5] but their use also depends upon use of surfactants to create foams and improve adhesion.

The use of wetting agents to suppress dust in various coal mining and preparation stages has been increasing even though no consensus exists regarding their overall effectiveness. The following conclusions by various investigators illustrate this observation:

"*. . . surfactants act through several mechanisms – increase wettability of particles, ease atomization of water and increase dust adhesion.*"[6]

"*. . . use of wetting agents reduced the dust loading of return air by 30% compared with the use of water alone.*"[7]

"*. . . wetting agents ineffective when mining the high volatile coal of the Pittsburgh seam.*"[8]

"*. . . a noticeable reduction in visible airborne dust in face areas resulted from adding a wetting agent to the water spray.*"[9]

"*. . . one possible solution that has been in use in some coal mines for a number of years and is now receiving renewed interest is the use of chemical surfactants.*"[10]

"*. . . laboratory tests indicate that 10 to 15 percent more respirable dust can be collected with wetting agents than with water alone.*"[11]

"*. . . we don't know why some agents work and some don't, some coals are wettable and some aren't.*"[12]

"*. . . no significant correlations among the four wetting tests were observed.*"[13]

Capture of Dust Particles by Water Sprays

The main objectives of water sprays used for in-mine dust removal are 1) to prevent particles from becoming airborne, and 2) to collect the airborne particles. The capture of dust particles by water droplets can be visualized in terms of a series of subprocesses which are:

1. Approach of dust particles to the droplet surface.

2. Adhesion of the dust particles with the droplet.

3. Engulfment of the particle within the droplet.

For effective dust control, all these sub-processes must be rapid, with the slowest sub-process determining the rate. The rate of capture of dust particles by water droplets can be written as:

$$\text{rate} \ \alpha \ \text{collision frequency X collision efficiency} \qquad (1)$$

The collision frequency depends upon the following:

- Particle size and droplet size
- Aerodynamics of the system
- Number density of the particles and droplets

In case of water sprays, the droplet size is primarily determined by the nozzle characteristics and pressure drop across the nozzle. Typical droplet diameter varies from 150-360 um,[14] with an average value of 250 um. The smaller the droplet size, the greater is the number density for the same amount of water sprayed. The particle size at the dust generation source would be from submicron sizes to ROM size coal. However, all the fragments produced in mining do not become airborne.[15] The characteristics of in-mine dust depends upon the nature of the mining method, coal seam, production rate, air velocities, etc.

The aerodynamics of the system are influenced by the particle and droplet sizes and their relative velocities. Three types of collision mechanisms can be envisaged, they are:

1. Inertial impaction

2. Flowline interception

3. Brownian diffusion.

Inertial impaction is the most common mode of collision for particles greater than 3 to 5 um, whereas Brownian diffusion is the predominant mode of collision for particles less than approximately 0.3 um. Flowline interception can be significant when the dust particle must flow through a series of collectors as in filtration.

The collision efficiency, (i.e., the effectiveness of a collision to result in particle capture), depends upon the wetting characteristics of the particle. Also known by the names, attachment coefficient, sticking factor, etc., this parameter is often forgotten. Since capture of particles must involve both adhesion and engulfment processes, the wetting behavior of particles is an important consideration.

Three kinds of wetting phenomena are involved in capture and engulfment of particles: adhesional wetting, spreading wetting and immersional wetting. Adhesional wetting refers to the process of formation of a three phase contact between the dust particle, water droplet and air. Spreading wetting refers to the movement of the liquid/air interface along the surface of the particle such that the solid/liquid interfacial area increases and the solid/air interfacial area decreases. Immersional wetting refers to the process of transfer of the particle from air into water. The free energy changes for the three wetting processes can be represented by the following relations:

$$\text{Adhesion:} \quad \Delta G_a = \gamma_{SL} - \gamma_{SA} - \gamma_{LA} = -\gamma_{LA}(1 + \cos\Theta) \qquad (2)$$

$$\text{Spreading:} \quad \Delta G_s = \gamma_{SL} - \gamma_{SA} + \gamma_{LA} = \gamma_{LA}(1 - \cos\Theta) \qquad (3)$$

$$\text{Immersion:} \quad \Delta G_i = \gamma_{SL} - \gamma_{SA} = -\gamma_{LA}\cos\Theta \qquad (4)$$

where γ_{SL}, γ_{SA} and γ_{LA} are the surface free energies of the solid/liquid, solid/air and liquid/air interfaces, and Θ is the contact angle. The interfacial free energies and the contact angle, and hence the conditions for wetting can be altered through adsorption of surfactants. The free energies for the three wetting processes, plotted as a function of contact angle in Figure 1, are quite different from each other. Capture of particles by adhesional wetting is most likely to occur because ΔG for this process is the smallest (or most negative). When particles are captured by this mode of wetting, they will remain at the surface of the droplet. For particles to be engulfed by the droplet, the liquid must spread on the particle surface before immersion can occur. Since G_s is positive for all values of Θ except when $\Theta = 0$, a necessary condition for engulfment of particles is that $\Theta = 0$. Thus, for wetting agents to be effective, lowering of both γ_{LV} and Θ are desired. Although the first condition, namely, lowering of γ_{LV}, is generally recognized, the second condition, namely, lowering of contact angle, is frequently overlooked. Figure 2 shows that the contact angle of coal is highly dependant upon rank parameters such as fixed carbon.[16] Therefore, dusts from mining of different coal types can be expected to behave very differently when exposed to water sprays. Wetting agents are of critical importance in wetting highly hydrophobic materials such as the higher rank coals. The remainder of this paper describes the effect of several different surfactants on the wetting behavior of coals of various ranks.

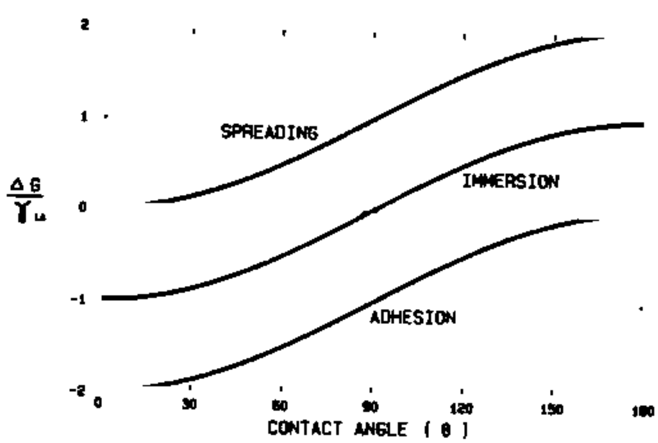


FIGURE 1. The free energies of spreading, immersional and adhesional wetting phenomena as a function of contact angle.

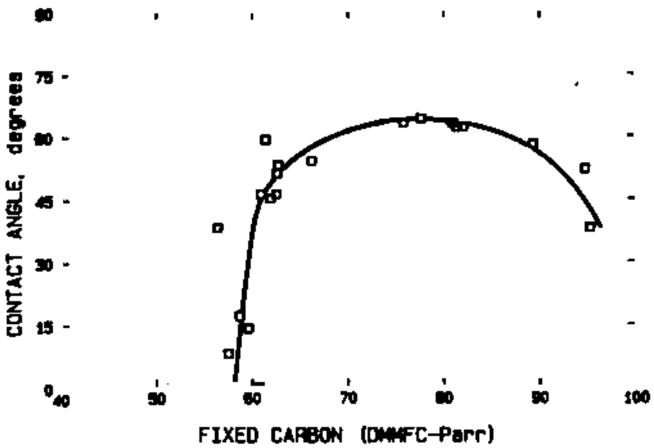


FIGURE 2. Captive bubble contact angles as a function of fixed carbon content for various coals.

Loading of Water Droplets by Dust Particles

The effectiveness of water sprays can be greatly enhanced if particles are imbibed (engulfed) by water droplets rather than attached to the surface of the droplets. The following calculation, in which typical in-mine conditions are used, illustrate this fact.

The total mass of respirable dust generated in a typical coal mine is about 3.5 gram/pound of coal mined[15] which is equivalent to about 8.3 kilogram per minute of respirable dust generated. Since the total dust generated, and not the respirable fraction alone, will be seen by water sprays, on an average of about 25 kilogram per minute dust will be exposed to 15 gallon per minute water spray. For an average droplet diameter of 250 um, the surface area available for capture of dust is 22.7 m^2/sec. The surface area occupied by a layer of dust particles in the same time period is 33.3 m^2 which implies that a particle loading factor of 150 percent is needed. For the same conditions, if particles could be imbibed into the droplet, the loading factor would be only about 25 percent or less. Therefore, the capacity of water droplets to capture dust can be significantly increased if particles, on capture, were imbibed into a droplet rather than just adhering to the droplet surface. Kobrick[17] has reported that the cutters run dry even when 25 gallon per minute water is used in water sprays,[17] probably due to complete coating of water droplets by dust particles.

Particles which are not easily wetted by water alone can be wetted by the addition of wetting agents to water. The effect of additives on wetting behavior depends on the nature of particles themselves (i.e., their wetting characteristics) and on the nature of the surfactant used. These aspects are discussed in a later section.

Experimental methods and materials

Wetting Rate — Modified Walker Technique

In this method, a 40 mg sample of 250 X 150 um coal was dropped on the surface of a surfactant solution and the amount of coal wetted by the liquid was measured by placing the pan of a Cahn electrobalance beneath the liquid surface. The initial wetting rates were determined from measurements of the amount of coal wetted as a function of time. The rate of wetting was found to be independent of the amount of the coal sample for the range 20-100 mg. The data reported for the wetting rates are an average of at least four replicate measurements in which the coefficient of variation was about 0.08. Additional details of the measurement technique are given elsewhere.[18]

Coal and Reagents

The coal sample used in this investigation was a HVA-bituminous coal from the Upper Freeport seam obtained from the Penn State Data bank (PSOC 1361P). The coal sample was crushed and screened to obtain a 250-150 um fraction which was then used for the wetting tests. The ethoxylated nonylphenol (Triton N-series) and octyl phenols (Triton X-series) were obtained from Rohm and Haas. The ethoxylated dodecylphenol (T-Det DD9) was obtained from Thomas Hayward Chemicals. Aerosol OT and Tween 80 were obtained from Fisher Scientific.

Results and Discussion

The initial wetting rates for the HVA-bituminous coal are given as a function of the surfactant concentration in Figure 3. The hydrophilic group in this series of surfactants was kept constant (about 9-10 moles of ethylene oxide) and the hydrophobic group was varied from an 8 carbon to a 12 carbon chain. In the range investigated, the wetting rate increases linearly with the logarithm of concentration. The minimum concentration at which wetting occurs is referred to as the critical wetting concentration, C_{cr} and it is obtained by extrapolating the wetting rate versus logarithm of concentration. The slope of the curves increases with a decrease in length of the hydrophobic group. The differences in the effect of surfactants on wetting rates are attributed to differen-

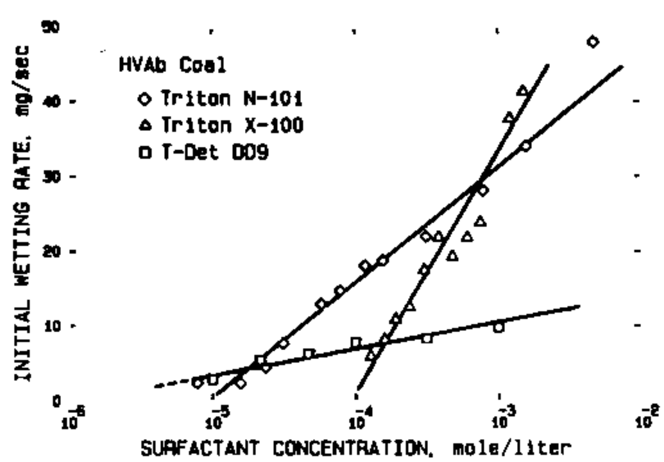


FIGURE 3. Initial wetting rates for a HVA bituminous coal for several surfactants with varying hydrophobic groups.

ces in the adsorption behavior of surfactants on the surface of coal.

The initial wetting rates for the coal versus surfactant concentration for different hydrophilic chain lengths are given in Figure 4. The hydrophobic portion of the surfactant was nonyl phenol in these cases and the hydrophilic chain length was varied by changing the number of ethoxy groups. The chain lengths of the hydrophilic group and other properties are included in Table I. The results in Figure 4 show that the concentration dependance of wetting rates, measured in terms of the slope of the wetting rate versus log concentration, first increases and then decreases with an increase in the number of ethoxy groups.

The hydrophilic-lipophilic-balance (HLB) is a number describing the relative attractions of a surfactant molecule for water and oil.[19] The HLB number for most nonionic surfactants increases with increase in the percentage weight of the hydrophilic portion of the molecule. A higher HLB number also indicates a higher water solubility. The initial wetting rates of coal for a 0.1 wt% surfactant concentration are plotted versus the HLB value in Figure 5, for ethoxylated octyl and nonyl phenols. The wetting rates are maximum at an HLB value of 13.5 for both the ethoxylated octyl and nonyl phenols. At lower HLB values, the adsorbed surfactant molecule has low water solubility and hence a low wetting rate. At higher HLB values, the surfactant molecule has a much higher water solubility and its adsorption on the coal surface is reduced. Similar observations were made by Variali[20] on the effect of HLB on rheology of coal-water slurries.

The initial wetting rates versus surfactant concentration for three different surfactants are given in Figure 6. The Triton N-101 is an ethoxylated nonyl phenol, Tween 80 is an ethoxylated sorbitan mono oleate with an etheylene oxide chain length of 20, and Aerosol-OT is a dioctyl sulfosuccinate. For this coal, Triton N-101 appears to be the most effective wetting reagent.

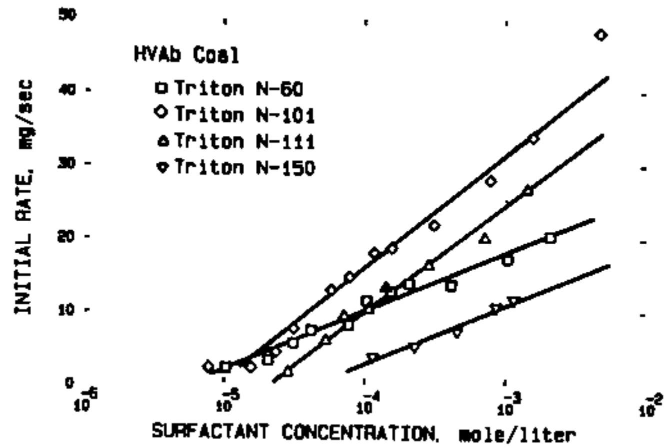


FIGURE 4. Initial wetting rates for a HVA bituminous coal for various ethoxylated nonyl phenols.

TABLE I

Hydrophile-Lipophile Balance of Surfactants Used in this Investigation

Surfactant	Hydrophobic group	No. of ethoxy groups (-C2H5O-)	H.L.B.
Triton N-60	Nonylphenol	6	10.9
Triton N-1-	Nonylphenol	9-10	13.4
Triton N-111	Nonylphenol	11	13.8
Triton N-150	Nonylphenol	15	15.0
Triton X-100	Octylphenol	9-10	13.5
T-Det DD9	Dodecylphenol	9	12.0
Tween 80	Sorbitan monooleat	20	15.0
Aerosol OT	Dioctyl	(anionic)	

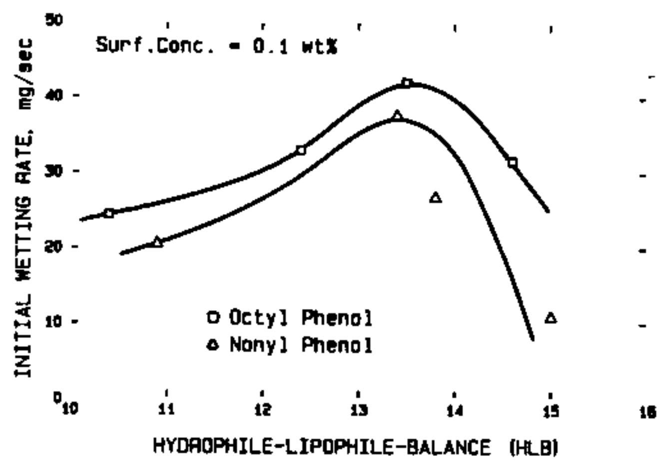


FIGURE 5. Initial wetting rates for a HVA bituminous coal as a function of the HLB number for a 0.1 wt% surfactant concentrations.

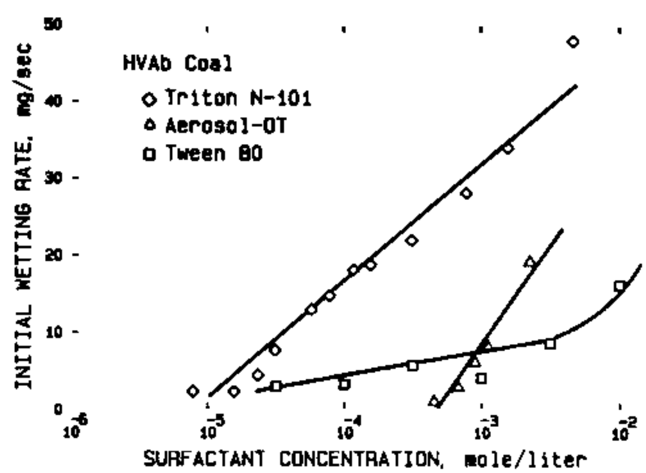


FIGURE 6. Initial wetting rates for a HVA bituminous coal as a function of surfactant concentration for Triton N-101, Aerosol-OT and Tween 80.

Results which have been reported elsewhere[18,21] show that the initial wetting rates in the presence of surfactants are a function of the coal type. When Triton N-101 is used as the surfactant, wetting rates decrease in the order: HVA-bituminous anthracite sub-bituminous, which is expected on the basis of the effect of coal rank on wettability of coal.

Conclusions

A review of the subprocesses involved in capture of dust particles by water droplets shows that wetting agents can significantly enhance the effectiveness of water sprays. Adhesional wetting controls the capture of dust particles, whereas spreading and immersional wetting control their imbibition (engulfment).

Wetting of coal particles is shown to depend upon the coal rank, surfactant type and concentration. At low concentrations, a larger hydrophobic group gives a higher wetting rate (cf. Figure 3) whereas at high concentrations, the surfactant with a smaller hydrophobic group gives a higher wetting rate. The effect of hydrophilic group is more complex and can be discussed in terms of HLB. As the HLB number increases from a low value, the wetting rate first increases and then decreases, the maximum rates occur for an HLB number of 13.5. The largest wetting rates for a HVA bituminous coal were observed for Triton N-101, a nonionic surfactant.

Acknowledgments

The authors acknowledge the support from the Mineral Institutes Program under Grant No. G1135142 from the Bureau of Mines, U.S. Department of the Interior, as part of the Generic Mineral Technology Center for Respirable Dust, The Pennsylvania State University.

References

1. **Naeye, R.G., J.K. Mahon and W.S. Dellinger:** Rank of Coal and Coal Workers Pneumoconiosis. *Am. Rev. Resp. Dis. 103*:350-355 (1971).

2. **Jayaraman, N.I.:** Dust Control for a Borer-Type Continuous Mines using a Venturi Scrubber on a Transfer Car. *U.S.B.M. Rep. of Investigations 8408*, pp. 1-12 (1979).

3. **Anon.:** Peabody Opens Underground Mine in Kentucky. *Mining Engineering 38*:872 (1986).

4. **Hartman I. and H.P. Greenwald:** Use of Wetting Agents for Allaying Coal Dust in Mines. *U.S.B.M. Information Circular 7131*, pp. 1-11 (1940).

5. **Volkwein, J.C., A.B. Cecala and E.D. Thimons:** Use of Foam for Dust Control in Mineral Processing. *U.S.B.M. Report of Investigations 8808*, pp. 1-11 (1983).

6. **Walker, P.L., Jr., E.E. Peterson and C.C. Wright:** Surface Active Agent Phenomena in Dust Abatement. *Ind. Eng. Chem. 44*:2389-2392 (1952).

7. **Anderson, F.G., R.L. Evans and R.G. Peluso:** A study of Dust Control Methods for Continuous Mining of Coal. U.S.B.M. Information Circular 8205, pp. 1-14 (1963).

8. **Levo, N. Jr.:** Dust Control in Coal Mines. *Trans. 53rd Nat. Safety Cong., Coal Min. Sesseions*, pp. 11-13 (1965).

9. **Godard, R.R.:** Dust Abatement Activities within United States Steel Coal Operations. *Coal Age 72*: 112 (1967).

10. **Papic, M.M. and A.D. McIntyre:** Surface Active Agents Evaluated in Canadian Study. *Coal Age 78*: 85-87 (1973).

11. **Courtney, W.G. and L. Cheng:** Control of Respirable Dust by Improved Water Sprays. *U.S.B.M. Information Circular 8753*, pp. 92-108 (1976).

12. **Zeller, W.H., quoted by R. Harold:** Surfactants vs. Dust – Do They Work? *Coal Age 84*:102-105 (1979).

13. **Zeller, W.H.:** Laboratory Tests for Selecting Wetting Agents for Coal Dust Control. *U.S.B.M. Report of Investigations 8815*, pp. 1-21 (1983).

14. **Pigford, R.L. and C. Pyle:** Performance Characteristics of Spray-Type Adsorption Equipment. *Ind. Eng. Chemistry 43*:1649-1662 (1951).

15. **Cheng, L. and P.P. Zukovick:** Respirable Dust Adhering to Run-of-Face Bituminous Coal. *U.S.B.M. Report of Investigations 7765*, pp. 1-9 (1973).

16. **Gutierrez-Rodriguez, J.A., R.J. Purcell Jr. and F.F. Aplan:** Estimating the Hydrophobicity of Coal. *Colloids and Surfaces 12*:1-25 (1984).

17. **Kobrick, T.:** Water as a Control Method -- State of the Art Sprays and Wetting Agents. *U.S.B.M. Information Circular 8458*, pp. 122-133 (1970).

18. **Chander, S., B.R. Mohal and F.F. Aplan:** Wetting Behavior of Coal in the Presence of Some Nonionic Surfactants. *Colloids and Surfaces* (1986) (in press).

19. **Anon.:** *Kirk-Othmer Encyclopedia of Chemical Technology*, 3rd Ed., Vol. 8, pp. 910. John Wiley and Sons, New York (1980).

20. **Varialli, G.:** Coal-Water Slurry – Influence of Surfactants HLB on the Properties of Mineral Mixtures. Paper presented at 191st A.C.S. National Meeting, New York, April 13-18, 1986.

21. **Mohal, B.R. and S. Chander:** A New Technique to Determine Wettability of Powders – Imbibition Time Measurements. *Colloids and Surfaces* (1986) (in press).

Electron Spin Resonance Detection of Reactive Free Radicals in Fresh Coal Dust and Quartz Dust and Its Implications to Pneumoconiosis and Silicosis

N.S. DALAL,[A] M.M. SURYAN,[A] B. JAFARI,[A] X. SHI,[A] V. VALLYATHAN[B] and F.H.Y. GREEN[B]

[A]Chemistry Department, West Virginia University, Morgantown; [B]National Institute for Occupational Safety and Health, Morgantown

It is well known that prevalence and severity of coal worker's pneumoconiosis (CWP) differ markedly in different regions and mines despite comparable exposures. These variations in the pathogenicity of different coal mine dusts can only partially be explained by the mineral composition of the coal mine dust and the rank of coal. Laboratory studies also do not correlate with the human experience. One major difference between human exposure and laboratory studies is that the coal miner breathes dust from freshly broken coal, while the animals or cells are exposed to stale dust. In an effort to find biochemical clues for resolving this apparent paradox, we have carried experiments to detect differences in chemical reactivities of fresh versus stale coal dust from several U.S. coal mines. Electron spin resonance (ESR) was used as a technique for the direct detection of the concentration and reactivity of free radicals. ESR measurements of freshly ground coal dusts of different ranks and composition showed significant differences in the amount and reactivities of the organic free radicals produced. The half-lives and reactivity patterns of these newly formed species of free radicals seem to correlate with the expected toxicity and pathogenicity of the dust, thereby, providing new clues to the biochemical mechanisms and pathogenesis of CWP. Similar detection of free radicals in freshly crushed quartz suggest that free radicals might play a significant role in the pathogenicity of quartz in causing fibrosis and eventually silicosis.

Introduction

The pathogenesis of coal workers' pneumoconiosis (CWP) has been an important topic of concern for decades, but the mechanism of CWP is still not understood. It is well known, for example, that the prevalence and severity of CWP differ markedly in different regions and mines despite comparable exposure[1,2] but these observations can only partially be explained by differences in mineral composition and rank of coal[3-5] Specifically, while epidemiological studies of coal miners indicate[1,2] that the effectiveness of coal in producing CWP correlates roughly with the rank (i.e. % carbon content) of coal, such correlation has not been established via biological studies.[4-6]

In an effort to find additional clues to the biochemical mechanism of CWP, we have examined the possible role in CWP of organic radicals formed in coal dust during the cutting of coal. This study[7,8] was prompted by the following observations. Free radicals such as O_2^- or its byproducts have been implicated in the pathogenicity of lung injury produced by activated macrophage or following radiation therapy. The relevance of free radicals in CWP was also suggested by our recent electron spin resonance (ESR) studies wherein a positive correlation was found between the severity of CWP and the concentration of organic free radicals in dry lung tissue of autopsied miners.[8] Moreover, three recent papers indicate that mechanical crushing of some coals leads to the formation of organic free radicals[9-11] In fact, Artmov and Reznik surmised that these radicals might be related to the pathogencity of CWP[9] However, the authors did not establish any correlation between any property (say, concentration or reactivity) of the radicals and the dust pathogenicity. It was also not shown that dust from freshly crushed coals, termed as "fresh dust" here from now on, was more pathogenic than the same dust kept in air for several days, called "stale dust" here. At about the same time (1982), Retcofsky reported ESR detection of organic free radicals in a dry lung tissue sample of an autopsied coal miner.[12] He concluded that the free radicals detected in the lung tissue reflect essentially the presence of dust particles embedded in the tissue and exhibit no characteristic relevant to CWP. However, as mentioned earlier, our own ESR studies of tissue from lungs of autopsied workers who had worked in a variety of mines showed a positive correlation between the severity of CWP and the concentration of organic free radicals in the lung tissue. In order to study systematically the relationship of free radicals in fresh coal dust as well as in lung tissue with CWP, we have carried out the following experiments:

1. We have validated and extended the earlier report[7,9] by a detailed ESR spectroscopic analysis of free radicals produced by fracturing of two carefully selected U.S. coals under different environmental conditions.
2. We have initiated biochemical studies to determine the relative cytotoxicity of freshly fractured and stale coal dusts.
3. We have measured free radical concentrations in the lungs of autopsied coal miners with varying degrees

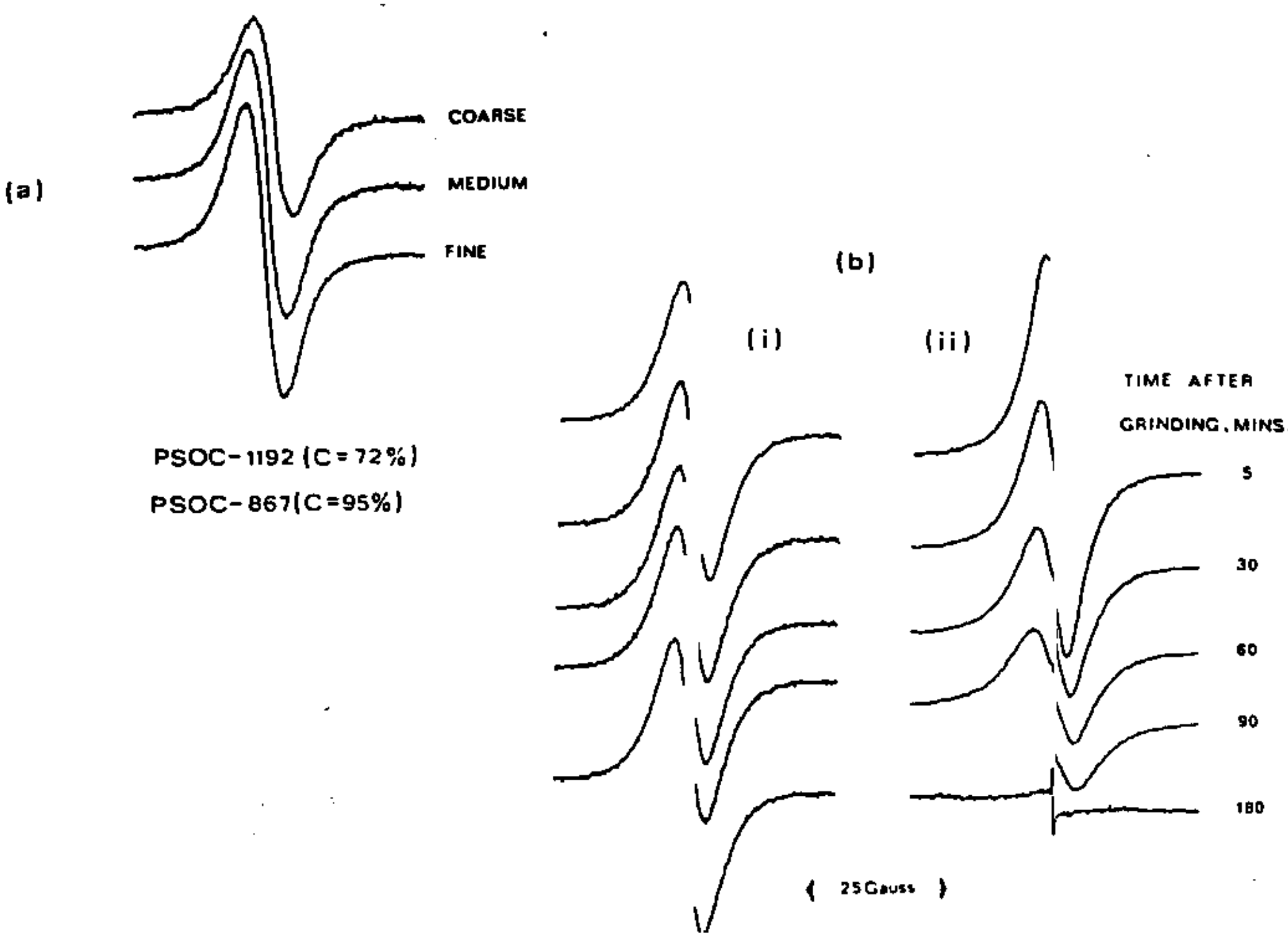


FIGURE 1. (a) Effect of grinding (under nitrogen) on the ESR signal intensity from a PSOC-1192 (bituminous coal); (b) Decay of (free radical) ESR signals after air exposure.

of CWP. The results of this study are reported separately.[8]

4. We have examined the production of free radicals in quartz particles ground under nitrogen and in air and measured the radical decay.

Methodology

Electron spin resonance spectroscopy was used as a technique for the identification and reactivity studies of the free radicals.[12,13] The ESR measurements were made with an IBM (model ER200D) ESR spectrometer operative in the X-band (10 GHz) range, and equipped with an Aspect 2000 microcomputer for automatic data acquisition and processing. As usual, the area under the ESR signal was taken to be proportional to the radical concentration. The two Pennsylvania coals studied here (PSOC-867, an anthracite, and PSOC 1192, a bituminous coal) and their composition data were obtained from the Pennsylvania State University coal data bank. For each ESR study, about 0.200 g of raw coal particles (a few millimeters in size) were outgassed for several hours to a vacuum of about 10^{-5} mm Hg and then crushed in a glove box under dry nitrogen atmosphere so as to exclude oxygen reactions with the free radicals. The coal particles were crushed mechanically (using an agat mortar and pestle) to produce particles from respirable to larger size so as to mimick the situation during coal mining. The same methodology was employed for the quartz studies.

For ESR studies of free radicals in lung tissues of workers diagnosed as having CWP, 10-50 mg of lung tissues were obtained from the National Coal Workers Autopsy study, NIOSH, Morgantown, West Virginia. Samples were selected to represent a wide range of CWP severity. Cytotoxicity studies of fresh and stale coal dust were carried out at NIOSH using sheep red blood cell hemolysis developed by Vallyathan at NIOSH, as described elsewhere.[14]

Results and Discussion

Coal Studies

Figure 1 shows typical ESR spectra of the organic free radicals from the two Pennsylvania coals. The signals were assigned to organic free radicals from their similarity to ESR signals from organic radicals in parent coals.[12,13] As is well known, the absolute value of area under an ESR peak is proportional to the concentration of the species (radicals here). Thus Figure 1(a) shows the effect of the extent of

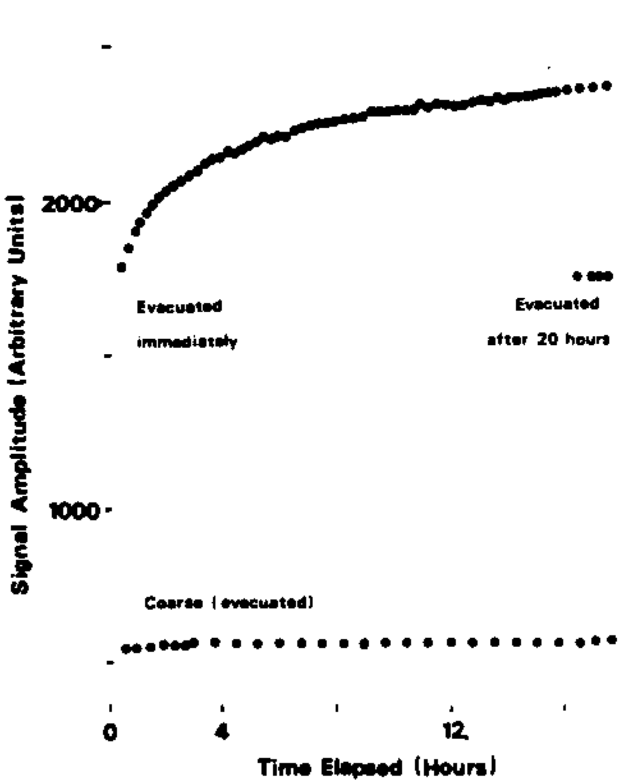


FIGURE 2. Time dependence of the decay of the free radical signals from a bituminous coal (PSOC-1192) crushed under nitrogen and exposed to air.

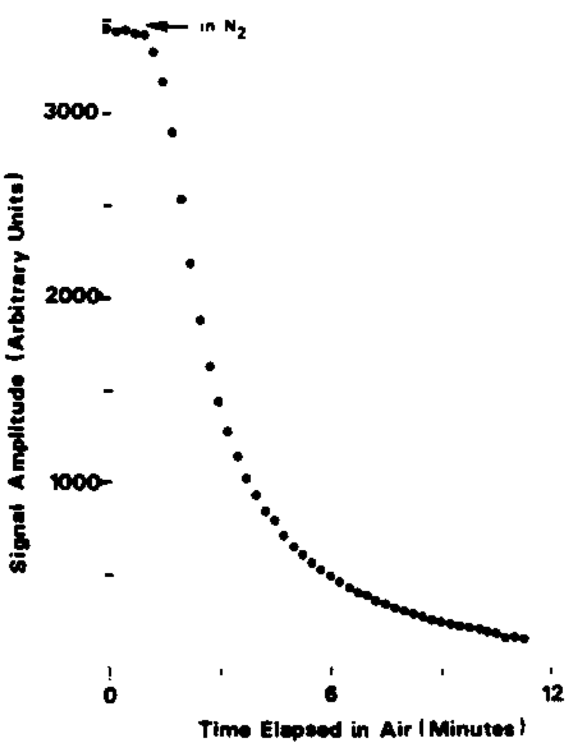


FIGURE 3. Decay pattern of the free radicals in an anthracite (PSOC 867) coal crushed under nitorgen and exposed to air.

crushing (as judged visually from the particle size) on the radical concentration for the bituminous coal sample (PSOC 1192, 72% carbon content). Here fine size was found to correspond roughly to the respirable size particles. We note that our grinding procedure is crude, but in this study our aim was to mimick the situation of coal production in a mine. It is seen that grinding produces free radicals. Perhaps an even more significant result was that the radical production was higher in the anthracite coal (PSOC 867 – 95% carbon content) for the same amount of grinding time, as may be seen from the ESR peaks in Figure 1(b). Moreover on exposure

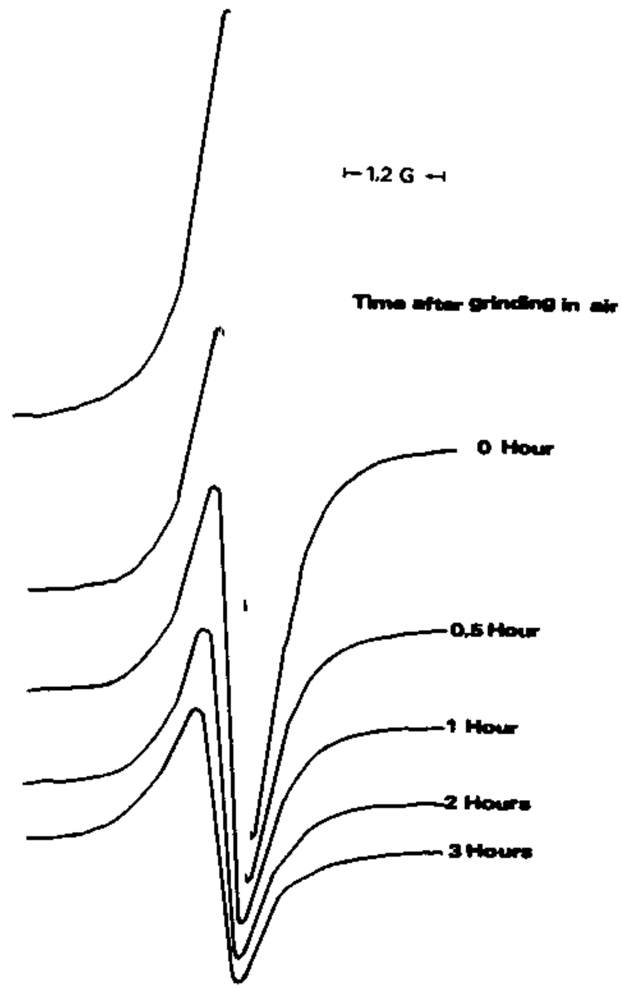


FIGURE 4. Decay pattern of free radicals from the same anthracite coal as in Figure 3 but crushed in air.

to air the free radicals produced in the anthracite coal (PSOC 867) decay at a much faster rate than those produced in the bituminous coal (PSOC 1192), as deduced qualitatively from the relative decreases with time (after grinding) in the ESR peaks of the two coals, as a function of time (Figure 1(b)). Figures 2 and 3 show these decreases quantitatively for the bituminous and the anthracite samples, respectively. While an accurate comparison of the radical decay rate needs more controlled grinding procedures (which we plan to complete in the future), the preliminary results presented in Figures 2 and 3 clearly show that the decay rate and hence the reactivity (with oxygen) of the free radicals produced in

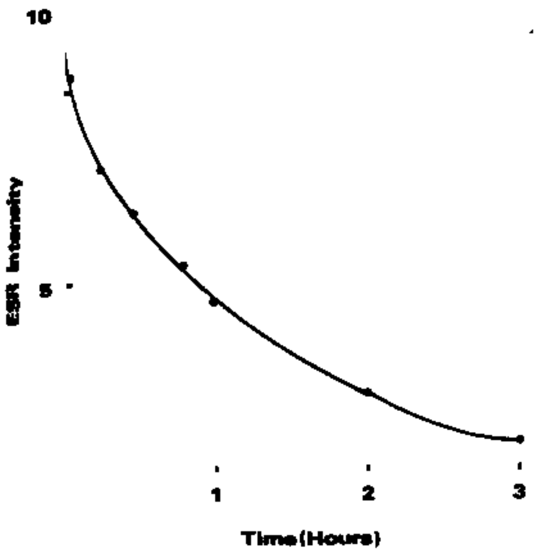


FIGURE 5. Time dependence of the decay of the free radicals in an air-crushed anthracite coal (PSOC-867).

the anthracite coal is about 300 percent higher than that in the bituminous sample. Another significant result to be noted from these figures is that under comparable grinding conditions, the yield of free radicals produced per gram from the anthracite coal is about an order of magnitude higher than from the bituminous coal. Thus for comparable exposures of fresh dust in an anthracite and bituminous coal mine, the anthracite miners would be exposed to dust containing significantly more quantity and also more reactive type of free radicals. If further experiments prove that these free radicals are involved in the mechanism of CWP, then the above results can be taken to provide a new clue to the well known but hitherto not understood observation that anthracite coal mine dust is significantly more pathogenic than bituminous dust.

We have also observed that crushing of coal in air also leads to the production of radicals which decay over a period of several hours. Figure 4 shows typical ESR signals of the PSOC 867 (anthracite) coal crushed in air and the changes over a period of three hours after crushing. Figure 5 shows a graphical representation of time dependence of the radical decay in air, after crushing in air. Again it is clear that the radicals produced decay smoothly by reaction with the oxygen in air.

Free Radicals in Fresh Quartz Dust

It is known that fracturing of quartz under ultra-high vacuum (10^{-10} torr) results in the production of silicon-based free radicals.[15] These studies were conducted in relationship to the semiconductor-industrial applications. While it has been occasionally mentioned that free radicals on the surface of quartz particles might be relevant to the fibrogenicity of quartz, no systematic ESR measurements of such radicals have been reported, especially as related to the biological activity.[16] Our preliminary results are summarized below.

Figure 6 shows typical ESR spectra of quartz (SiO2) particles ground in air as a function of time after grinding. It is clearly seen that the radical concentration, as measured from the peak-to-peak height of an ESR spectrum, decreases with

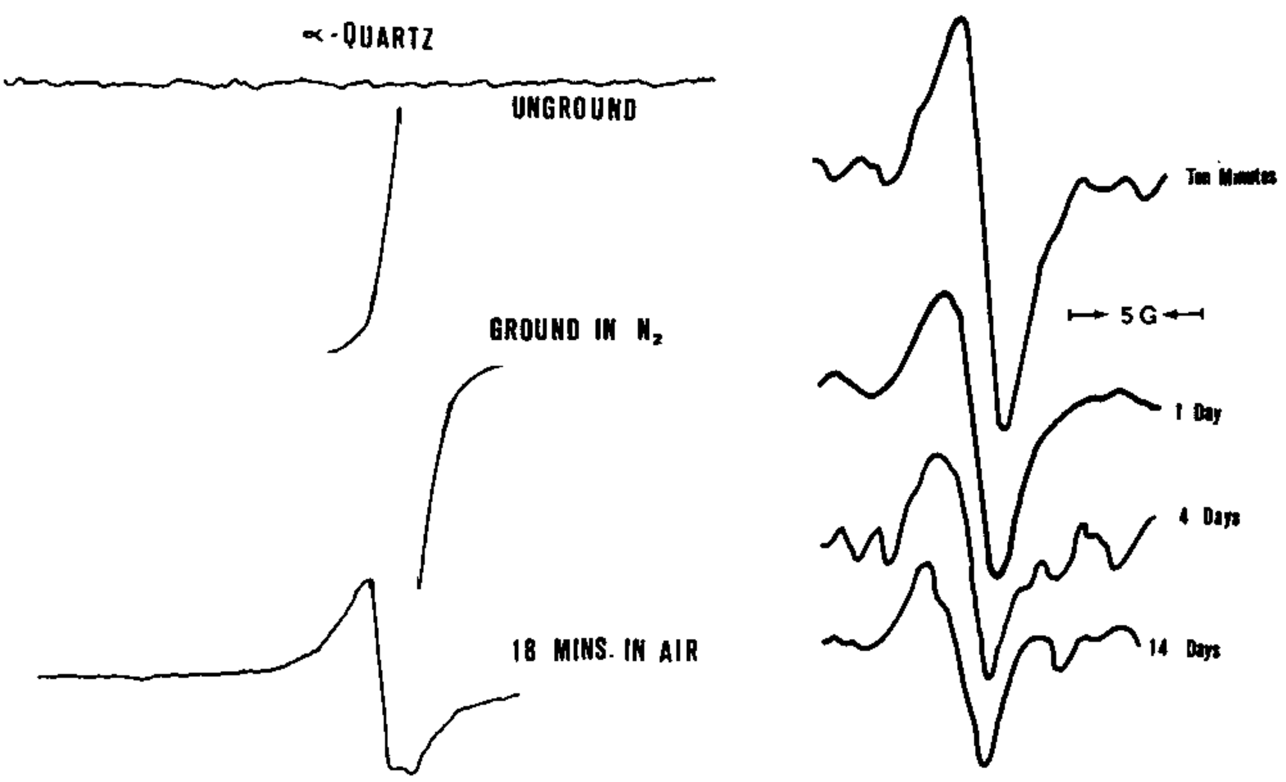


FIGURE 6. Typical ESR spectra of quartz particles crushed in air.

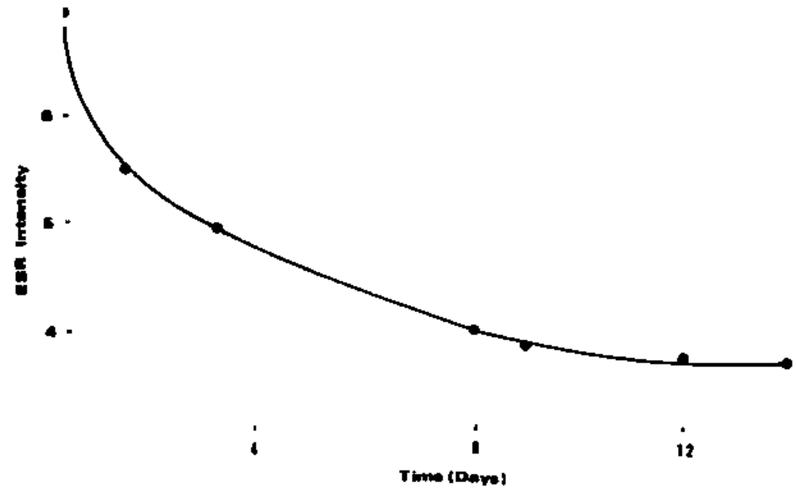


FIGURE 7. Time dependence of the decay of the free radicals in an air-crushed quartz sample.

time as the quartz dust is left exposed to air. Figure 7 shows a plot of the time dependence of the radical concentration decrease. These results are somewhat similar to the radical decay pattern for the organic free radicals in fresh coal dust. Therefore, in this respect coal and quartz exhibit similar surface chemical reactivity

Implications to CWP and Silicosis

The above described ESR studies establish that the surfaces of fresh coal as well as quartz contain highly reactive free radical species, and hence the potential for cytotoxicity via chemical reaction (bond formation) with the cell membrane. Preliminary tests carried out using the sheep red-blood cell hemolysis[7] procedure indicate fresh coal dust, prepared by crushing of the anthracite (PSOC 867) coal exhibits significantly higher homolytic activity than the same dust left in air for several hours. Since exposure of fresh dust to air causes a decrease in the amount of the free radicals, as well as to a decrease in the cytotoxicity, it is possible that the free radicals do contribute to the coal dust's cytotoxicity. As for quartz, while hemolytic activity has not yet been studied, we have obtained an indirect evidence of the role of free radicals in the quartz's cytotoxicity: the free radical concentration decreases on heating freshly crushed quartz to about 700°C in a rough proportional manner to the decrease in the cytotoxicity of quartz as reported earlier.

Thus, while much further work remains to be done, the hypothesis that free radicals present in fresh quartz as well as coal dust contribute to their cytotoxicity seems to have some experimental basis.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

References

1. **Reisner, M.T.R. and K. Robock:** Results in Epidemiological, Mineralogical and Cytotoxicological Studies of Pathogenicity of Coal-Mine Dusts. *Inhaled Particles 4*, p. 703 (1977).

2. **Hurley, J.F. et al:** *Simple Pneumoconiosis and Exposure to Respirable Dust: Relationships from Twenty-five Years' Research at Ten British Coal Mines.* Institute of Occupational Medicine Report, No. TM/79/13 (1979).

3. **Christian, R.T., J.B. Nelson, T.E. Cady et al:** Coal Workers' Pneumoconiosis: *In Vitro* Study of the Chemical Composition and Particle Size as Causes of the Toxic Effects of Coal. *Environ. Res. 20*:358-365 (1979).

4. **Christian, R.T. and J. Nelson:** Coal: Response of Cultured Mammalian Cells Corresponds to the Incidence of Coal Workers' Pneumoconiosis. *Environ. Res. 15*:232-241 (1978).

5. **Hatch, G.E., D.E. Gardener and D.B. Menzel:** Stimulation of Oxidant Production in Alveolar Macrophages by Pollutant and Latex Particles. *Environ. Res. 23*:121-136 (1980).

6. **Heppleston, A.G.:** Changes in the Lungs of Rabbits and Ponies Inhaling Coal Dust Underground. *J. Path. Bact. 67*:349-359 (1958).

7. **Dalal, N.S., M.M. Suryan, B. Jafari et al:** Detection of Organic Free Radicals in Fresh Coal Dust and Its Implications to Pneumoconiosis. Presented at the Sixth International Symposium on Inhaled Particles, Cambridge, England (1985).

8. **Jafari, B., N.S. Dalal, V. Vallyathan and F.H.Y. Green:** Detection of Organic Free Radicals in Coal-Dust Exposed Lung Tissue and Correlations with Their Histopathological Parameters. *Respirable Dust in the Mineral Industries: Health Effects, Characterization, and Control*, pp. XXXXX. Cincinnati, OH (1987).

9. **Artemov, A.V. and L.A. Reznik:** Questions on the Methodology of Biological Investigations of the Fibrogenicity of Coal Dust. *Gib. Tr. Zabol. 2*:51-55 (1980).

10. **Lebedev, V.V., T.M. Khrenkova and M.L. Goldenko:** The Formation of Paramagnetic Centers During Crushing of Coal. *Sol. Fuels Chem. 12*:117-119 (1978), and references to earlier Russian

literature cited therein.

11. **Duliba, E.P. and R.B. Clarkson:** A Magnetic Resonance Study of Native and Modified Illinois Coal. *Proc. Nato Summer School on Magnetic Resonance of Fossil Fuels*, a preprint (1984).

12. **Retcofsky, H.L.:** Magnetic Resonance Studies of Coal. *Coal Science 1*:43-82 (1982).

13. **Petrakis, L. and D.W. Grandy:** Free Radicals in Coals and Synthetic Fuels, Chap. III and IV. Elsevier, Amsterdam, (1983).

14. **See, for example, Wallace, W.E., V. Vallyathan, M.J. Keane, V. Robinson:** *J. Toxic. Env. Health 16*:415-424 (1985).

15. **Hochstrasser, G. and J.F. Antonini:** Surface States of Pristine Silica Surfaces. *J. Surface Sci. 32*:644-664 (1972).

16. **Gabar, S. and Z. Anca:** Effect of Silica on Lipid Proxidation in the Red Cells. *Int. Arch Arbeitsmed. 32*:327-332 (1974).

MEASUREMENT

Numerical Technique for Calculating the Equivalent Aerodynamic Diameter of Particles

VIRGIL A. MARPLE, ZHANG ZHIQUN and BENJAMIN Y.H. LIU
Particle Technology Laboratory, University of Minnesota, Minneapolis

Introduction

It is commonly understood that aerosol particles may be injurious to human health if they are of a size that enables them to enter the respiratory tract. Coal Workers' Pneumoconiosis (CWP) is one disease known to be caused by coal mining related particles.

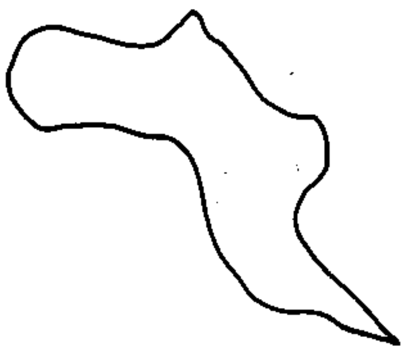


FIGURE 1. Determination of the aerodynamic diameter of an irregularly shaped particle.

The location in the respiratory tract where the particles are deposited is primarily a function of the equivalent aerodynamic diameter (EAD) of the particle. The equivalent aerodynamic diameter is the diameter of a spherical particle with a density of 1.0 gm/cm^3 with the same falling speed as the particle in question. For a spherical particle the calculation is rather simple in that the equivalent aerodynamic diameter is simply the diameter of the particle in question multiplied by the square root of the density of the particle. For irregularly shaped particles, such as coal particles, there is no simple way to make the EAD calculation. For example, Figure 1 is only one of an infinite variety of particle shapes that can be found in practice and the aerodynamic size of this particle and, therefore, its deposition location in the respiratory tract would be nearly impossible to estimate accurately.

The normal method for determining the aerodynamic diameter of particles has been to experimentally measure the size of the particles in a settling chamber or with an inertial classifier such as an impactor, cyclone or a centrifuge, since inertial classifiers have the property of classifying the particles according to their aerodynamic diameters.[1] However, these devices can only give limited information on the EAD of a single particle with a specific shape. Impactors and cyclones, for example, collect particles in size ranges and not at a specific size, so the determination of the EAD of a specific particle is not possible. A centrifuge, on the other hand, can measure the EAD of a specific particle but the equipment is costly and procedure laborious, and it may not be possible to disperse a particle of a specific shape into the centrifuge. The centrifuge can be used to determine the EAD of clusters of spheres in various arrays, but introducing particles of a specific irregular shape may not be feasible. Furthermore, the EAD is a function of the orientation of an irregularly shaped particle and the orientation of a particle in an inertial classifier is unknown. The orientation may also vary as the particle passes through the classifier.

Because of the difficulty in determining the EAD of an irregularly shaped particle, we have undertaken a program to apply theoretical numerical methods to calculate the EAD of any shape particle. In our laboratory we have, for some time, been using numerical methods to determine the flow field of air within instruments such as impactors,[2] inlets,[3] and virtual impactors.[4] Recently, this technique has been expanded into the three-dimensional regime, and the flow fields and particle motion characteristics within cyclones[5] and glove boxes have been studied. We have now begun to use these numerical three-dimensional flow programs to study the flow field around irregularly shaped particles to determine their drag coefficients, falling speed, and thus, their EAD.

Although it is quite easy to obtain answers from numerical programs, the routines may or may not be converging to a correct answer. The technique must be extensively

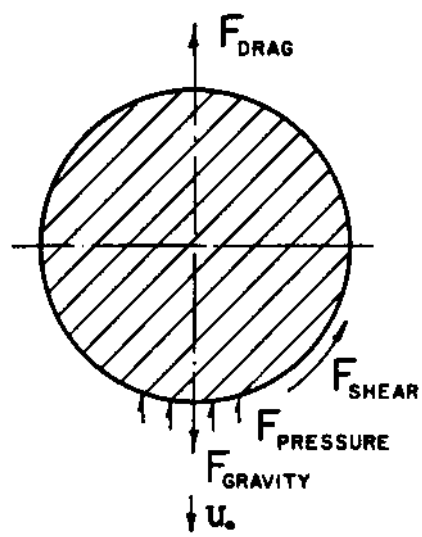


FIGURE 2. Numerical solution of drag acting on a sphere contributed by pressure and shear (Dp = 10 um; U_O = 10 cm/s).

TABLE I

Comparison of Drag Forces on Spheres Calculated by Numerical Analysis, F_{Dn}, and Stokes Law, F_{DS}

D_p (um)	F_{Dn}/F_{DS}	Error %
2.0	1.035	3.5%
5.0	1.041	4.1%
10.0	1.015	1.5%

evaluated before one has confidence in it. Therefore, the first step in our study is to use the computer techniques developed for two-dimensional flows and calculate the drag coefficients around particles of a simple shape for which the drag coefficient has been determined analytically or experimentally. If the agreement is good between the numerical solutions and the analytical or experimental solutions, the technique can be expanded into the three-dimensional regime with confidence.

This paper describes the results of the initial phase of the program, i.e., the verification that the numerical solutions in two dimensions can provide the correct drag coefficients for regular shape particles. The particles studied are those that can be generated by rotation of the coordinate system such as spheres, rods of infinite length in cross flow, disks, and chain spherical particles with axial flow along the chain.

Numerical Analysis Technique

Numerical analysis of the Navier-Stokes equation has been used extensively in recent years to obtain information on flow fields. Although several techniques have been used to solve the Navier-Stokes equations, they are all basically the same in that the finite difference form of the equation is expressed in terms of the stream function and vorticity, or in terms of the velocity vector components and the pressure. A grid is placed over the area of interest and the finite difference equations are solved at the node points (intersection of the grid lines) of the grid. The solution is achieved by an iterative relaxation procedure that determines the value of the stream function and vorticity or the velocity vector components and the pressure at each node point. Since numerical solution techniques have been used extensively and many cases reported in the literature, the techniques will not be described in detail here.

The particular solution technique that has been used in the work described here is the one described by Suhas Patankar,[7] and the reader is referred to his textbook for details of the technique. This technique is one that solves for the velocity vector components and the pressure at the node points rather than the stream function and vorticity. However, once the velocity vectors and pressure are known, the stream function and vorticity can be calculated if desired. The stream function is often calculated so that the stream lines (lines of constant stream function) can be shown to give a clearer understanding of the nature of the flow field.

Most of the work utilizing finite difference solutions to the Navier-Stokes equations has been in two dimensions, but three-dimensional solutions can be obtained.[5] Three-dimensional solutions, however, are much more costly in computer time than two-dimensional solutions. Although three-dimensional solutions must be used to study irregularly shaped particles, we have chosen to use two-dimensional solutions of regular shape particles to prove the feasibility and to provide confidence in the results.

TABLE II

Comparison of Drag Force on a Cylinder in Cross Flow Calculated by Numerical Analysis F_{Dn}, and by Tomokita and Aoi[8] Solution, F_{DL}

Dp (um)	F_{Dn}/F_{DL}	Error%
10.0	1.0245	2.45%

In the past we have used numerical analysis techniques to successfully analyze the performance of aerosol instruments such as impactors,[2] virtual impactors,[4] and inlets[3] However, in these cases the flow field within the instrument was calculated and then the particles were put into the flow field and their trajectories calculated. For these cases, the particle was much smaller than the grid spacing, and the trajectory of the particle was calculated as it passed through the grid matrix.

FIGURE 3. Typical grid pattern for numerical solution.

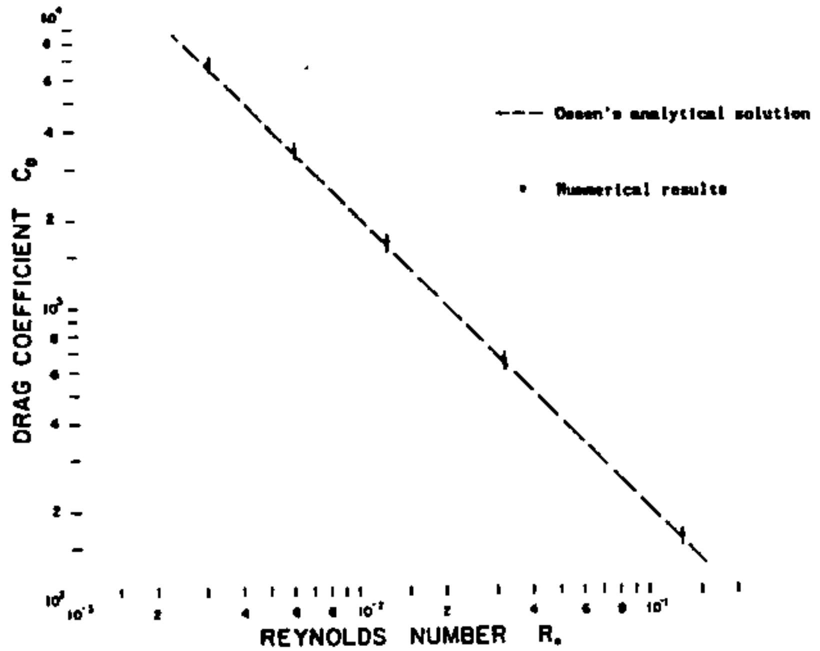


FIGURE 4. Drag coefficient of disks, CD, Vs Reynolds number, comparison of Oseen's analytical solution with numerical results.

To study the flow around a particle and thus determine its drag and aerodynamic diameter, it is now necessary that the grid spacing be much smaller than the particle. The number of grid lines required to define the particle contour will depend upon the degree to which the features of the particle are to be described.

Solution Technique as Applied to Particles

Since the object of the program is to determine the aerodynamic diameter of a particle and since the aerodynamic diameter is defined as the diameter of a unit density sphere which falls at the same speed as the particle in question, the problem reduces to one of determining the falling speed of a particle. As shown in Figure 2, this problem further reduces to one of determining at what speed the drag force is equal to the gravitational force on a particle, for these are the conditions which must exist when the particle is falling in equilibrium at its terminal settling speed.

The drag force on a particle will be the sum of both the pressure forces on the particle and the shear forces resulting from the fluid flowing past the surface of the particle. The numerical technique used here provides information on these two components of the drag force. For example, as shown in Figure 2, for a 10 micrometer diameter particle falling with a velocity of 10 cm/sec, the drag force due to the pressure difference is half the drag force due to the shear. This, incidentally, is the same ratio that will be found from analysis of the Stokes Drag Law.

Information on the drag force, presented in Figure 2, was found by application of the Navier-Stokes numerical analysis technique on a grid pattern such as that shown in Figure 3. Since the particle is a symmetrical sphere, the shape need only be defined as a semicircle as shown in the figure. The

TABLE III

Comparison of Drag Forces, Shape Factors and Drag Coefficients for Disks Calculated by Numerical Analysis and by Oseen's Solution[10]

Re	F_{Dn}/F_{Do}	K_n'	K_o'	C_{Dn}	C_{Do}
3.26×10^{-3}	1.058	0.898	0.849	6.11×10^3	6.25×10^3
6.52×10^{-3}	1.05	0.891	0.849	3.28×10^3	3.125×10^3
1.30×10^{-2}	1.045	0.887	0.849	1.63×10^3	$1.563 \times 10_3$
3.26×10^{-2}	1.02	0.865	0.849	6.37×10^2	6.25×10^2
1.30×10^{-1}	1.015	0.861	0.849	1.58×10^2	1.56×10^2

K_n' = Shape Factor obtained from numerical study.

K_o' = Shape factor obtained by taking the limit case of the shape factor from Oseen's formula.

C_{Dn} = Drag coefficient of disks obtained from numerical results.

C_{Do} = Drag coefficient of disks obtained from Oseen's solution.

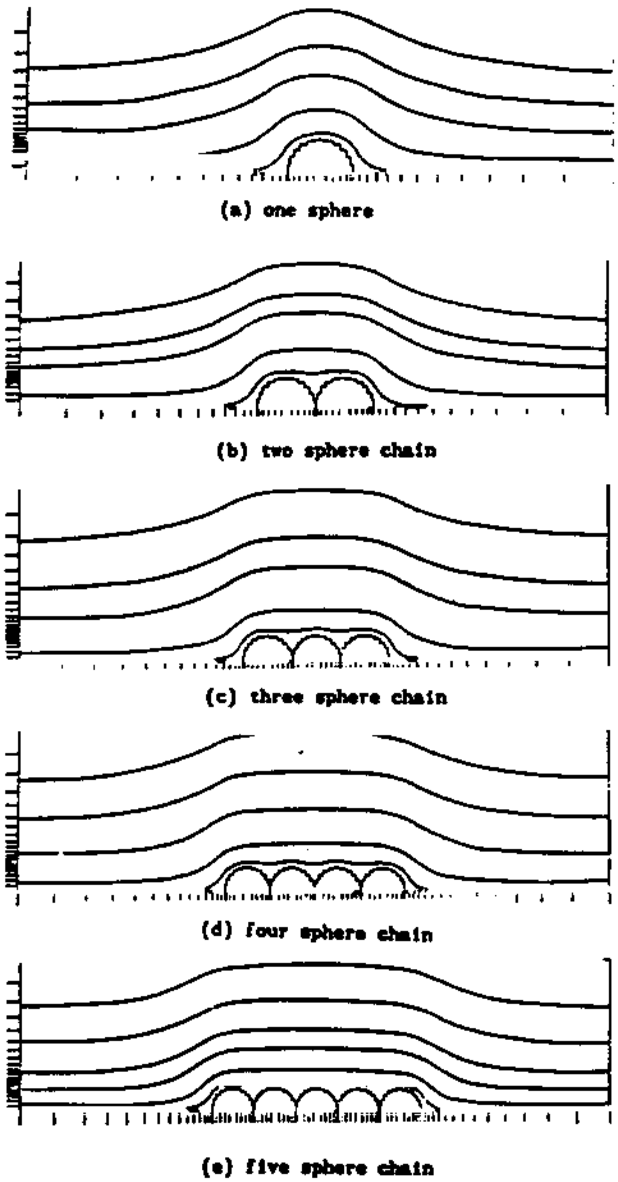


FIGURE 5. Flow field streamlines past a straight chain of spheres consisting of 1 to 5 spheres.

coordinates are two-dimensional (radial and axial) cylindrical coordinates with no flow in the angular direction. Note that to define the particle with sufficient detail, the number of grid lines near the particle must be increased and the spacing between the grid lines decreased. The detail to which the contour of the particle can be defined is a function of the number of grid lines that are used.

In the technique described by Patankar,[6] the specification of the domain occupied by the particle is rather easy in that the viscosity is simply set to a very large number in this domain. The Navier-Stokes equations are then solved over the entire grid pattern (even through the particle). Since the viscosity is defined as being very large in the area of the particle, the flow does not move in this area and one has essentially defined an obstacle to the flow.

This same general technique will be used when three-dimensional analysis of the particles is performed. Due to the fact that the particles will no longer be symmetrical, no symmetry axis can be used, and the flow around the entire particle will be involved in the solution. However, the particle will still be defined by placing very high values of viscosity at all node points lying within the particle boundaries.

The grid shown in Figure 3 is in cylindrical coordinates so as to take advantage of the symmetry of a spherical particle. The same coordinate system is used when determining the drag force on a disk. However, in some cases it may be preferable to use rectangular coordinates, as in the case for an infinite cylinder in cross flow. Figure 3 could also represent the grid system for the cylinder in cross flow, but now the semicircle would represent one-half of a cylinder, and the coordinate system would be in x-y coordinates with no flow in the z direction. When the program is expanded into three dimensions, it may be advantageous to use rectangular rather than cylindrical coordinates for ease in defining the shape of the particle.

Results

The two-dimensional analysis has been applied to single spherical particles, cylinders in cross flow, disk shape particles, and spherical particles connected in chains. In all cases the shapes were selected because there was a prior determination of the drag force on the particle, either by analytical or experimental methods, and reported by other investigators, since it was the object of this portion of the project to gain confidence in a numerical technique.

For the single spherical particle, the drag force from the numerical solution was compared to the drag force predicted by Stokes law.[7] The results of this analysis are shown in Table I for particle diameters of 2, 5, and 10 um. In general, it was found that the calculation of the drag force on a particle agreed within four percent of that determined by Stokes law. This was believed to be quite good since the number of node points defining the particle was only approximately 40 in all cases. Thus, the sphere is actually approximated by 11 stacked cylinders, creating steps along the surface of the particle. As the number of grid points

TABLE IV

Comparison of Dynamic Shape Factor for Straight Chain Aggregates of Uniform Spheres Calculated by Numerical Analysis and Determined Experimentally by Stober[12]

	Numerical Analysis Results				
No. of Sphere	Dp = 0.4 um	Dp = 1 um	Dp = 4 um	Dp = 10 um	Experimental Results (Stober)
2	1.148	1.179	1.1225	1.1238	1.12
3	1.213	1.267	1.320	1.340	1.27
4	1.221	1.296	1.353	1.378	1.32
5	1.336	1.411	1.482	1.513	1.45

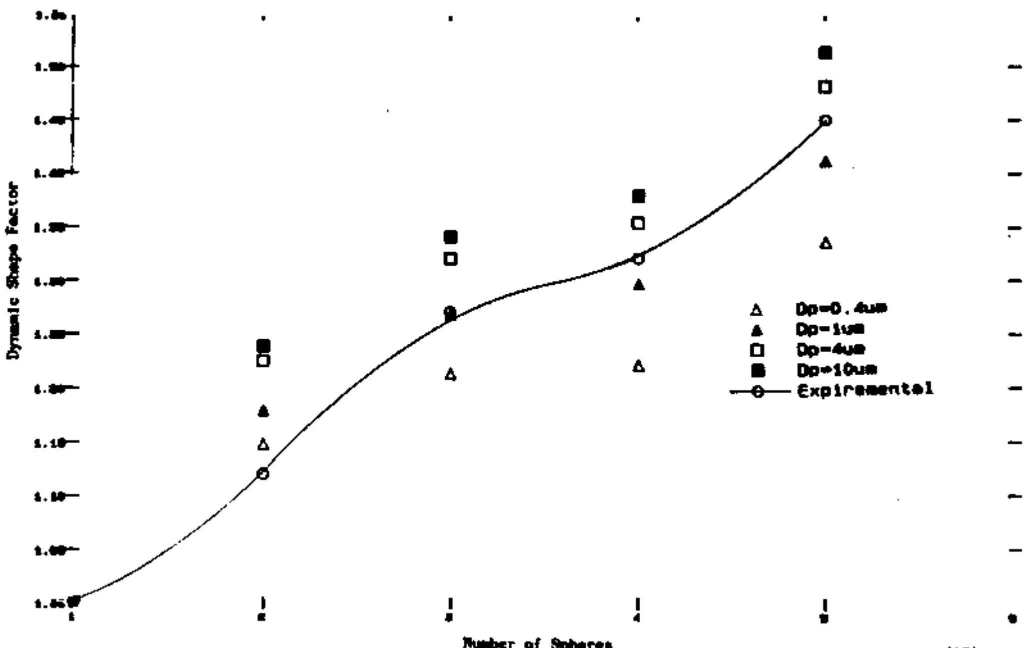


FIGURE 6. Dynamic shape factor of a straight chain of spheres, comparison of numerical results with experimental results,[12] Dp = Diameter of primary sphere.

(cylinders) increases, the size of the steps will decrease and more closely approximate the sphere.

For the case of cylinder in cross flow, which utilized rectangular coordinates, only one case was analyzed (10 um diameter) and compared to the analytical solution as defined by. Tomokita and Aoi[8] and reported by White.[9] The result of this comparison is shown in Table II. There is good agreement between the two techniques. The difference is only approximately 2.5 percent. Again, the cylinder was defined by about 40 node points.

The next configuration studied was the disk in cross flow which again utilized cylindrical coordinates. The results of this test were compared to that of Oseen's solution[10] as reported by Fuchs.[11] Oseen studied the flow around ellipsoids, and in one limiting case, the ellipsoid can be made to resemble a disk. In the case of the disk the analysis was run for several values of the Reynolds Number. As shown in Table III, the error in the drag forces increased with decreasing Reynolds Number from approximately 1.5 percent at a Reynolds Number of 0.13 to about 6 percent at a Reynolds Number of 0.00326. The drag coefficients and the shape factor defined as the ratio of the drag force on an irregularly shaped particle to that on a sphere of the same frontal projected area are also presented in this table. The comparison of the drag coefficients for the two techniques for the disk are shown in Figure 4 and shows that the agreement is within the error bars on the numerical solution. These errors are estimates due to the inaccuracy in the numerical flow fields.

The final test of the numerical analysis technique was to study spherical straight chain agglomerates. Figure 5 shows the flow field around the chains containing from one to five spheres. In this case the dynamic shape factor of the straight chains was calculated and compared to those values reported from experiments performed by Stober[12] using a centrifuge to determine the shape factor. The numerical technique was performed on primary spheres of sizes 0.4, 1, 4, and 10 um diameter and compared with the experimental results which used latex spheres of several particle sizes on the order of 1 um diameter. The results of the comparison are shown in Table IV and Figure 6. The agreement is seen to be quite good considering the uncertainties in the orientation of the particles in the centrifuge. It is interesting to note in Figure 6 that both experimental and numerical generated dynamic shape factor versus number of particle curves have "S" shapes. The reason for the "S" shape of the curves is not clear, but it is felt to be significant that both the experimental and numerical results give the same curve shape.

The numerical technique gives more detail on the forces of the particles than can be obtained experimentally. For example, in Figure 7, the percent of the total drag contributed by each sphere is presented as a function of the number of spheres in the chain. It is of interest to note that the drag force contributions by the leading and trailing spheres are nearly the same and approximately equal to twice the drag force on the intermediate spheres.

Optimum Grid Pattern

As has been indicated earlier in this paper, a particle can be better defined by increasing the number of grid lines used to define the particle contour. However, as the number of grid lines increase, the number of node points over which the Navier-Stokes equations must be solved rapidly increases and soon becomes large enough to adversely affect the time and cost required to obtain a solution. Figure 8 shows the results of a study made in determining the drag on a sphere as a function of the node points used in the problem. This shows that as the number of node points increases, the percent error between the numerical solution and that obtained from Stokes Law rapidly decreases up to a value of approximately 800 node points. As the number of node points is increased beyond 800, the increase in accuracy is only slight. Also shown on the chart is the computer central processing time, and this curve, although not as dramatic as the error curve, does increase at a more rapid rate for the

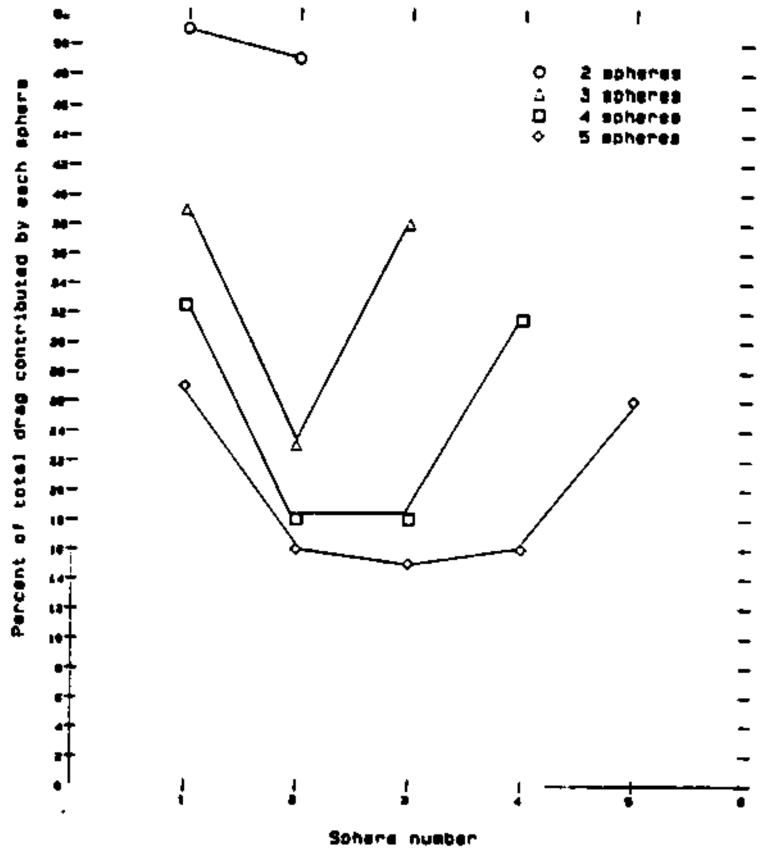


FIGURE 7. Drag distribution on a straight chain of spheres.

larger number of node points. For this reason, we have used approximately 800 node points per problem definition.

In some cases it will be necessary to use more than 800 node points to define the outline of an irregularly shaped particle. To avoid the large cost associated with the large number of node points, it was decided to solve the problem in steps, with each step increasing the fraction of the area of interest covered by the particle. An example of this step process is shown in Figure 9. At the top of Figure 9 is the initial step where the particle is defined by only a few grid lines, with most of the space reserved for the flow around the particle. The reason for having such a large space around the particle is so that the boundary conditions can be assumed to be unaffected by the presence of the particle. The resulting solution of this problem will define a velocity profile at all grid points within the solution domain, as shown by the dashed lines in the upper figure. If the area within the dashed lines is now enlarged, there can be more grid lines used to

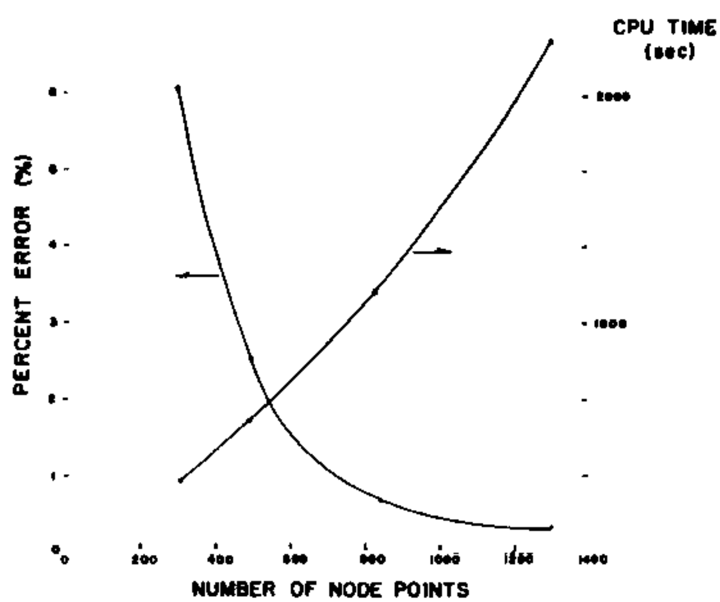


FIGURE 8. The effect of grid resolution on the accuracy of numerical solutions of spheres and on the computer time.

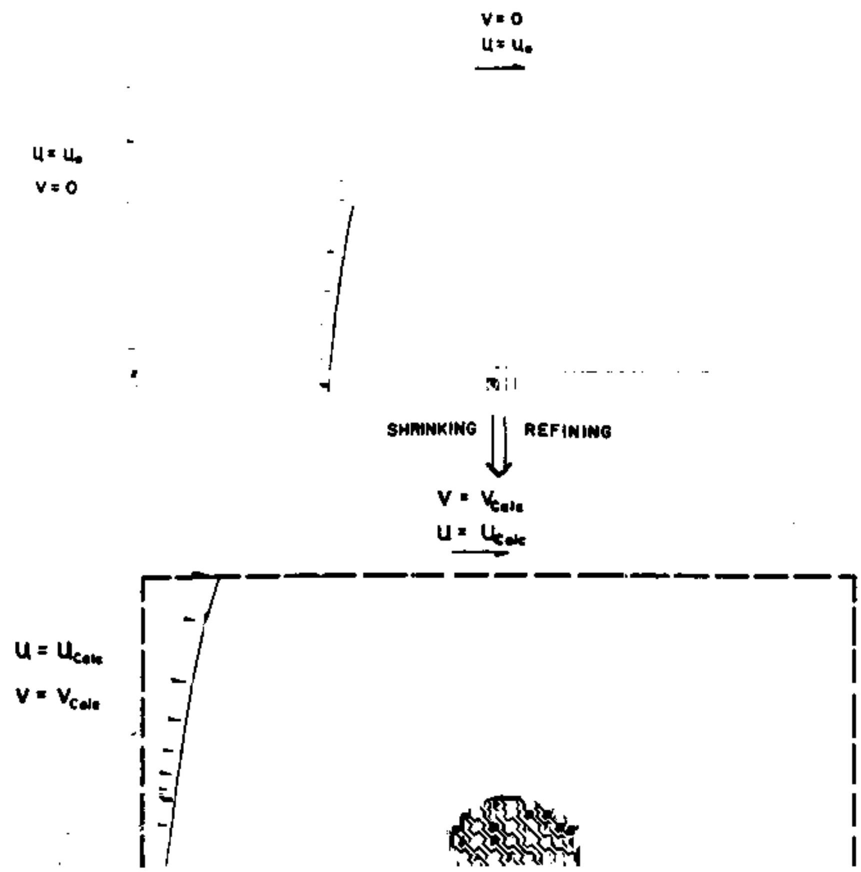


FIGURE 9. Grid lines used when shrinking calculation domain around a particle to increase resolution of the flow field.

define the outline of the particle and the boundary conditions are now those resulting from the first step.

This process can be continued in a stepwise fashion until sufficient definition of the particle contour has been obtained. In this manner, the flow around a very complex particle can be obtained and the number of node points kept on the order of 800, which is found to be optimum in obtaining an accurate answer at reasonable cost.

Conclusion

The two-dimensional numerical solution to the Navier-Stokes equations provides drag forces for particles that are in good agreement with those determined by other methods. For example, these drag forces on spheres agreed well with that given by the Stokes law. Similarly, cylinder drag agreed well with the analytical solution by Lamb, and the disk drag agreed with those determined by the Oseens solution. All solutions agreed within about five percent, and only about 40 node points were used to define the particle contour.

The technique, as applied to straight chains of spherical particles, also showed good agreement with experimental values of the dynamic shape factor determined by experimental centrifuge analysis. Although the numerical technique predicted dynamic shape factors somewhat larger than those determined experimentally, the dynamic shape factor as a function of the number of particles in the chain correlated well.

The two-dimensional analysis of particles, as reported in this paper, indicates that the contour of the particle can be satisfactorily defined with approximately 40 node points. It should, therefore, be possible to determine the drag force of irregularly shaped particles using three-dimensional numerical methods. For three-dimensional studies the computer time will be much more than for two dimensions, but information on the particle drag for these particles can be obtained in detail that is not obtainable by any other means. It is believed that any particle shape can be digitized, defined by a three-dimensional grid and analyzed to determine its aerodynamicdiameter.

Acknowledgment

This research has been supported by the U.S. Department of Interior's Mineral Institutes program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under allotment grant no. G1135142.

References

1. **Hinds, W.C.:** *Aerosol Technology*, pp. 104-126. John Wiley and Sons, New York (1982).
2. **Marple, V.A.:** A Fundamental Study of Inertial Impactors. Ph.D. Thesis, Mechanical Engineering

Department, University of Minnesota, Minneapolis, MN (1970).

3. **Agarwal, J.K.**: Aerosol Sampling and Transport. Ph.D. Thesis. Mechanical Engineering Department, University of Minnesota, (1975).

4. **Marple, V.A. and C.M. Chien**: Virtual Impactors: A Theoretical Study. *Env. Sci. Tech. 14*:976-985 (1980).

5. **Marple, V.A. and D.J. Rader**: Recent Developments in the Application of Finite Difference Solutions to the Study of Flow Fields and Particle Trajectores. *Proceedings from Third Symposium on Advances in Particle Sampling and Measurement*, Daytona Beach, Florida, October 18-21 (1981).

6. **Patankar, S.V.**: *Numerical Heat Transfer and Fluid Flow*. McGraw-Hill-Hemisphere Publication, New York (1979).

7. **Hinds, W.C.**: *Aerosol Technology*, pp. 40-42. John Wiley and Sons, New York (1982).

8. **Tomokita, S. and T. Aoi**: The Steady Flow of Viscous Fluid Past a Sphere and Circular Cylinder at Small Reynolds number. Q. J. Mech. Appl. Math., Vol. III, pp. 140-161 (1950).

9. **White, F.M.**: *Viscous Fluid Flow*. McGraw-Hill Book Company, New York (1974).

10. **Oseen, C.**: *Neuere Methoden und Zrgebnise in der Hydrodynamik.* Leipzig (1927).

11. **Fuchs, N.**: *Mechanics of Aerosols*, Chap. II, pp. 21-70, Pergamon Press, Oxford (1964).

12. **Stober, W.**: A Note on the Aerodynamic Diameter and the Mobility of Non-Spherical Aerosol Particles. *J. Aerosol Sci.*, pp. 453-456 (1971).

MINIRAM Performance in the Coal Mining Environment

JOHN A. ORGANISCAK,[A] KENNETH L. WILLIAMS[B] and THOMAS OZANICH[C]

[A]Mining Engineer; [B]Supervisory Physical Scientist; [C]Mining Engineering Technician, Pittsburgh Research Center, Pittsburgh, PA

The Bureau of Mines conducted an underground performance evaluation on the MINIRAM. This new compact light-scattering instrument measures relative instantaneous respirable dust concentrations by passively allowing environmental air to flow through an open-ended sensing chamber. A personal sampler adapter (utilizing a 10-mm nylone cyclone) that fits over the sensing chamber, in combination with a personal dust pump, also can be used to actively measure relative instantaneous dust concentrations and collect a gravimetric sample.

Tests to compare the MINIRAM (passively and actively) with the RAM-1 and the personal gravimetric sampler were conducted at two continuous miner sections and one longwall section. Active sampling results indicate that the seal (foam padding) on the MINIRAM personal sampler adapter may not be adequate in all cases and might eventually deteriorate making the MINIRAM's instantaneous and gravimetric measurements significantly higher than those of the RAM-1 and the personal sampler. When a good seal exists between the MINIRAM's sensing chamber and personal sampler adapter, the instantaneous and gravimetric measurements correspond well with those of the RAM-1 and personal sampler. Passive sampling with the MINIRAM yields values that are higher although well correlated with the values obtained by active sampling using the personal sampler adapter. The higher values are probably due to water droplets and/or larger dust particles entering the sensing chamber during passive sampling.

Introduction

Respirable dust monitoring of the underground mining environment is vital for safeguarding the respiratory system of mine workers. Improvements in the mine air quality are achieved through identifying dust sources, developing effective dust controls, and ensuring that controls are utilized and maintained. The essential tools for this purpose are dust sampling instruments. Two types of instruments commonly used are gravimetric and light-scattering. Gravimetric instruments use a suction pump to draw a constant volume flow of the mine air through a physical classifier and collect the respirable dust on a filter. The mass collected on the filter for a known time period, at a specified sampling flow volume, gives the average dust concentration for that period. One important advantage of gravimetric sampling is that a physical mass is collected from a known volume of air, making this a more absolute dust concentration measurement. However, gravimetric samplers do not provide information about specific instantaneous dust concentrations during the sampling period. This limits their use for identifying dust sources and evaluating control technology to some short-term gravimetric sampling strategies.[1]

Usually, light-scattering instruments operate by measuring light scattered in a near forward direction by an aerosol or dust. A light-emitting diode operating in the near-infrared region (approx. 0.9 um wavelength) is commonly used as an illumination source and a silicon photovoltaic-type diode is used as a means of scattered light detection. The respirable portion of the aerosol can be sampled either by a passive or an active method. The passive method allows the mine air to flow freely through an open sensing chamber and the respirable portion of the dust is approximated by detecting the light scattered in a near forward angle range (MINIRAM's detection angle is 45-95 degrees). Problems associated with passive sampling include water droplet detection, some nonrespirable dust detection, and zero drift due to dust fallout in the sensing chamber.[2-4] The active method mechanically draws a sample of the mine air through a respirable dust classifier before it is measured in the sensing chamber. These classifiers commonly use a gravitational elutriation or a centrifugal method to remove nonrespirable dust from the air. Also, most water droplets should be removed by the classifier because they are usually in the nonrespirable size range. Active sampling, using physical classifiers, minimizes respirable dust measurement errors caused by water droplets and nonrespirable dust.[2-4] Also, some active sampling light scattering instruments have clean air purged over the emitting and detecting optic surfaces to eliminate zero drift.

An advantage of the light-scattering instrument is its ability to measure relative dust concentrations continuously (instantaneously) throughout a mining process. This capability enables the instrument to identify the major dust sources and processes in mining.[5] Also, dust controls used during specific phases of the mining process can readily be evaluated with this type of instrument. A disadvantage of the light-scattering instrument is its dependence on the physical characteristics of dust being measured (size distribution, density, shape and surface properties).[4,6]

A dust sampling instrument recently developed under a Bureau of Mines contract that has both light scattering and gravimetric measurement capability is the MINIRAM personal monitor (Figure 1).[7] This makes the instrument more versatile and useful for a wide range of dust monitoring applications. The purpose of this paper is to present the results of the MINIRAM performance in the mining environment as compared to the personal sampler and Real-Time Aerosol Monitor (RAM-1). These have been extensively tested with good performance in the laboratory and under-

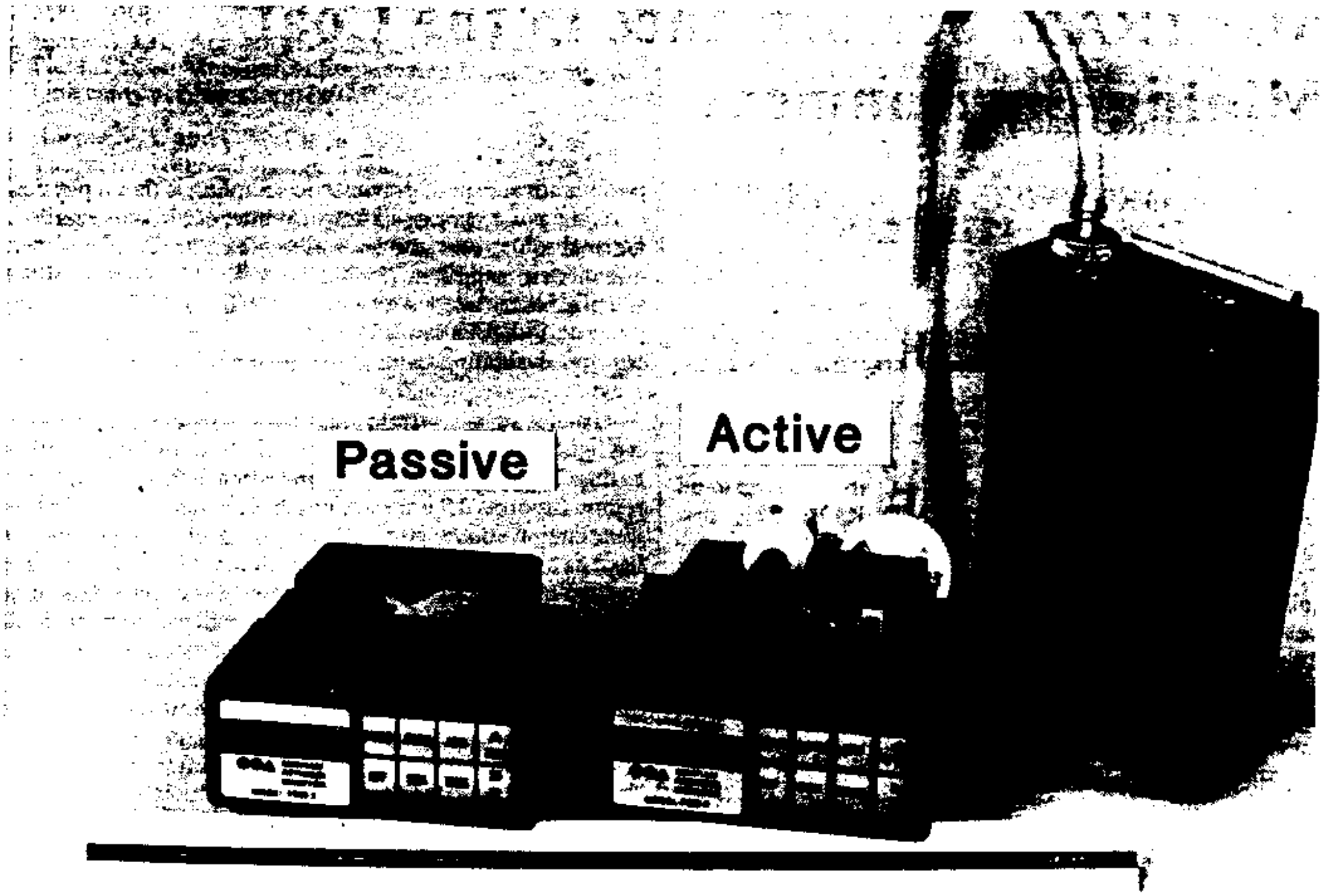


FIGURE 1. MINIRAM dust monitor (passive and active).

ground environments.[6,8-10] A brief description of the dust sampling instruments compared is given in the Appendix.

Laboratory MINIRAM Calibration

Before any underground comparison tests between the MINIRAM, RAM-1, and personal sampler were undertaken, MINIRAMs were calibrated against the Bureau's transfer standard RAM-1, using Pittsburgh coal dust. Pittsburgh coal, ground to –325 mesh was fed into a static dust chamber with a TSI fluidized bed aerosol generator. (Reference to specific products does not imply endorsement by the Bureau of Mines. The RAM and MINIRAMs located outside the dust chamber were remotely connected to 10-mm cyclones located inside the dust chamber. Table I shows laboratory results of six MINIRAMs at several stages of calibration.

The first test conducted was the comparison of six MINIRAMs, calibrated to Arizona Road Dust by the manufacturer, to the Bureau's standard transfer RAM, calibrated to Pittsburgh coal dust. Average MINIRAM measurements were about 97 percent higher than the RAM measurements and the coefficient of variation between the MINIRAMs was 20.8 percent. MINIRAMs were calibrated by adjusting the potentiometer screw until the displayed measurements are equivalent to the standard RAM. After repeated calibration adjustments to fine tune the MINIRAMs to the standard RAM, the MINIRAMs' measurements were slightly lower (2.5%) than the standard AM and the coefficient of variation between MINIRAMs was 5.0 percent. The relative calibration and precision of the MINIRAMs after this stage of calibration were considered as good as possible for underground testing.

Underground MINIRAM Tests

Initial underground comparison tests of the MINIRAMs, RAM, and personal sampler were conducted on a continuous miner section and a longwall section for several days.

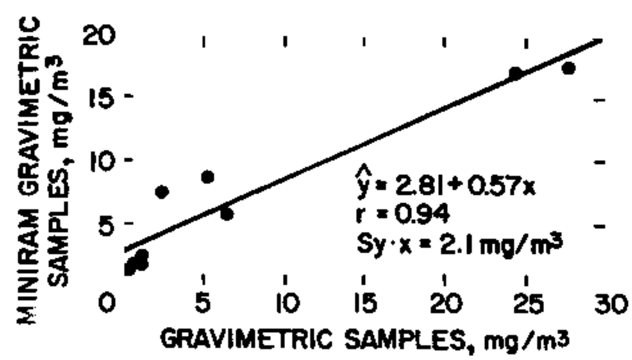


FIGURE 2. Comparison of gravimetric respirable dust concentrations measured with personal samplers and active sampling MINIRAMS.

TABLE I

Results of MINIRAM Calibration Against Bureau Standard RAM

Test No.	Average Concentration of transfer Standard (RAM Units)a	Calibration Status of MINIRAM	Average Concentration of six MINIRAMS (RAM Units)	Standard Deviation of MINIRAMS (RAM Units)	Coefficient of Variation of MINIRAM
1	3.92	Manufacture	7.71	1.60	20.8%
2	5.27	First Cal	5.01[b]	0.76	15.2%
3	5.15	Second Cal.	5.12	0.41	8.0%
4	6.22	Third Cal.	6.13	0.30	4.9%
5	5.79	Third Cal.	5.59	0.29	5.2%

[a] A RAM unit is a uniform relative (linear) unit of measure that can be calibrated to a specific type of dust. In this case the RAM unit is equivalent to one mg/m3 of Pittsburgh coal dust.

[b] Only 5 MINIRAMs were included in this average because one MINIRAM malfunctioned.

Two sampling locations were selected on each section. Two personal samplers, a MINIRAM sampling actively and a MINIRAM sampling passively were located on the continuous miner, just out by the boom hinge point, or at the shearer midpoint. Two personal samplers, a MINIRAM sampling actively and a RAM, were placed on the immediate return side of the continuous miner or at the longwall tailgate. The dust sampling instruments were run for most of the shift and all instantaneous data were collected from the instrument's analog output with a Metrosonics dl-331 data logger.

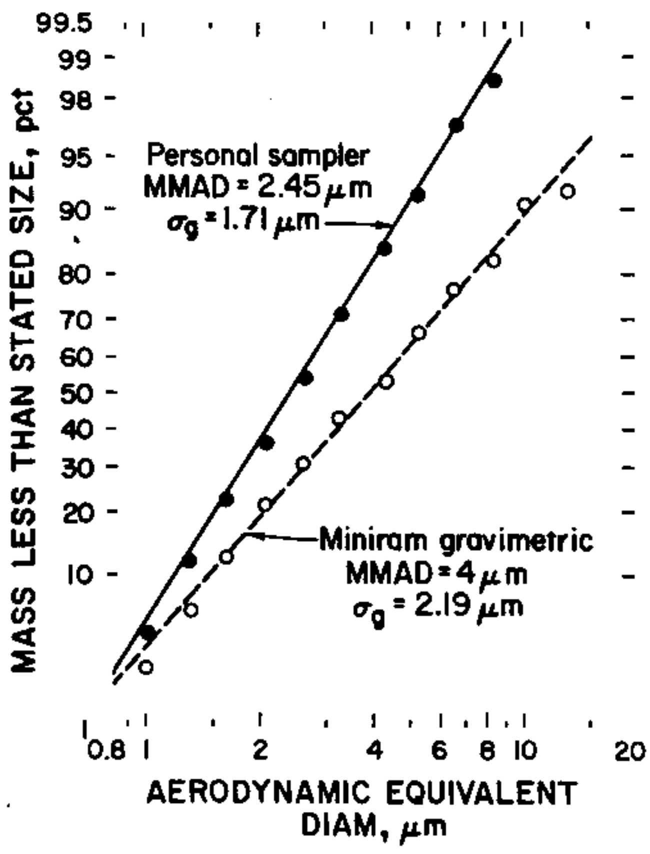


FIGURE 3. The aerodynamic equivalent size distributions for a personal sampler and an oversampling MINIRAM on the continuous mining machine.

Gravimetric measurements between the MINIRAMs and personal samplers were treated by regression analysis and the best fit line is shown in Figure 2. The MINIRAM gravimetric measurements did not correspond well with the personal samplers. In most instances the MINIRAM seemed to oversample, but in extremely high dust concentrations it seemed to undersample. Statistical analysis of the regression model has shown that at a 95 percent confidence level there was significant difference between gravimetric measurements with the MINIRAM and with the personal sampler (Table II).

Particle size distributions were determined by Coulter counter analysis for several gravimetric samplers where discrepancies were evident. Figures 3 and 4 show the aerodynamic equivalent size distributions (determined from mass distributions) between the personal sampler and an oversampling MINIRAM on the continuous miner and at the longwall tailgate, respectively. The MINIRAMs oversampled by 104 percent at the miner and 216 percent at the tailgate. These graphs indicate that MINIRAMs were sampling more dust throughout the entire size range. This oversampling is attributed to poor sealing between the personal sampler adapter and the MINIRAM's sensing chamber, which allows more airborne dust to bypass the cyclone and deposit on the cassette filter.

Figure 5 shows the aerodynamic equivalent size distributions for the personal sampler and an undersampling MINIRAM at the miner return, when extremely high dust concentrations were sampled. The MINIRAM undersampled by 38 percent, and noticeable undersampling occurred at sizes greater than 2.58 um. The instantaneous zero drift of 1.33 was higher than normally observed for active sampling (usually less than 0.3). The higher zero drift suggested that MINIRAM gravimetric undersampling was probably caused by dust fallout in the sensing chamber. The second day of sampling in the miner return, the MINIRAM significantly undersampled again and the zero drift was 2.14.

TABLE II

Statistical Analysis Results for Underground Tests

Instruments Compared	Location	*Regression Equation	Hypothesis	df	t.025	#Tstat	Conclusion
MINIRAM Grav. (Y) vs Personal Grav (X)	Miner & Return Shearer Tailgate	$Y = 2.81 + 0.57X$ $r = 0.94$ $s_{y \cdot x} = 2.10$	H_o: ß1 = 1 H_a: ß1 = 1	10	-2.228	-6.474	Reject Null Hypothesis
MINIRAM Active (Y) vs. Miniram Passive (X)	Miner	$Y = 0.49 + 0.55X$ $r = 0.97$ $S_{y \cdot x} = 0.17$	H_o: ß1 = 1 H_a: 1 = 1	30	-2.042	-18.558	Reject Null Hypothesis
	Shearer	$Y = 1.35 + 0.45X$ $r = 0.87$ $S_{y \cdot x} = 0.7$	H_o: ß1 = 1 H_a: ß1 = 1	17	-2.110	-8.572	Reject Null Hypothesis
MINIRAM Active (Y) vs. RAM-1 (X)	Miner Return	$Y = 0.88 + 1.22X$ $r = 0.98$ $S_{y \cdot x} = 1.21$	H_o: ß1 = 1 H_a: ß1 = 1	31	2.040	4.623	Reject Null Hypothesis
	Tailgate	$Y = 0.29 + 1.67X$ $r = 0.91$ $S_{y \cdot x} = 0.93$	H_o: ß1 = 1 H_a: ß1 = 1	33	2.036	5.172	Reject Null Hypothesis

*Statistical Model: Y = ßo + ß1
Y — Dependent Variable Estimate from Model
ß1 — Slope Estimate of Model.
r — Correlation Coefficent
Sy.x — Standard Deviation of Regression (Standard Error of Estimate).
df — Degrees of Freedom.
t.025 — Student's t Critical Point at the 95% Confidence Level for a Two Tailed Test.

#Tstat = ß1 - ß1/Sß1.
ßo — Intercept Estimate of Model.
ß1 — Population Slope.
Sß1 — Standard Deviation of 1 Sampling Distribution.

Instantaneous comparisons were made between a MINIRAM sampling passively vs. actively, and a MINIRAM sampling actively vs. the RAM-1. The instantaneous concentrations on data loggers were averged into corresponding 15-minute average dust concentrations. These 15-minute averages were analyzed using straight line regression models to compare instrument measurements. Since the MINIRAM's zero factor (see appendix) is not instrumentally subtracted from its analog output, these regression models have intercepts other than zero because the least squares line is shifted by the zero factor(s) from the origin of the axis. This will not affect the slope of regression lines for comparative measurements between the instruments. The slope of the regression lines indicates how well the instruments' relative measurements correspond. For ideal correspondence between instruments, the slope is one.

Figures 6 and 7 show the least squares line for the MINIRAM sampling passively vs. actively at the continuous miner and shearer. The optional sun shield was used on the MINIRAM sampling passively because the MINIRAM measurements can be overloaded by direct light from cap lamps and machinery. The MINIRAMs sampling actively during these tests were suspected of mine air leakage into the sealed sensing chamber, because of gravimetric oversampling. These regression lines, with slopes significantly different from one (Table II), clearly show that the instantaneous values of passive sampling are significantly higher than those obtained by sampling actively. The higher instantaneous measurements obtained when sampling passively were probably due to the instrument's increased response to water sprays and larger particles entering the open ended sensing chamber. A higher zero drift was observed for passive sampling because of increased dust fallout on the optics in the sensing chamber. Average zero drift at the miner was 0.27 (passively) and 0.04 (actively). At the shearer the average zero drift was 1.63 (passively) and 0.57 (actively). The higher zero drift experienced at the shearer for both passive and active sampling may have been caused by higher dust concentrations and increased external water application at the shearer.

Figures 8 and 9 show the least squares line for the MINIRAM sampling actively vs. the RAM-1 at the continuous miner return and longwall tailgate. The MINIRAM sampling in high dust concentrations at the miner return undersampled the gravimetric dust concentration and had a higher than normal zero drift. Its instantaneous measurements, as compared to the RAM-1, were higher with a regression slope significantly different from one (Table II). These higher measurements obtained with the MINIRAM were probably due to dust fallout over the optics in the sensing chamber, increasing instantaneous dust measurements and zero drift. The MINIRAM sampling at the longwall tailgate was suspected of environment leakage into the sealed sensing chamber because of gravimetric oversampling. Its instantaneous measurements, as compared to the RAM-1, were higher, with a regression slope significantly different from one (Table II). These higher MINIRAM values were probably due to the extra dust leakage into the sensing chamber.

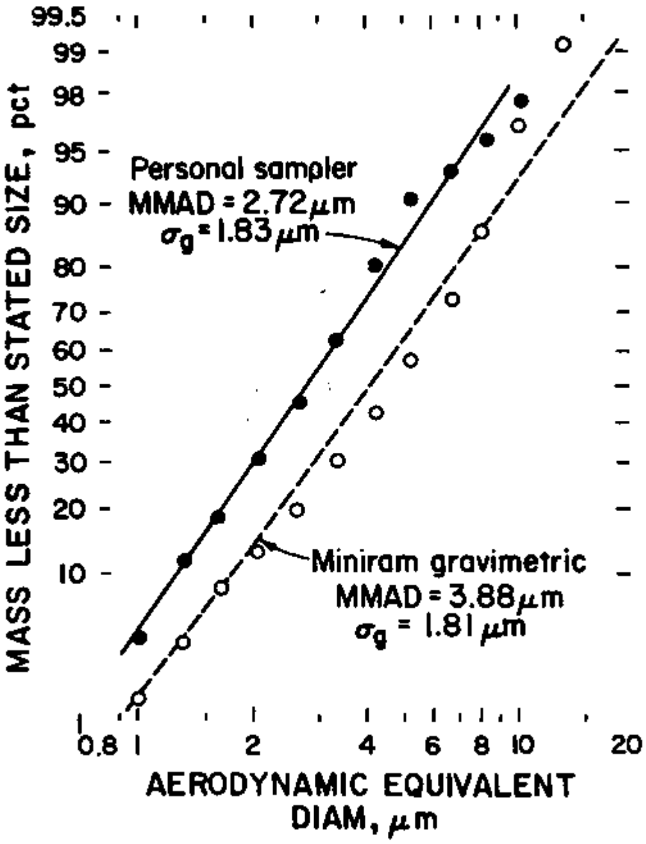


FIGURE 4. The aerodynamic equivalent size distributions for a personal sampler and oversampling MINIRAM at the longwall tailgate.

These underground tests have shown significant differences for MINIRAM, personal sampler and RAM-1 measurements. Discrepancies between passive and active MINIRAM sampling were expected, due to the classification methods of respirable dust and water droplet interference. However, significant differences between measurements made with an active sampling MINIRAM and the other instruments were not expected, and were attributed to a sealing problem between the personal sampler adapter and the MINIRAM sensing chamber. Laboratory tests were conducted to determine if there was a problem with the personal sampler adapter seal, and if so, how to correct it.

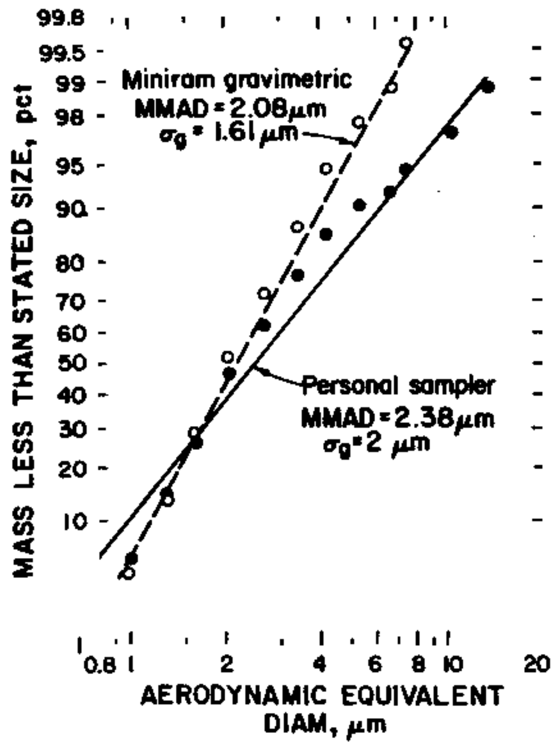


FIGURE 5. The aerodynamic equivalent size distributions for a personal sampler and an undersampling MINIRAM in the miner return.

MINIRAM Laboratory Tests

Gravimetric sampling tests were conducted in the laboratory with a MINIRAM that undersampled in high dust concentrations (MINIRAM No. 1) and with a MINIRAM

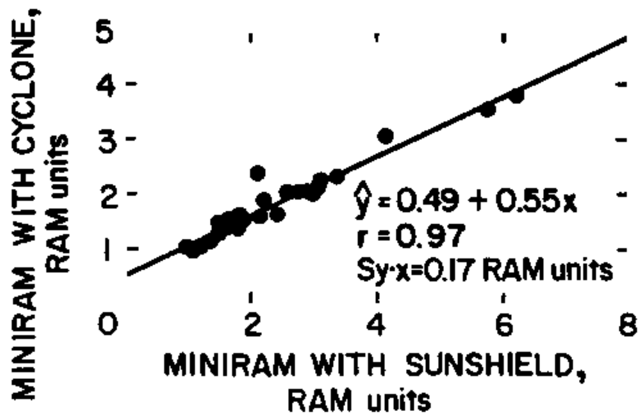


FIGURE 6. Comparison of instantaneous respirable dust concentrations measured with a passive sampling MINIRAM and an active sampling MINIRAM that gravimetrically oversampled at the continuous mining machine.

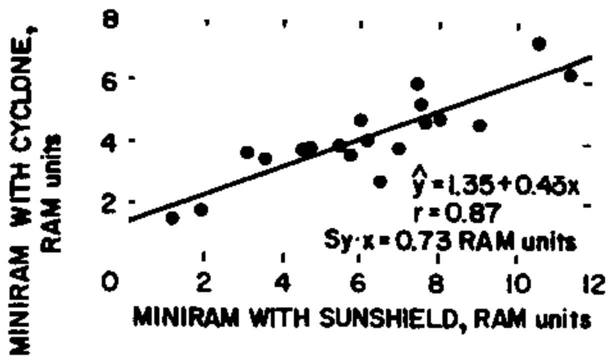


FIGURE 7. Comparison of instantaneous respirable dust concentrations measured with a passive sampling MINIRAM and an active sampling MINIRAM that gravimetrically oversampled at the longwall shearer.

that consistently oversampled (MINIRAM No. 2). These tests were conducted in the return of the Bureau's full scale model mine facility. Dust concentrations during these tests ranged from 20-60 mg/m^3 for a sampling period of 30-66 minutes. The gravimetric samples of these two MINIRAMs were compared to the average of three personal samplers during a series of seal tests. For the first two tests, the MINIRAMs were used in the same condition as in the underground tests. The average results of these two tests are shown in Figure 10 plot A. There was a negligible difference between MINIRAM No. 1 and the personal samplers; MINIRAM No. 2 continued to oversample significantly.

For the second set of tests, the seal around the personal sampler adapter on MINIRAM No. 1 was disassembled and reassembled between tests to inspect the resilience or quality of the foam seal with continued use. The foam seal was noticeably compacted for this set of tests. The personal adapter on MINIRAM No. 2 was sealed with caulking in probable areas of seal leakage. The average results of these two tests are shown in Figure 10 plot B. A negligible difference continued between MINIRAM No. 1 and personal samplers; oversampling of MINIRAM No. 2 had decreased

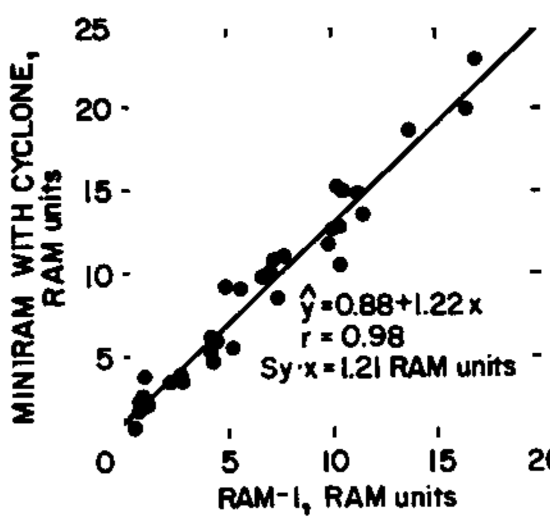


FIGURE 8. Comparison of instantaneous respirable dust concentrations measured with a RAM-1 and an active sampling MINIRAM that gravimetrically undersampled in the miner return.

During the third set of tests, disassembly and reassembly of the personal sampler adapter of MINIRAM No. 1 continued between tests. Compaction of the seal was becoming more pronounced. The seal of MINIRAM No. 2 was improved by using 1/16" neoprene gaskets cut to fit between the sensing chamber and the original foam seal. The average results from these two tests are shown in Figure 10 plot C. MINIRAM No. 1 now oversampled significantly with MINIRAM No. 2 had a negligible difference as compared to the personal samplers.

These laboratory results indicated that the most common oversampling discrepancies between the active sampling MINIRAM, personal sampler, and RAM-1 were caused by a poor seal between the personal sampler adapter and MINIRAM sensing chamber. The foam seal used on the personal sampling adapter seems to lose resilience and to compact over time. A follow-up underground study was conducted using the neoprene gaskets to test for improvements in MINIRAM performance.

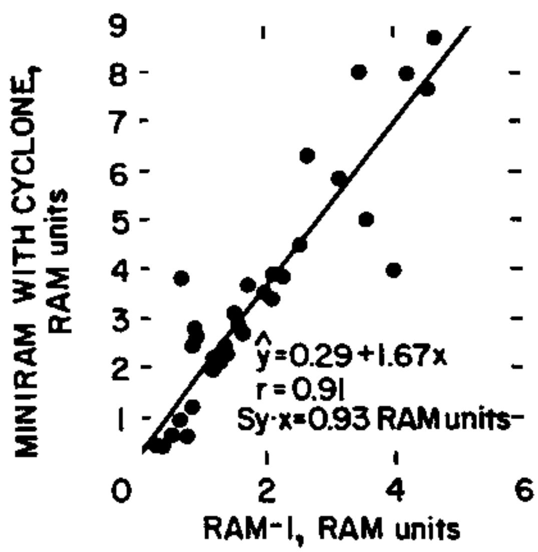


FIGURE 9. Comparison of instantaneous respirable dust concentrations measured with a RAM-1 and an active sampling MINIRAM that gravimetrically oversampled at the longwall tailgate.

Although significant MINIRAM gravimetric undersampling was observed in a few instances of very high dust concentrations (> 20 mg/m^3) underground, this was not observed with the same MINIRAM in similar dust concentrations during the laboratory tests. Two factors that could have contributed to the presumed dust fallout in the sensing chamber when very high dust concentrations were measured underground, were the longer sampling periods and the water-saturated air in the miner return. Gravimetric undersampling with the MINIRAM may not pose any problems in the majority of underground dust monitoring applications, but the possibility of undersampling in high dust concentrations (> 20 mg/m^3) should not be overlooked.

Follow-up MINIRAM Underground Tests

Underground sampling was conducted on a continuous miner section for several days, as was done previously.

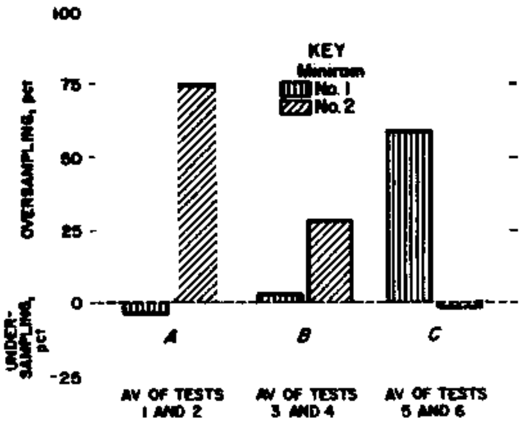


FIGURE 10. Results of the MINIRAM gravimetric tests in the laboratory.

Neoprene gaskets were used between the sensing cahmber and foam seal of the personal sampler adapter of MINIRAMs sampling actively. Again, comparative samples were taken at the continuous mining machine and its return. Similar analysis was conducted on the gravimetric and instantaneous data.

Gravimetric results are shown with the best fit least squares line in Figure 11. The regression model shows a dramatic improvement in gravimetric correspondence between the MINIRAM and the personal sampler. No significant difference was found between the instruments at the 95 percent confidence level (Table III). No significant amount of MINIRAM gravimetric oversampling and undersampling was observed.

Particle size analysis (Coulter counter analysis) conducted on typical corresponding gravimetric samples collected by the MINIRAM and the personal sampler in the miner return are shown in Figure 12. The graph shows a negligible difference between size distributions of respirable dust collected with the MINIRAM and personal sampler. This indicates that the MINIRAM's personal sampler adapter collection characteristics are similar to the personal sampler, provided a good seal exists between the adapter and the sensing chamber.

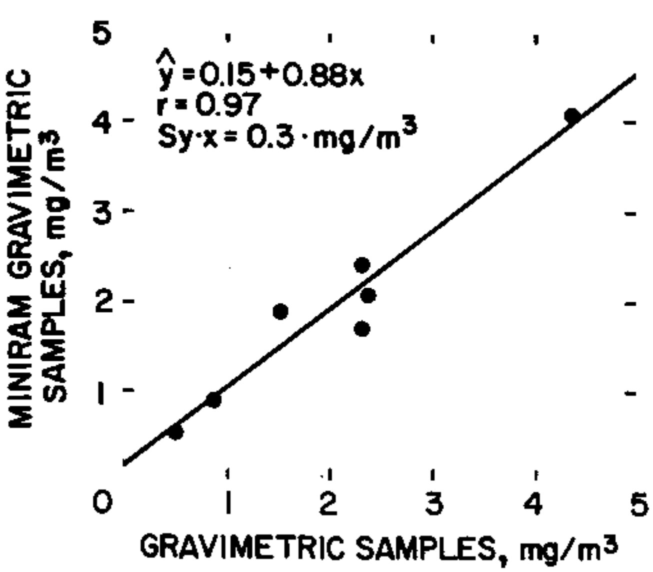


FIGURE 11. Comparison of gravimetric respirable dust concentrations measured with personal samplers and active sampling MINIRAMs (follow-up underground tests).

Figure 13 shows the least squares line for instantaneous MINIRAM sampling passively vs. actively at the continuous miner. The sun shield was again used on the MINIRAM sampling passively and gravimetric measurements indicated no oversampling with the MINIRAM sampling actively. The results clearly show that passive values are still significantly greater than active values (Table III) due to dust size classification and/or water mist.

Active MINIRAM sampling vs. RAM-1 sampling at the miner return is shown in Figure 14. The regression line shows improved relative correspondence between the instruments. The regression model for these measurements shows no significant difference between two instantaneous instruments (Table III), which seem to respond similarly to dust concentrations.

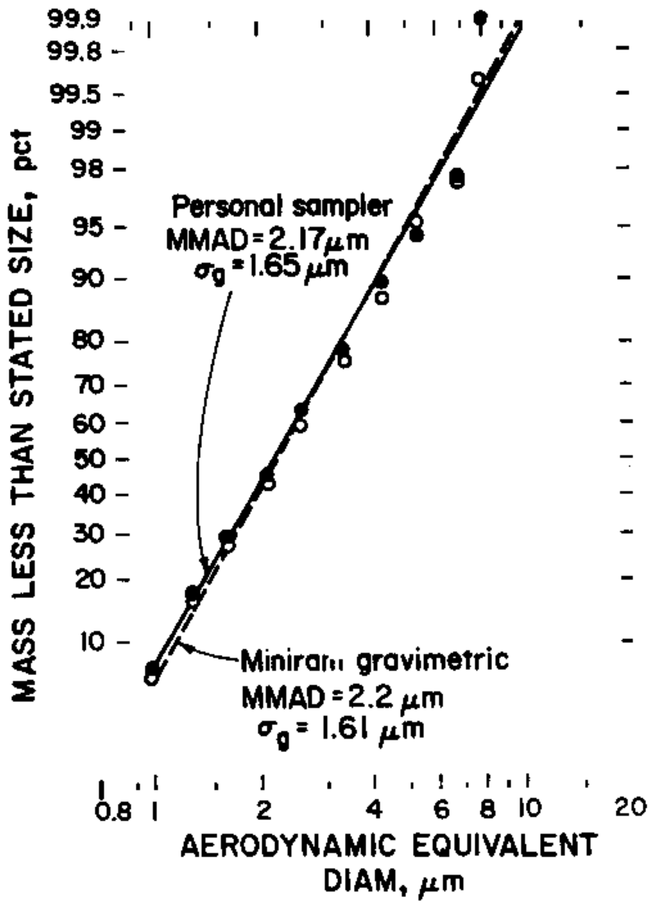


FIGURE 12. The aerodynamic equivalent size distributions for a personal sampler and a MINIRAM in the miner return (follow-up underground tests).

Conclusions

Performance tests indicate that the MINIRAM sampling actively is capable of performing as well as the personal sampler and RAM-1, provided a good seal is achieved between the personal sampler adapter and the sensing cham-

TABLE III

Statistical Analysis Results for Follow-up Underground Tests

Instruments Compared	Location	*Regression Equation	Hypothesisa	df	t.025	#tstat	Conclusion
MINIRAM Grav. (Y) vs. Personal Grav. (X)	Miner & Return	Y = 0.15 + 0.88 X r = 0.97 $S_{y \cdot x}$ = 0.30	H_o: ß1 = ß1 H_a: ß1 = ß1	5	-2.571	-1.262	Cannot Reject Null Hypothesis
MINIRAM Active (Y) vs MINIRAM Passive (X)	Miner	Y = 2.15 + 0.37 X r = 0.93 $S_{y \cdot x}$ = 0.3	H_o: ß1 = ß1 H_a: ß1 = ß1	30	-2.042	-22.959	Reject Null Hypothesis
MINIRAM Active (Y) vs. RAM-1 (X)	Miner Return	Y = 2.49 + 0.89 X r = 0.92 $S_{y \cdot x}$ = 0.26	H_o: ß1 = ß1 H_a: ß1 = ß1	12	-2.179	-1.017	Cannot Reject Null Hypothesis

**Statistical Model: Y = ßo + ß1
Y — Dependent Variable Estimate from Model
ß1 — Slope Estimate of Model.
r — Correlation Coefficent
Sy.x — Standard Deviation of Regression (Standard Error of Estimate).
df — Degrees of Freedom.
t.025 — Student's t Critical Point at the 95% Confidence Level for a Two-Tailed Test.

#Tstat = 1 - 1/S 1.
ßo — Intercept Estimate of Model.
ß1 — Population Slope.
Sß1 — Standard Deviation of 1 Sampling Distribution.

ber. The active sampling MINIRAM provides an average gravimetric concentration, an instantaneous time-weighted average concentration and relative instantaneous dust levels for the sampling period. These types of measurements made by the same instrument is advantageous because the relative instantaneous measurements can be adjusted (multiplied) by a gravimetric-instantaneous factor to yield more accurate instantaneous measurements. This factor is the ratio of the average gravimetric concentration to the instantaneous time weighted average (obtained from MINIRAM electronic memory). Active sampling with the MINIRAM will improve the accuracy of instantaneous dust measurements made in various types of dusts.

The MINIRAM sampling passively correlates well with an active sampling MINIRAM, but its measurements are sig-

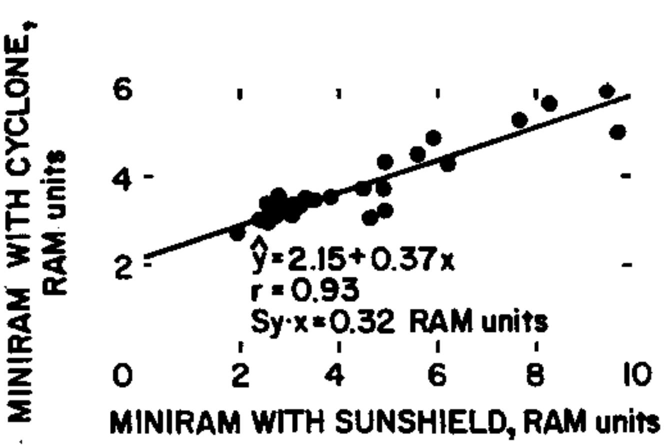


FIGURE 13. Comparison of instantaneous respirable dust concentrations measured with a passive sampling MINIRAM and an active sampling MINIRAM at the continuous mining machine (follow-up underground tests).

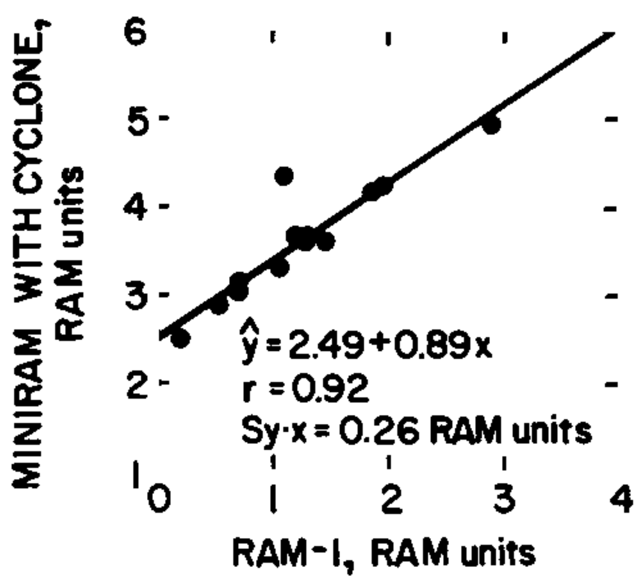


FIGURE 14. Comparison of instantaneous respirable dust concentrations measured with a RAM-1 and an active sampling MINIRAM in the miner return (follow-up underground tests).

nificantly higher. This is attributed to respirable dust size classifiction and to water droplets. The instrument used passively should indicate significant dust sources and improvements obtained with dust controls. However, respirable dust concentrations and dust control efficiencies measured with a passive sampling MINIRAM may not be truly represented when significant amounts of water droplets are present in the air and/or significant changes occur to the dust size distribution. Dust control with water sprays and scrubbers commonly add water droplets into the environment and change the dust size distribution. MINIRAM sampling actively can minimize these discrepancies and improve instantaneous accuracy because the cyclone removes water droplets and physically classifies respirable dust, and the instantaneous measurements can be adjusted by a gravimetric-instantaneous factor.

APPENDIX

Description of Dust Sampling Instruments

Personal sampler

This gravimetric instrument is used extensively in the United States coal mining industry to determine average worker dust exposure. It operates by drawing 2 lpm of dusty air through a 10-mm Dorr-Oliver Cyclone and collecting the cyclone overflow on a 5 um preweighed cassettee filter. The overflow of coal dust from the 10-mm cyclone operating at 2 lpm closely approximates the respirable dust deposition in lungs as defined by U.S. Atomic Energy Commission [11] This sampler has proved to be reasonably accurate and precise for measuring average dust concentration.[9,10]

Real-time aerosol monitor (RAM-1)

This is an instantaneous light scattering instrument developed under a Bureau of Mines contract by GCA Environmental Instruments.[12] The RAM-1 is an active light scattering instrument that utilizes a 10-mm Dorr-Oliver cyclone, sampling at a flow of 2 lpm to classify the respirable dust measured in the sensing chamber. This instrument has no internal averaging or recording capabilities and provides output via liquid crystal display or analog output. Results of laboratory tests indicate that the RAM-1's response is precise, linear and well correlated with mass concentration.[6,8] However, response depends on dust characteristics, making calibration to the specific dust is necessary for absolute measurements.

MINIRAM

This is a new passive instantaneous instrument that was developed under a Bureau of Mines contract by GCA (Figure 1).[7] This instrument is significantly smaller than the RAM and has internal averaging capabilities. It also has a re-zero capability to account for zero drift due to dust fallout in the sensing chamber (all passive light scattering instruments have zero drift because of dust fallout). The re-zero function measures the amount of dust settled in the sensing chamber when in a dust-free environment and stores this number (zero factor) in memory. When the instrument is used to measure dust concentrations, this zero factor is internally subtracted from the displayed dust measurements, it is not subtracted from the analog output.

Another feature of the MINIRAM is that it can be used actively with a optional personal sampler adapter and a personal sampling pump (Figure 1). The personal adapter fits over the open ended sensing chamber to seal the chamber from the environment. The inlet side of the closed sensing chamber has a 10-mm Dorr-Oliver cyclone for respirable dust classification, the outlet side of the chamber has a cassette filter to collect respirable dust for gravimetric measurement of the respirable dust. The mine air is drawn through the sensing chamber and onto the filter by a pump operating at 2 lpm. The optical surfaces are not purged with clean air to eliminate zero drift. The personal sampler adapter adds flexibility to the MINIRAM's capabilities. Using the MINIRAM actively has several advantages. One is that the respirable dust is physically classified by a standardized method rather than approximated by light scattering. Also, the MINIRAMs instantaneous response to water droplets from water sprays is minimized by cyclone capture because water droplets are usually nonrespirable is size.[2,4] Finally, a gravimetric measurement is obtained by active MINIRAM sampling.

References

1. **Page, S.J., R.A. Jankowski and F.N. Kissell:** *How to Evaluate Longwall Dust Sources with Gravimetric Personal Samplers. Bureau of Mines* IC 8894, 14 pp. (1982).

2. **Thakur, P.C., R.W. Hatch and J.B. Riester:** Performance Evaluation of Machine-Mounted Respirable Dust Monitors for U.S. Coal Mines. *Aerosols in the Mining and Industrial Work Environment*, Vol. 3, Chap. 49, pp. 647-663. V.A. Marple and B.Y.H. Liu Eds. Ann Arbor Science, Ann Arbor, MI (1983).

3. **Ford, V.H.W., R. Minton and D. Mark:** Comparative Trails in Coal Mines for the TM-Digital and Simslin Dust Monitors. *Ibid.*, Chap. 54.

4. **University of Minnesota:** *Respirable Dust Measurements* (contract J0113042). Bureau of Mines OFR 90-85, 154 pp.; NTIS PB 85-245843-XAB (1984).

5. **Taylor, C.D., R.A. Jankowski, S.K. Ruggieri and T.L. Muldoon:** The Use of Instantaneous Samplers to Evaluate the Effectiveness of Respirable Dust Control Methods in Underground Mines. *Aerosols in the Mining and Industrial Work Environment*, Vol. 2, Chap. 32, pp. 433-440. V.A. Marple and B.Y.H. Liu, Eds. Ann Arbor Science, Ann Arbor, MI (1983).

6. **Williams, K.L. and R.J. Timko:** *Performance Evaluation of a Real-time Aerosol Monitor.* Bureau of Mines IC 8968, 20 pp. (1984).

7. **GCA Corporation:** *Personal Dust Monitor – Light Scattering* (contract H0308132). Bureau of Mines OFR 95-83, 40 pp.; NTIS PB 83-205435 (1982).

8. **Tomb, T.F. and A.J. Gero:** Development of a Machine-mounted Respirable Coal Mine Dust

Monitor. *Aerosols in the Mining and Industrial Work Environment,* Vol. 3, Chap. 48, pp. 647-663. V.A. Marple and B.Y.H. Liu, Eds. Ann Arbor Science, Ann Arbor, MI (1983).

9. **Eastern Associated Coal Corp.:** Development of an *Area Sampling Methodology* (contract HO133108). Bureau of Mines OFR 105-79, 99 pp. (1976).

10. **Breslin, J.A., S.J. Page and R.A. Jankowski:** *Precision of Personal Sampling of Respirable Dust* in *Coal Mines.* Bureau of Mines RI 8740, 12 pp. (1983).

11. **Lippermann, M and W.B. Harris:** Size Selective Samplers for Estimating "Respirable" Dust Concentrations. *Health Physics* 8:155-163 (1962).

12. **GCA Corporation:** *Improved Light Scattering Dust Monitor* (contract H0377092). Bureau of Mines OFR 90-79, 19 pp.; NTIS PB-299-938.

Measurements of Respirable Dust Concentrations by Using Various Samplers in Underground Coal Mines

C.Y. HWANG, Ph.D.
Cape Breton Coal Research Laboratory,
Canada Centre for Mineral and Energy
Technology (CANMET)

The specific etiological factors of coal workers' pneumoconiosis have not yet been fully understood. The prevention of this occupational disease depends upon elimination or suppression of airborne dust to which miners are exposed.
The Canada Centre for Mineral and Energy Technology's (CANMET) research on respirable dust in underground coal mines emphasizes the identification and control of dust sources and the investigation of the mineralogical composition of the airborne dust.

As part of the Centre's ongoing research program, measurements of respirable dust concentrations were made by using various personal samplers and portable sampling systems in two underground coal mines. The relationships between concentrations measured by different samplers and those determined by Casella Gravimetric Samplers (CGS) Type 113A are described.

Dust concentrations determined by personal samplers consisting of DuPont constant flow pumps (Model P-2500A) fitted with Casella cyclones approached that determined by the CGS. Personal samplers consisting of MSA Fixt-Flo pumps (Model I) fitted with Dorr-Oliver nylon cyclones measured respirable concentration values on an average at 46 percent for the one mine and 58 percent for the other mine of the values determined by the CGS. The end-of-shift average respirable dust concentrations determined by a SIMSLIN II light-scattering system were lower than those measured by the CGS (with an average ratio 0.58 for the one mine and 0.81 for the other mine), while concentrations determined by weighing the filters used in the SIMSLIN II were higher than those measured by the CGS (with an average ratio 1.16 for the one mine and 1.19 for the other mine). Two Anderson Eight-Stage Marple Personal Cascade Impactors which evaluated respirable dust concentrations and respirable fractions of coal mine dust were also used and preliminary results show that the respirable dust concentration ratio of the cascade impactor to the CGS varies from 0.69 to 1.03.

Precision and practical aspects of coal mine dust measurement by using personal samplers and other sampling systems are discussed.

Introduction

The etiological factors of coal workers' pneumoconiosis have not been fully understood. Coal or quartz itself has long been suspected to cause fibrosis of the lung in coal miners.

The prevention of this occupational disease depends upon elimination or suppression of airborne dust to which miners are exposed. The Canada Centre for Mineral and Energy Technology's (CANMET) research on respirable dust in underground coal mines emphasizes the identification and control of dust sources and the investigation of the mineralogical composition of the airborne dust.

Numerous respirable dust sampling systems or samplers are commercially available for use to determine respirable dust concentrations in underground coal mines. They are differentiated by the use of particle size selectors, pumps, and dust collectors or detectors. For the purpose of assessing long-term dust exposure or evaluating the effectiveness of a dust control technique, the results obtained by measurements using different samplers must be reproducible and comparable. This paper describes the relationships between various sampling systems used for the CANMET's ongoing dust research program.

Methods and Procedures

Eighteen shift-length tests were carried out in two Canadian underground coal mines. One colliery (Mine A) employed advancing longwall mining and the other colliery (Mine B) used retreating longwall mining.

The dust samplers used are shown in Table I. SIMSLIN II is a light-scattering dust monitor with single laser diode as a light source and scattered light collected between 12 and 20 degrees to the forward direction. It employs a parallel plate elutriator as particle size selector and its internal filter can be used for gravimetric determination of respirable dust concentration.

For gravimetric measurements of respirable dust concentration, various types of membrane filters shown in Table II were used. Substrates of greased film of Mylar disc were also used in a Marple Cascade Impactor 298 as dust collecting media.

The calibrated sampling systems were set up in an area at the breathing zone height near the high side rib in the tailgate of a longwall section. The SIMSLIN II was factory calibrated on coal dust and at the beginning of each dust sampling its readout zeroed. This sampling location is 70 m from the faceline. The Casella Gravimetric Samplers (CGS) and SIMSLIN II were installed parallel to the tailgate such that the intake air to the sampler elutriators has the same direction as the return air in the tailgate. Four to five personal samplers were also installed in upright positions close

TABLE I

Types of Sampler and Sampling Flow Rates Used for Field Tests in Two Underground Coal Mines

Sampler Type	Sampling Flow Rate (lpm)
Casella Gravimetric Sampler Type 113A	2.5
Personal Sampling Systems:	
DuPont Pump P2500A + Casella Cyclone T13026.2	1.9
MSA Fixt-Flo Pump Model I + Durr Oliver 10 mm Nylon Cyclone	2
Gilian Sampler HFS 113A + Casella Cyclone T13026/2	1.9
Gilian Sampler HFS 113A + Marple Cascade Impactor (Model 298)	2
SIMSLIN II Dust Monitoring System	0.625

to the CGS. This meant that the inlets of the Casella cyclones faced downward while the inlets to the Dorr-Oliver cyclones faced towards the return airstream. An inlet visor and an inlet cowl were used as parts of a Cascade Impactor Model 298. The shift average air velocity at this sampling location in the tailgate of a longwall varies from test to test ranging from 1.2 to 1.6 m/s in Mine A and 2.0 to 2.6 m/s in Mine B. Actual sampling time varied from 122 to 319 minutes depending on the start and the end of coal cutting during a shift. Nine tests were carried out during the period December 1984 to March 1985 in three wall sections of Mine A and an additional nine tests in two wall sections of Mine B during the period December 1985 to May 1986.

The end-of-shift average concentration readout of the SIMSLIN II was recorded at the time when the system was switched off at each test. The dust laden filters and substrates were kept within the samplers and brought back to the laboratory for desication and for determination of mass by using a CAHN Electrobalance C-29.

Results

Variability of Concentration Measurement Made by Casella Gravimetric Samplers 113A

Two or three sets of the Casella Gravimetric Samplers were used for each field test. The standard deviation and percent variation, which is standard deviation expressed as percentage of the average of concentrations measured by the CGS, were evaluated for each test and are shown in Figures 1 and 2, respectively. In both figures, the abscissa represents the concentration values normalized to the maximum average concentration determined during a given test. The standard deviation shown in Figure 1 varies from test to test ranging from 0.01 mg/m^3 at a normalized concentration of 0.61 to 0.34 mg/m^3 at 0.41. The variation appears to be fixed regardless of the normalized concentration and thus indicates a systematic error of measurement as high as 0.34 mg/m^3. The percent variation shown in Figure 2 varies from

TABLE II

Membrane Filters Used in Sampling Systems for Gravimetric Dust Measurements

Filter Type	Pore Size	Diameter (mm)	Used in Sampler
Whatman Glass Fibre GF/A	1.6	47	SIMSLIN II
Whatman Glass Fibre GF/A	1.6	55	Casella Gravimetric Sampler 113A
Whatman Glass Fibre 934AH	1.5	37	Casella Cyclone T13026
Millipore Membrane Filter AAWP03700 (mixed cellulose acetate and nitrate)	0.8	37	Casella Cyclone T13026
MSA PVC FWS-C	0.8	37	Dorr-Oliver 10 mm Nylon Cyclone

0.1 percent at the normalized concentration of 0.61 to 10.3 percent at 0.23. For Mine A, this percent variation appears to decrease with increasing concentration but for Mine B it increases slightly with increasing concentration.

The average CGS concentration in a test will be used to calculate the relative dust concentrations measured in this test by the other dust sampling systems.

Relative Respirable Dust Concentrations Determined by Personal Samplers

For a field test, different types of personal sampling systems and filters were used for respirable dust concentration measurements and for a given personal sampler, the ratio of concentration measured by this personal sampler to the average concentration determined by CGS was evaluated. These ratios were then grouped and summarized for the two mines in Table III. The respirable dust concentration values determined by the Casella cyclones used with various con-

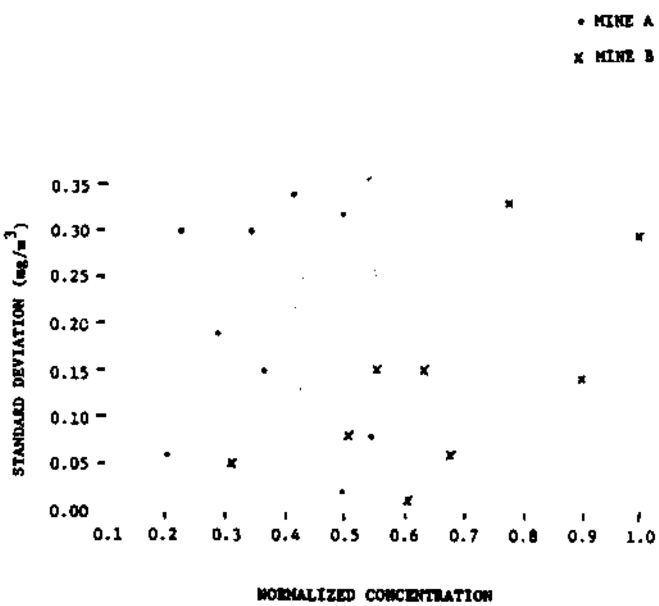


FIGURE 1. Standard deviation of concentrations measured by Casella Gravimetric Samplers 113A for each test in Mine A or Mine B.

stant flow pumps, shown in Table I, approaches those measured by CGS which used elutriators as particle size selectors. However, the averaged ratios shown in Table III are less than 1.00 for Mine A and greater than 1.00 for Mine B. The ratio measured in Mine A by using a personal sampling system with a Casella cyclone, varied more as compared to the ratio measured in Mine B by using the same type of personal sampling system. The Dorr-Oliver nylon cyclones used with the MSA pumps measured the concentration values on an average at 46 percent for Mine A and 58 percent for Mine B of the values determined by CGS.

Measurement of Respirable Dust by SIMSLIN II

The end-of-shift average respirable dust concentrations determined by a SIMSLIN II light-scattering system were lower than those measured by CGS (with an average ratio

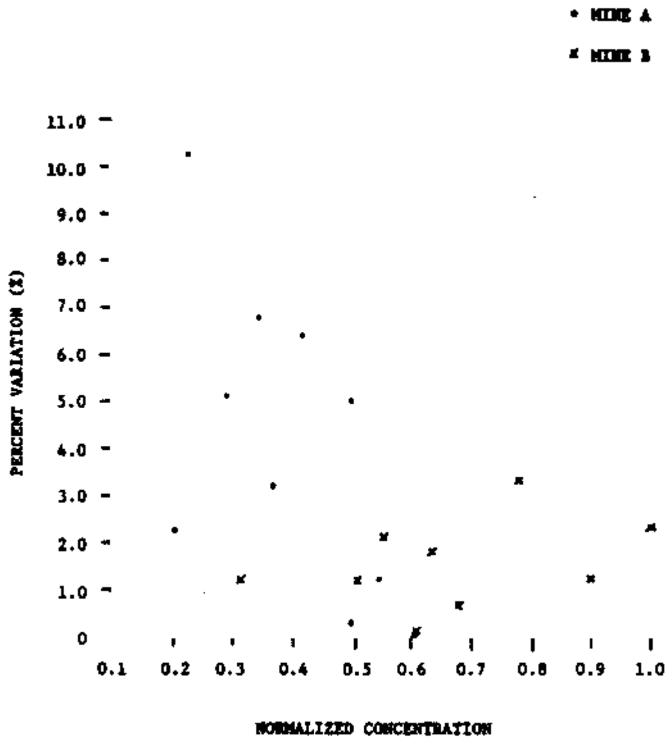


FIGURE 2. Percent variation of concentrations measured by Casella Gravimetric Samplers 113A for each test in Mine A or Mine B.

0.58 for Mine A and 0.81 for Mine B), while the concentrations determined by weighing the filters used in the SIMSLIN were higher than those measured by the CGS (with an average ratio 1.16 for Mine A and 1.19 for Mine B). The linear relationships between the SIMSLIN's concentrations determined by light-scattering or gravimetric technique and those measured by the CGS are depicted by Figures 3 and 4. In Figure 3 the regression line (with a correlation coefficient $R = 0.83$ and a standard error of estimate $S = 0.92\ mg/m^3$) of the concentration determined by CGS on that determined by the SIMSLIN light-scattering system in Mine A has greater slope than the regression line (with $R = 0.89$ and $S = 1.28\ mg/m^3$) determined in Mine B. In Figure 4, the

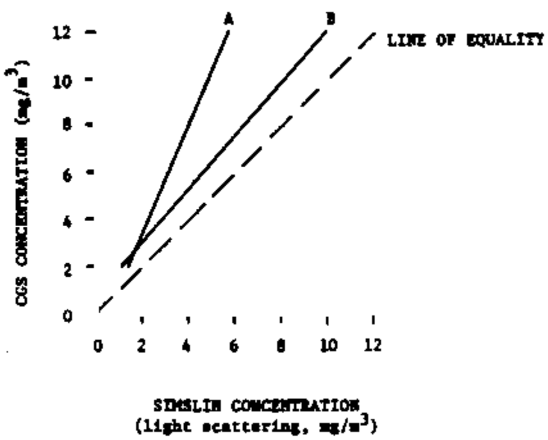


FIGURE 3. Regression line of the average concentration determined by CGS on that determined by the SIMSLIN light-scattering system in Mine A or Mine B.

TABLE III

Average of Ratios of Concentration Measured by a Personal Sampling System to the Average Concentration Determined by the Casella Gravimetric Samplers 113A

	MINE A			MINE B		
Sampling System*	Average Ratio	Standard Deviation	Number of Ratios	Average Ratio	Standard Deviation	Number of Ratios
DCM/MRE	0.96	0.12	10	1.01	0.03	5
DCG/MRE	0.90	0.12	7	1.02	0.03	5
MCM/MRE	0.94	0.12	5	--	--	--
MCG/MRE	0.89	0.13	2	--	--	--
GCM/MRE	--	--	--	1.05	0.05	4
GCG/MRE	--	--	--	1.05	0.04	4
MNP/MRE	0.46	0.03	4	0.58	0.04	6

* MRE = Casella Gravimetric Sampler Type 113A.

DCM = DuPont Pump + Casella Cyclone + Millipore. (MP) Membrane Filter (37 mm dia., 0.8 um pore).

MCM = MSA Pump + Casélla Cyclone + MP Membrane Filter.

DCG = DuPont Pump + Casella Cyclone + Glass Fibre (GF). Filter (37 mm dia., 1.5 um pore).

MCG = MSA Pump + Casella Cyclone + GF Filter.

MNP = MSA Pump + Nylon Cyclone + PVC Filter (37 mm dia., 0.8 um pore).

GCM = Gilian Pump + Casella Cyclone + MP Membrane Filter.

GCG = Gilian Pump + Casella Cyclone + GF Filter.

regression line (with a correlation coefficient R = 0.73 and a standard error of estimate S = 1.15 mg/m^3) of the concentration determined by CGS on that determined gravimetrically by the SIMSLIN II in Mine A also has greater slope than the regression line (with R = 0.93 and S = 1.07 mg/m^3) determined in Mine B.

Respirable Dust Measurements by Using Marple Personal Cascade Impactors

The Cascade Impactors Model 298 has eight stages of dust collection by inertial impaction onto radially-slotted circular substrates. Dust particles which escape impaction are finally collected by a 34 mm backup filter. At the nominal flow rate of 2 liters per minute (lpm) drawn by a Gilian (Model HFS 113A) pump, the cut points of the impactor Stages No. 1 to No. 8 are 21, 15, 10, 6, 3.5, 2, 0.9, and 0.5 um, respectively. Two cascade impactors (i.e. M1 and M2), pumped by one of the two Gilian constant flow samplers were used for each of the six field tests in the same wall section of Mine B. The size distributions (expressed as percent by mass) derived from side-by-side sampling are similar and shown in Figures 5, 6 and 7. In these figures, all the distribution curves have peaks on Stage No. 5 with 3.5 um cut point. The inconsistent results of size distribution derived from side-by-side sampling are shown in Figures 8, 9 and 10. The inconsistency is likely due to the spillage of dust samples collected on the substrate of Stage No. 5 of the impactor M2 (Figure 8) or to the dust spillage that occurred in Stages No. 3 and 4 of the impactor M1 (Figure 9) and to the external contamination of dust samples on the substrates of the first stages of both impactors after the completion of dust sampling (Figures 9 and 10). When the dust collected on the sub-

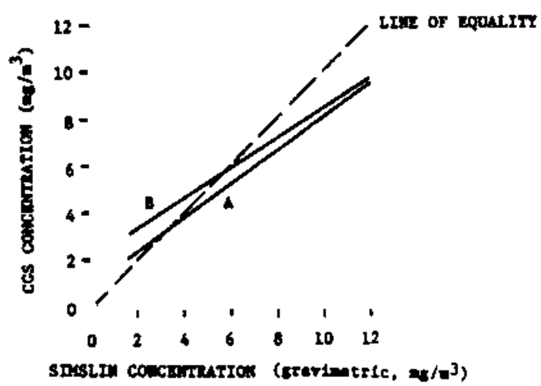


FIGURE 4. Regression line of the average concentration determined by CGS on that determined gravimetrically by the SIMSLIN II in Mine A or Mine B.

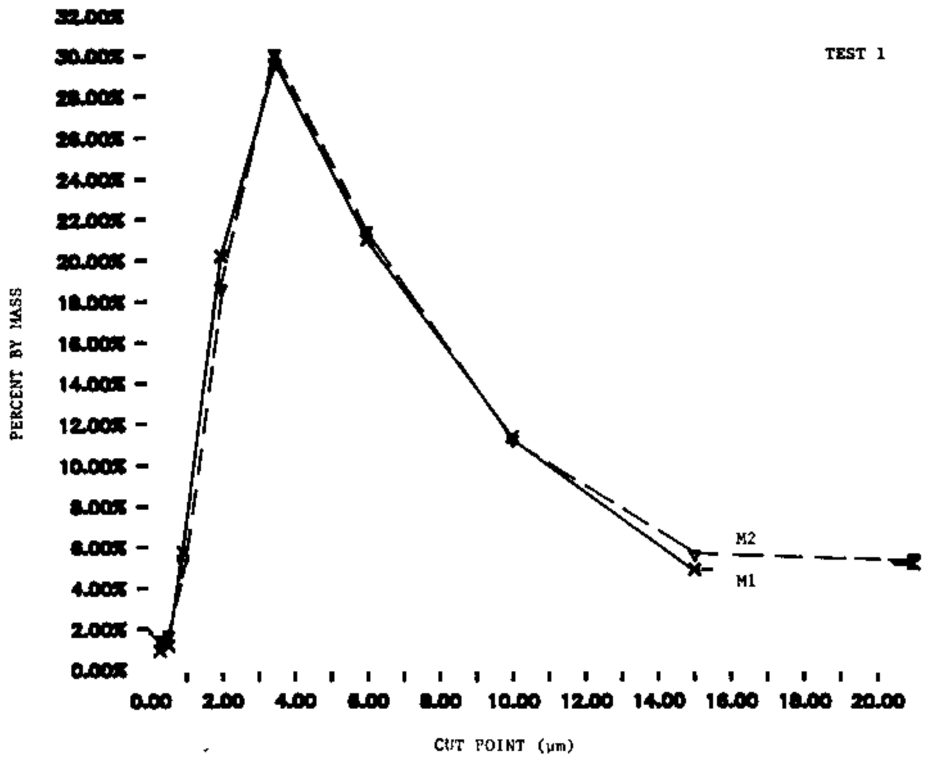


FIGURE 5. Size distributions of airborne dust in Mine B (Test 1) as determined by M1 and M2.

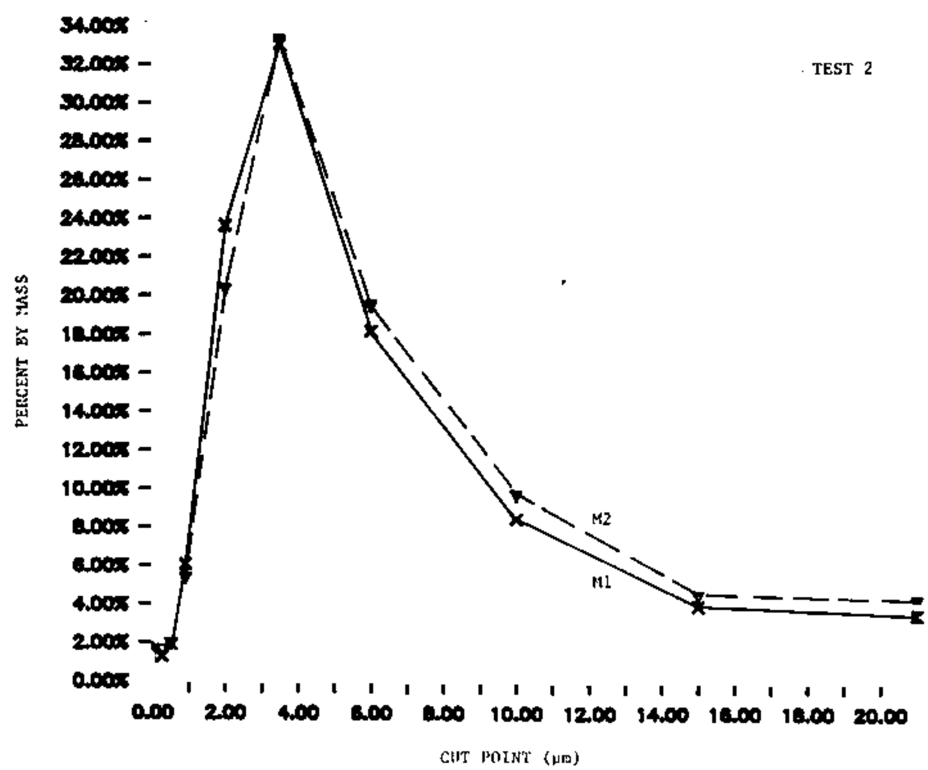


FIGURE 6. Size distributions of airborne dust in Mine B (Test 2) as determined by M1 and M2.

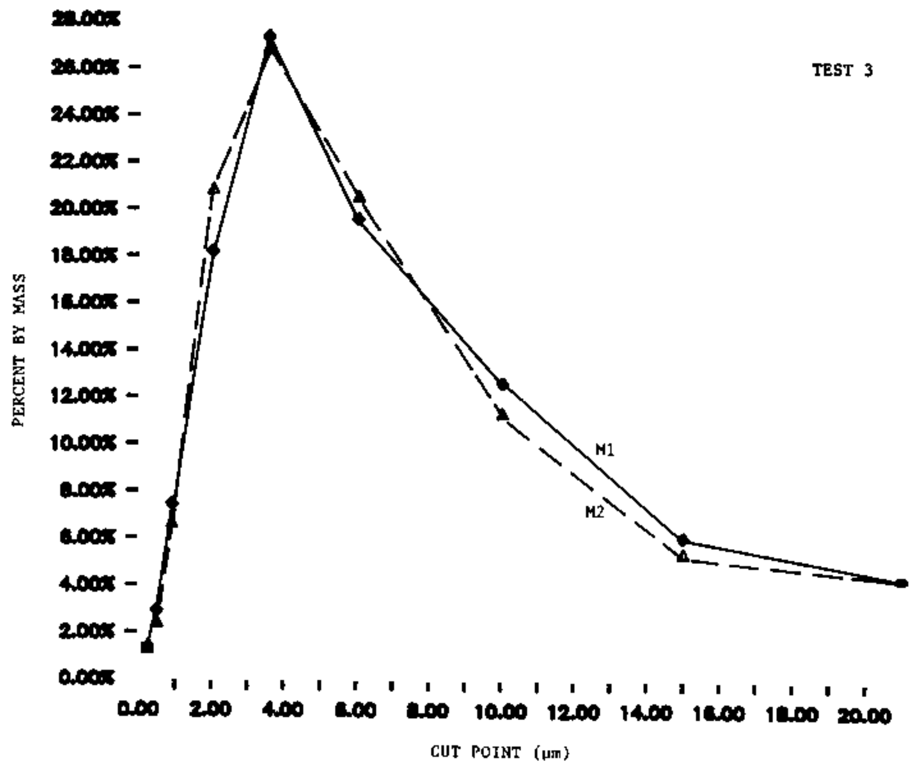


FIGURE 7. Size distributions of airborne dust in Mine B (Test 3) as determined by M1 and M2.

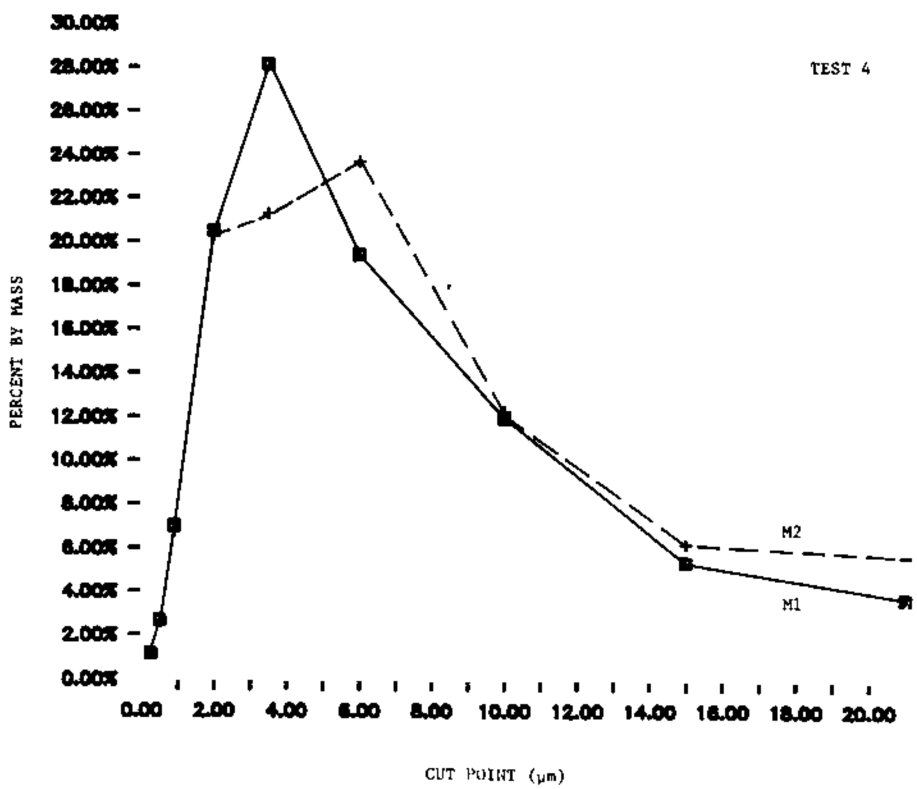


FIGURE 8. Size distributions of airborne dust in Mine B (Test 4) as determined by M1 and M2.

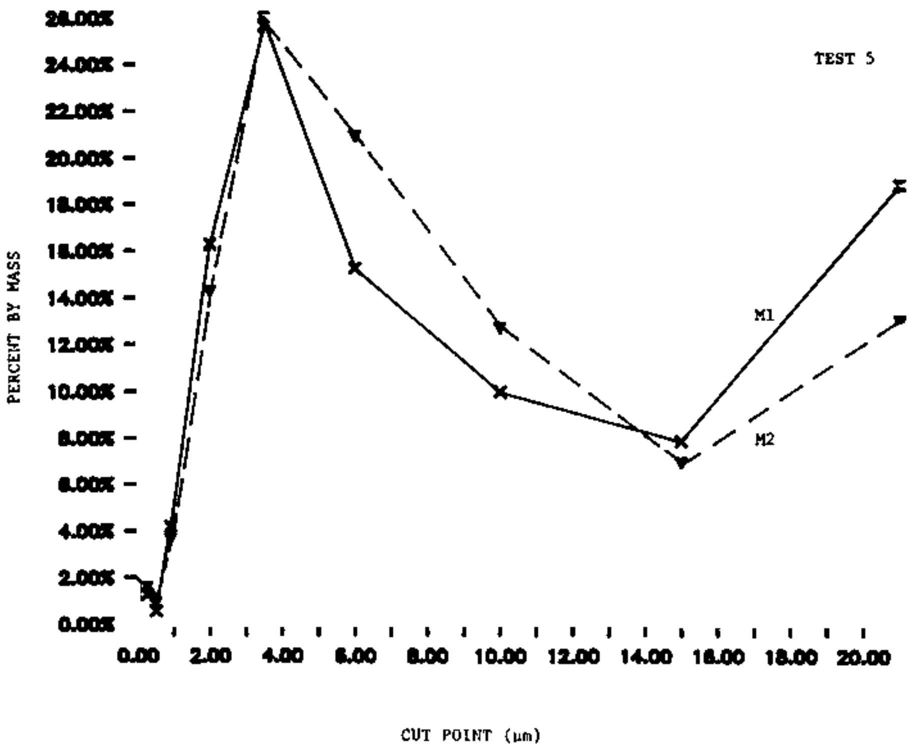


FIGURE 9. Size distributions of airborne dust in Mine B (Test 5) as determined by M1 and M2.

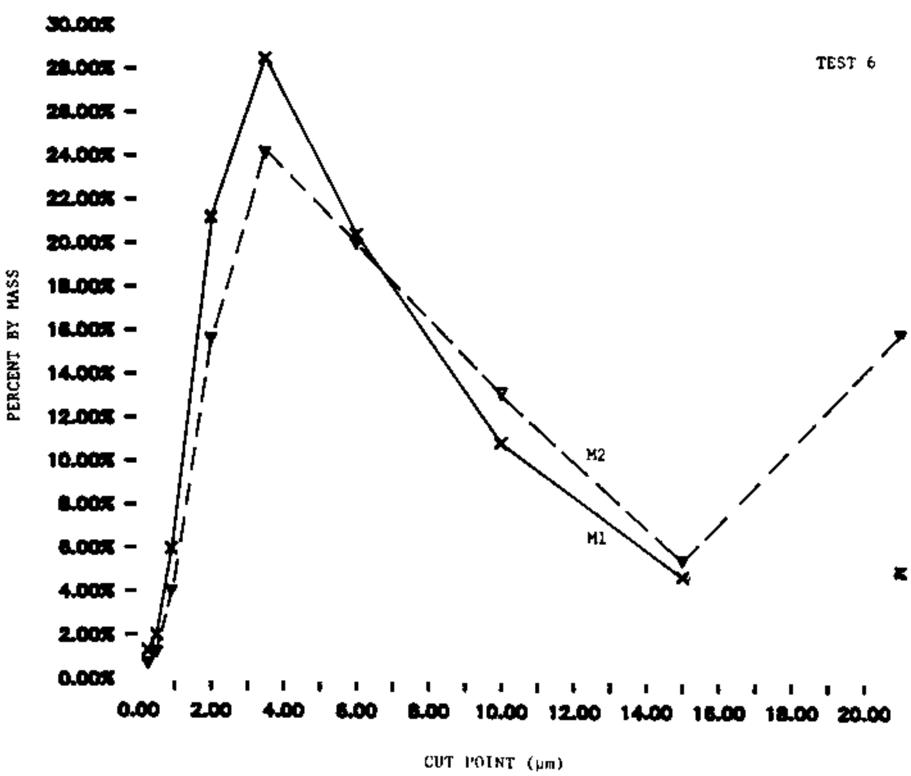


FIGURE 10. Size distributions of airborne dust in Mine B (Test 6) as determined by M1 and M2.

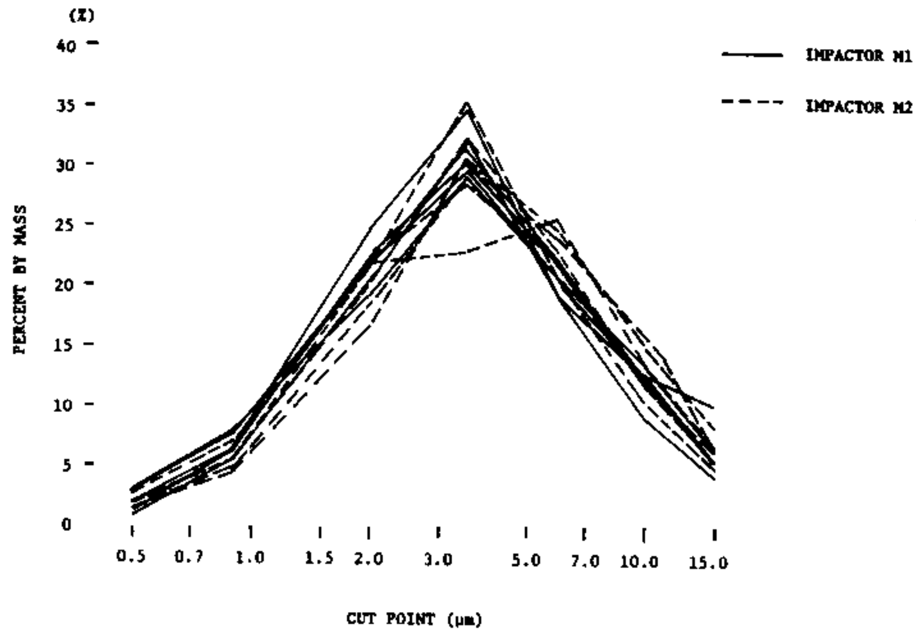


FIGURE 11. Size distributions of airborne dust in Mine B (Tests 1-6) determined by impactors M1 and M2 (calculated by using dust collected on Stages No. 2 to No. 8).

strates of the first stage (with cut point of 21 um) and backup filter was not used in calculating the size distributions of the sampling systems using the cascade impactors and all the size distributions were plotted on a graph (Figure 11), all but one of the distributions are shown to be similar with characteristic peaks at 3.5 um cut point. The impactor M1 collects on average a lesser proportion of dust on Stages No. 3 and No. 4 but more on the Stages No. 6 and No 7.

To evaluate respirable dust concentrations and respirable fractions, the mass determined for Stages No. 5 through No. 8 and for the backup filter (i.e. dust particles less than 6 um in aerodynamic equivalent diameter for spheres of unit mass) were summed as respirable portion. The relative respirable dust concentrations determined by the impactors M1 and M2 are plotted in Figure 12 against the average CGS concentration normalized to the maximum value. The relative concentration decreased from 1.03 to 0.81 determined by M1 and from 1.04 to 0.69 by M2 as the normalized average CGS concentration increases from 0.4 to 1.0. In the two tests when the normalized CGS concentrations were 0.71 and 1.0, differences in relative concentrations determined by M1 and M2 were more than twice as great than those determined in the other tests.

Respirable fraction is the ratio of respirable mass to total mass of dust collected by a given sampler and in the case of a sampler using Cascade Impactor Model 298 as its size selector, the total mass is the sum of the mass determined gravimetrically for all the eight stages plus the mass of dust collected on the backup filter. The respirable fractions (expressed as percentages) are shown in Figure 13 in which inconsistency (equal or greater than the 8 percent point) between the fractions determined by the impactors M1 and M2 occurred during the tests when the normalized CGS concentrations were 0.81 and 1.0.

Discussion

The results reported in this paper are based on the limited number of shift-length field tests in two underground coal mines. The ratio (or relative respirable concentration) of respirable concentrations determined by a given personal sampler to those determined by CGS varies with the normalized average CGS concentration. The relative concentration determined by a personal sampling system which consists of a constant flow pump and a Casella cyclone or a Dorr-Oliver cyclone appears to increase with increasing dust levels in mines measured by CGS. This increase might be due to the difference in the nature of airborne dust in the two mines which employ different coal mining techniques. This in-

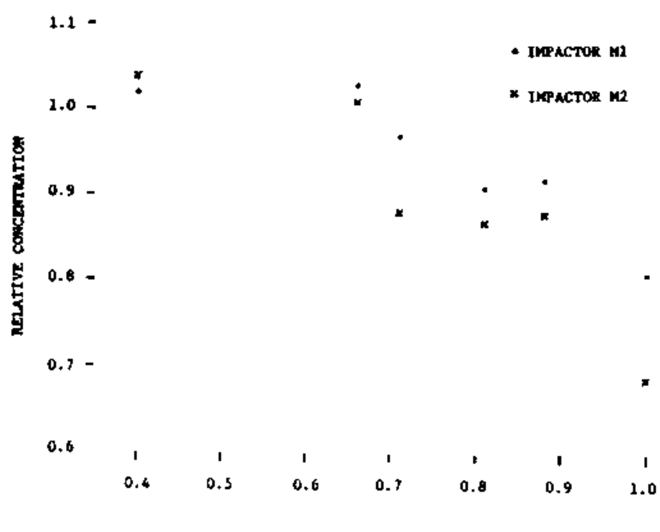


FIGURE 12. The relative respirable dust concentrations determined in Mine B by cascade impactors M1 and M2.

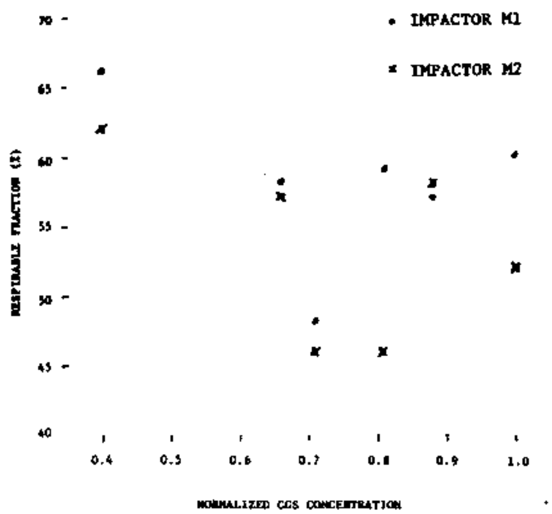


FIGURE 13. The respirable fraction (percent) determined in Mine B by cascade impactors M1 and M2.

crease might also be due to the difference in particle selection characteristics between the personal samplers and the CGS, the improved technical aspects of dust measurements such as filter handling/weighing, laboratory environmental control of humidity and temperature, and the care and use of samplers during the entire dust sampling work. A slight increase in the relative dust concentration has been found in the reported Pittsburgh Technical Support Center's Dust Group (PTSCDG) data comparing modified MSA personal samplers with CGS over the concentration range of 2.5 to 13.5 mg/m^3.[1]

The linear relationships between the data obtained by the SIMSLIN II and that obtained side-by-side by CGS in the two mines (Figures 3 and 4) are different and thus indicate that the results of the respirable dust concentration measurements are site specific. This specificity has also been reported.[2] Inthe case of the measurement by the SIMSLIN light-scattering technique, the nature of dust particles (especially size and mineralogical composition) may play an important role in the difference resulting from the measurements made in the two mines.

The results obtained by using the two cascade impactors as size selectors for dust sampling in a wall section of Mine B are preliminary and have indicated a decrease in the respirable dust levels determined by the cascade impactors relative to the CGS as the measured level of the dust cloud increases (Figure 12). If the efficiency of particle selection in the elutriators of the CGS does not change in a denser dust cloud, this decrease in the relative respirable concentration might be explained by the increasing probability of particle interaction in the initial stages (i.e. No. 1 to No. 4) by collision and/or aggregation in this denser dust cloud. This would result in a greater portion of the particles being deposited in the initial stages.

References

1. **Tomb, T.F., H.N. Treaftis, R.L. Mundell and P.S. Parobeck:** *Comparison of Respirable Dust Concentrations Measured with MRE and Modified Personal Gravimetric Sampling Equipment*. Report of Investigations 7772, Bureau of Mines, United States Department of the Interior (1973).

2. **Ford, V.H.W., R. Minton and D. Mark:** Comparative Trials in Coal Mines of the TM-Digital and SIMSLIN Dust Monitors. *Aerosols,* Vol. 3, Ch. 54, pp. 759-775. Ann Arbor Science, Ann Arbor, MI (1983).

Theoretical and Experimental Studies on Dust Transport in Mine Airways: A Comparative Analysis

R.V. RAMANI and R. BHASKAR
Department of Mineral Engineering, The Pennsylvania State University

Introduction

The behavior of dust clouds in mine atmospheres has been a subject of longstanding interest due to both health and safety reasons. Pioneering studies in Germany and SMRE focussed on ambient dust concentration, principally aimed at determining optimum velocities for effective dilution. A summary of studies related to this area is provided by Hall.[1] Efforts to understand dust deposition from the explosion hazard point of view led to experiments in return airways[2-4] followed by experiments in longwalls.[5] Concerted efforts, either experimental or theoretical, were not made until recently to relate ambient concentration with dust deposition in mines. In 1974 Hwang *et al*[6] developed a computer model to predict dust concentration which considered deposition-concentration relationships. Also, experimental studies involving concurrent dust deposition and ambient concentration were conducted in the U.S. by Courtney *et al*[7] in operating mines. Efforts to relate theory with experimental results have been made by Owen[8] and Hwang *et al*[6] for dust deposition. There has been limited work, however, to determine the application of the theories and assumptions from aerosol sciences for modeling dust flows in mine atmospheres.[9] This is the objective of the work currently underway in the Generic Technology Center on Respirable Dust since 1983 under a project titled, "Prediction of Ambient Dust Concentration in Mine Atmospheres." The scope of the project activities include:

1. Development of a mathematical model to predict dust deposition and concentration in mine atmospheres.
2. Experimental studies on dust transport and deposition in mine airways.
3. Comparison of the model results with the experimental data.

The specific objective of this paper is to present the results of the comparative analysis and to examine the applicability of the various mechanisms used in the model to describe particle behavior with respect to flow in mine airways.

Mathematical Modeling

In the first phase of the project, a mathematical model was developed for studying the behavior of dust clouds in mine airways (Figure 1). The model was designed to predict

1. Dust deposition along the length of an airway.
2. Ambient concentration at various points in a mine airway.

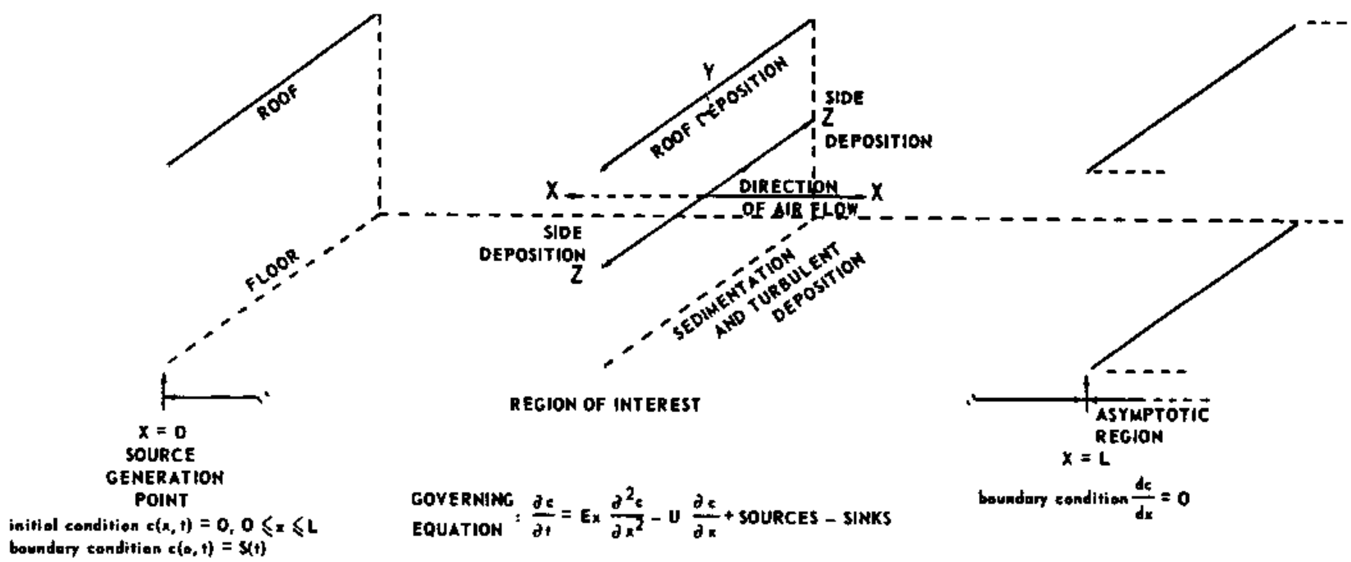


FIGURE 1. Schematic of dust flow in a mine airway.

3. Size distribution of dust at various points in the airway.

The model takes into account a number of factors affecting dust transport, including source dust characteristics (amount, size distribution, density), airway characteristics (size, shape, length, friction factor), airflow characteristics (velocity, viscosity, temperature, dispersion) and coagulation of dust in mine airways.[10]

Since the size-dependent behavior of dust in mine airways is the major difference between dust flows and gas flows, considerable attention was focussed on those mechanisms which are size-dependent. In fact, the principal part of modeling was devoted to modeling the dust deposition phenomenon. The three major mechanisms of particle deposition in turbulent flow that were modeled are Brownian and eddy diffusion, and sedimentation. While all three mechanisms were used to predict deposition on the floor, Brownian and eddy diffusion were considered for the roof and sides of the airway. Coagulation was considered as a mechanism that affects the size distribution and hence deposition rate. The transfer of dust in turbulent air flow was described using a dispersion coefficient developed by Skubunov.[11] A step type function describes the dust emission from the source as a function of its operating duty cycle. The concentration is determined from the numerical solution of a convection-diffusion population balance equation.

A computer program was developed to solve the equation for various size classes with applicable size-dependent relationships for each class. The overall behavior of the dust cloud is obtained as the sum effect of the individual size classes. The ambient concentration was calculated from a mass-balance of the convection-diffusion equation describing the concentration change. Sensitivity analysis of the model

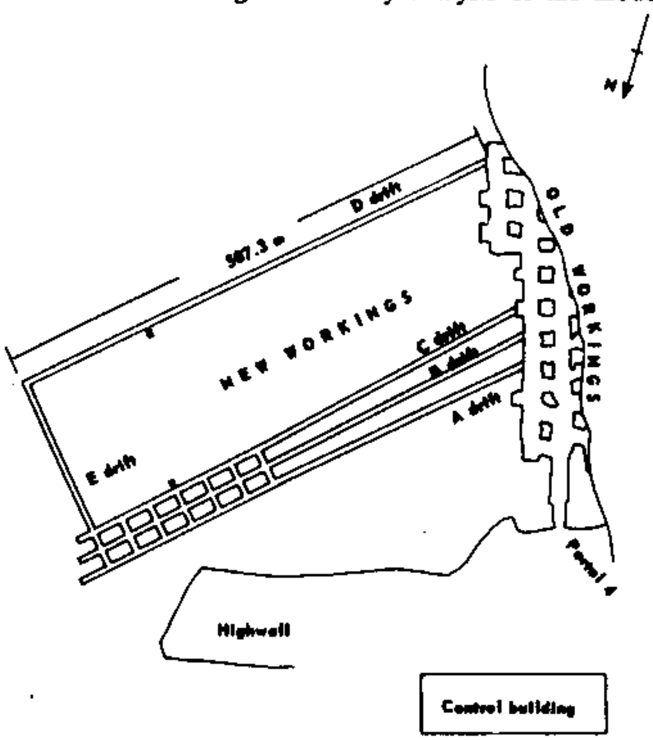


FIGURE 2. Plan view of Lake Lynn Laboratory underground workings.

TABLE I

Salient Details of Controlled Experiments

Experiment	Dust Type	Velocity, m/s
Experiment 1	Semi-anthracite	0.838
Experiment 2	Bituminous	0.838
Experiment 3	Semi-anthracite	1.855
Experiment 4	Bituminous	1.855
Experiment 5	Semi-anthracite	1.525
Experiment 6	Bituminous	1.525

parameters was performed to identify the relative importance of various factors in the model.

Experimental Work

To complement the theoretical work and to compare the model prediction with actual behavior, a set of experiments were conducted at the Lake Lynn Laboratory Mine of the U.S. Bureau of Mines (Figures 2 and 3). Six tests using two types of dust at three different velocities for each coal type were performed (Table I).[10]

Ambient concentration and floor deposition of dust were measured for the period dust was dispersed. The experimental data were analyzed to yield the following information: 1) variations in ambient concentration (both total and respirable size range) along the length of the airway, 2) variations in deposition of the dust (both total and respirable size range) along the length of the airway, 3) changes in the size distribution of the airborne dust as the cloud travels in the airway, 4) variations in dust concentration across the airway at three different stations, 5) variations in dust deposition across the airway at different stations, 6) relationship between the average cross-sectional concentration and the concentration in the center of the airway, and 7) relationship between the average deposition in an airway cross section and the deposition in the center.

Comparative Analysis

The experimental data and results provided not only a better understanding of spatial and temporal behavior of dust in mine airways but also a comprehensive set for evaluation of the mathematical model of dust flows.

For the purposes of the comparative analyses, the model was used to predict the ambient concentration and dust deposition along the airway. The inputs to the model were derived from the experimental conditions and included source dust characteristics, mine airway characteristics, and mine airflow characteristics.

Source Dust Characteristics

The description of the source dust involved determining the maximum, minimum, median size, and standard deviation of the source dust, as well as its density, release rate, and time duration of dust release. Due to the relatively high concentration of dust released at the source, some of the dust

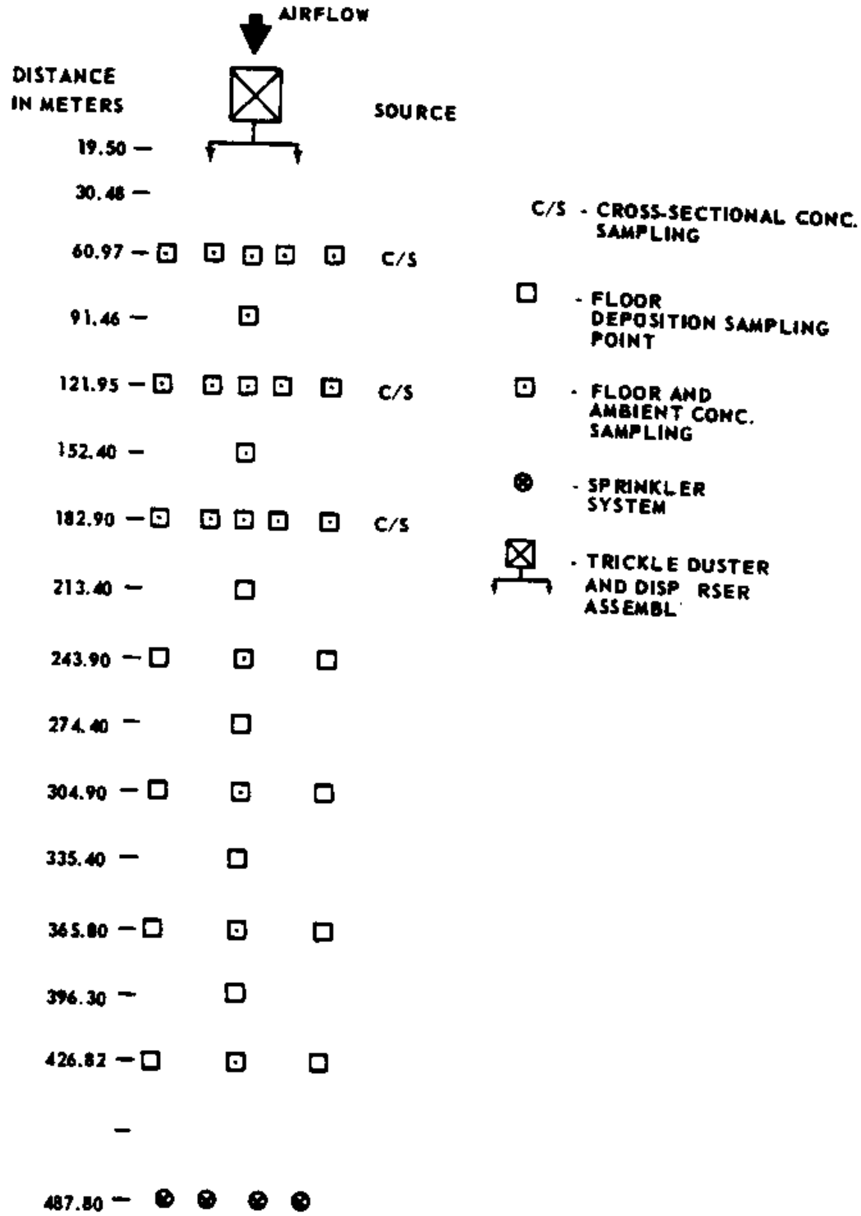


FIGURE 3. Schematic of the airway showing the location of the sampling points (Experiment 6).

failed to get mixed in the air and settled just beneath the source. Approximately eighteen percent of the dust released by the dispenser did not get airborne. This is taken into account when determining model source input.

Mine Airway Characteristics

The mine parameters input to the model are the dimensions and the friction coefficient. The friction coefficient was determined using an altimeter survey. The dispersion coefficient used in the model is obtained from the work of Skubunov[11] The dispersion coefficient assumes that particulate transfer in airflow is independent of particle size.

Mine Airflow Characteristics

The flow conditions were represented by the average flow velocity, air temperature and viscosity of air.

Observations on Experimental Results

The experiments revealed several findings which are significant for comparing model results with experimental results.

1. The cross-sectional data indicated that the average concentration in the mine airway was approximately 75 percent of the concentration in the center of the airway. The model assumes thorough mixing and equal concentration across the airway. This difference is taken into account by multiplying centerline concentration obtained from experiments by a factor of 0.75.
2. Similarly, floor deposition data showed an increased deposition in the center of the airway than at the sides. Experiment and station specific factors were

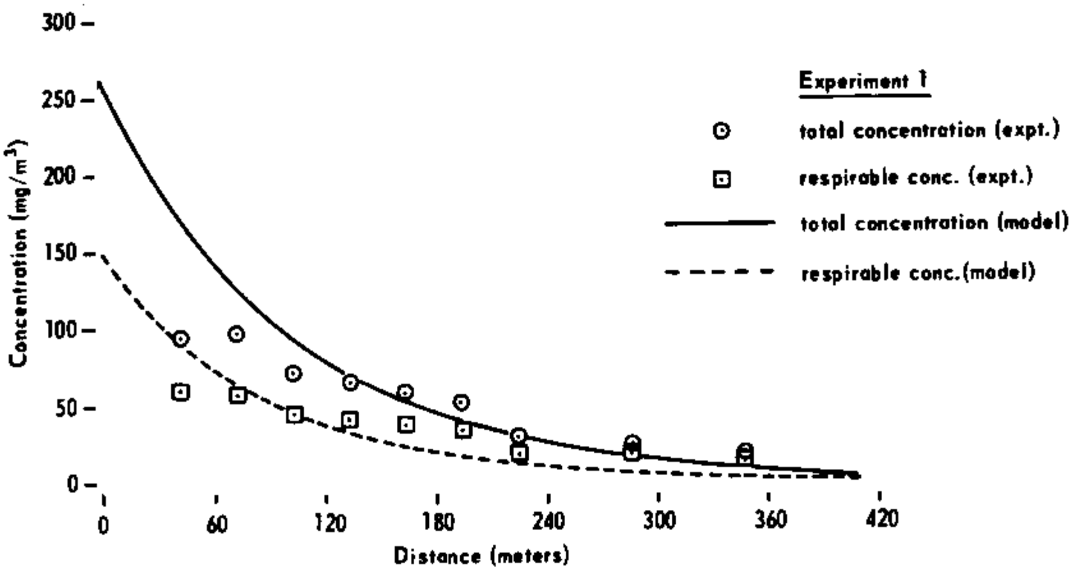


FIGURE 4. Comparison of model predicted ambient concentration with experimental data (Experiment 1).

used to relate centerline to average readings. At stations where such factors could not be determined because only one deposition plate was used, the factor used was the average of those of the station preceding and the station following.

While every effort was made to ensure isokinetic sampling of dust, deviation from isokinetic sampling occurred for some experiments and stations. All the ambient concentration data were adjusted to account for deviations from isokinetic sampling using procedures described by Belyaev and Levin.[12]

4. In the experiments, dust was dispersed at four points, each in the center of a quadrant in the airway cross section. This resulted in less than complete mixing for some distance from the source. Therefore, for comparative purposes, emphasis is placed on data collected at stations farther from the source.

Results

The ambient concentration and dust deposition along the length of the airway as observed in experiments were com-

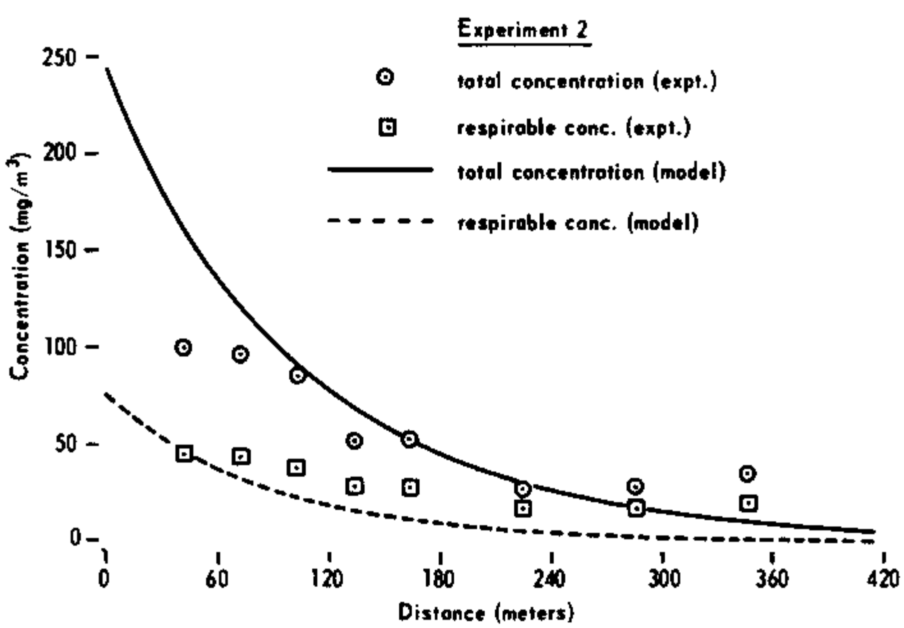


FIGURE 5. Comparison of model predicted ambient concentration with experimental data (Experiment 2).

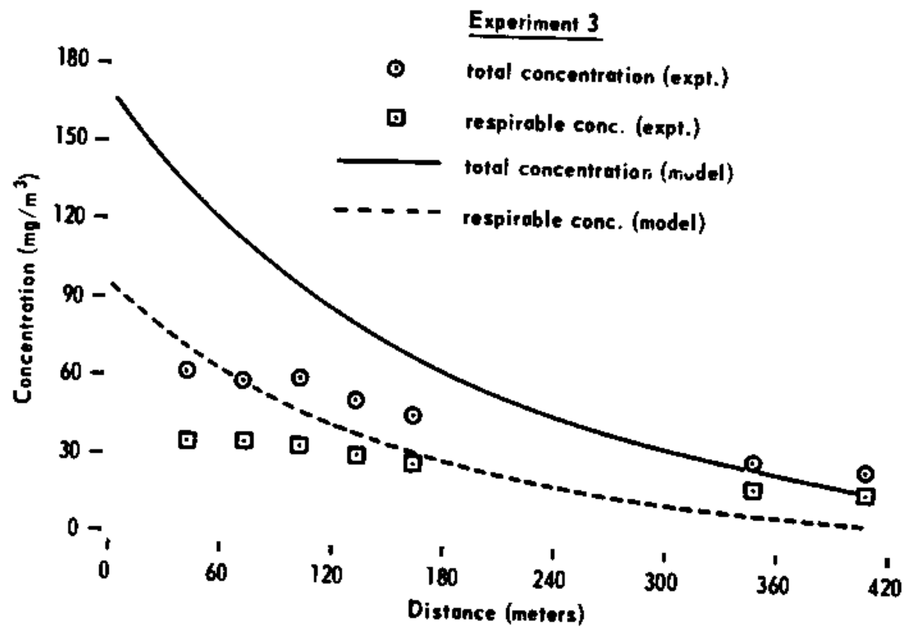


FIGURE 6. Comparison of model predicted ambient concentration with experimental data (Experiment 3).

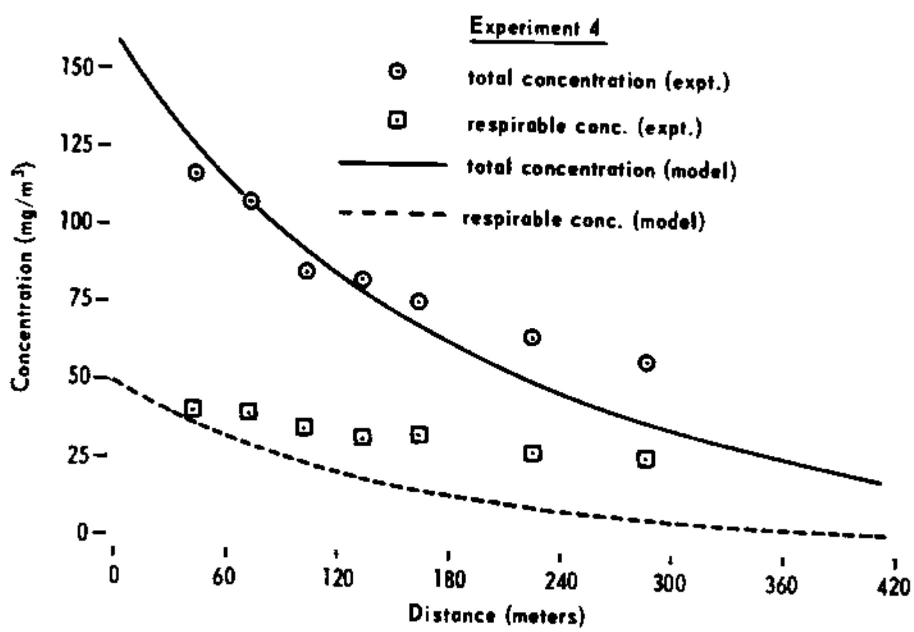


FIGURE 7. Comparison of model predicted ambient concentration with experimental data (Experiment 4).

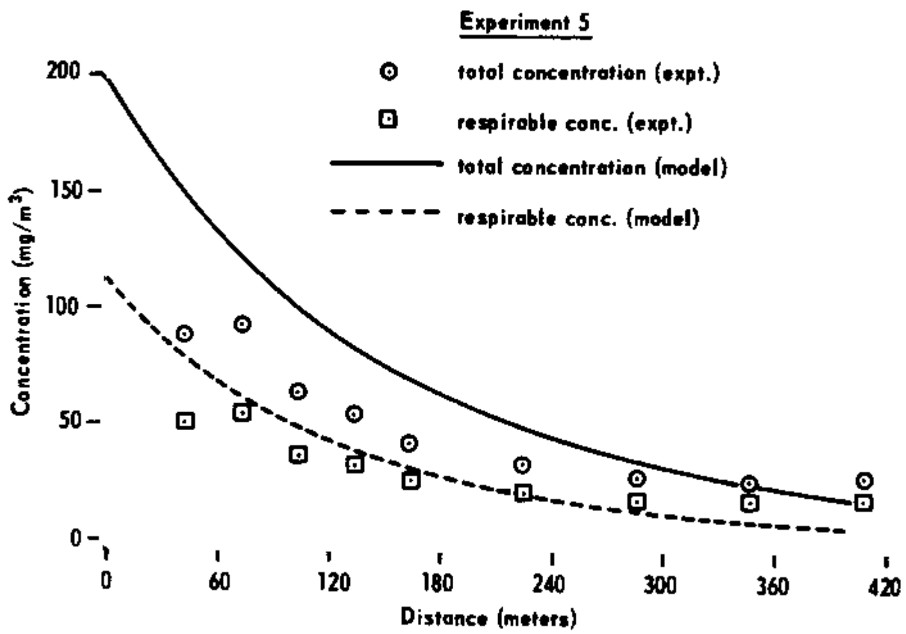


FIGURE 8. Comparison of model predicted ambient concentration with experimental data (Experiment 5).

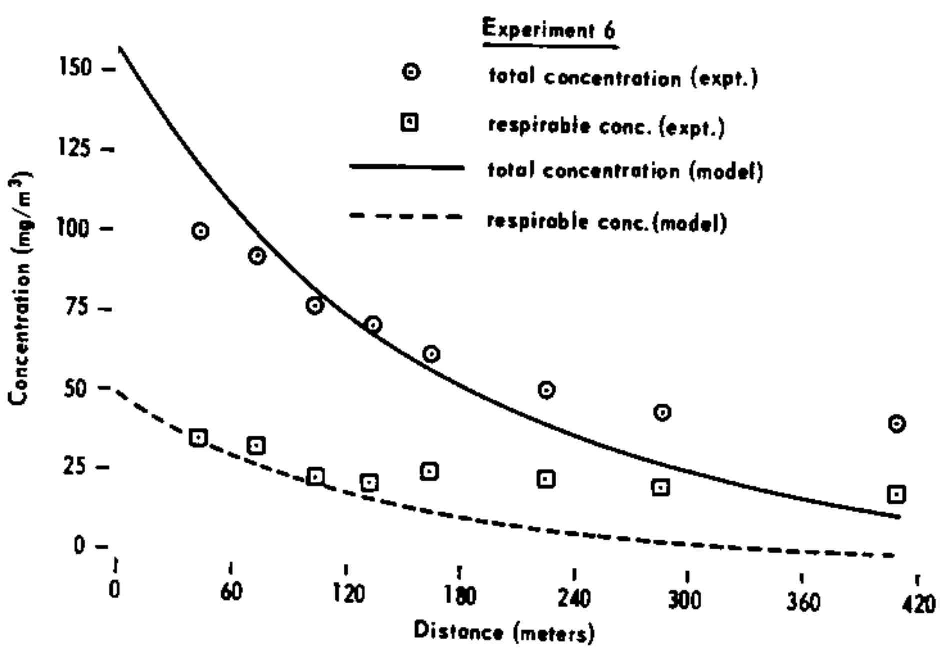


FIGURE 9. Comparison of model predicted ambient concentration with experimental data (Experiment 6).

pared with the model predictions. The comparisons were made for both the total and respirable size ranges.

Ambient Total Concentration

The experimental data and corresponding model output for ambient concentration (mg/m^3) are shown respectively for the six experiments in Figures 4 through 9. Experiments 1 and 2 were performed at 0.838 m/s, 3 and 4 at 1.855 m/s, and 5 and 6 at 1.525 m/s. The model output in Figures 4, 5, 7, and 9 are, in general, in agreement with the experimental data for total dust except for the first two stations. Thereafter one notices an exponential decline in model output, tracking the experimental data points to approximately 300 meters. Thereafter, the experimental points tend to be flat while the model output continues its decline. Comparison of model output and experimental data for experiments 3 and 5 shows the experimental data to be consistently lower than model predicted values.

Ambient Respirable Concentration

In the model, respirable dust is assumed to be made up of particles less than or equal to 5 u. Therefore, for comparative purposes, the amount of dust in the 5 u and below ranges in the total dust from the experiment is considered respirable dust. The respirable concentrations are also shown in Figures 4 through 9. The experimental results and model outputs are in better agreement closer to the source than away from the source. In fact, in all the experiments, the respirable concentration becomes asymptotic whereas the model continues to show a decline in concentration. Also, the observed respirable concentrations are higher than the predicted concentration.

Deposition (Total and Respirable)

The experimental results and model outputs for total and respirable deposition and shown in Figures 10 through 15. In general, good agreement is obtained between model output and experimental data testifying to the appropriateness of the deposition equations used in the model. Deposition data in the respirable range is also in close agreement with model output, barring the first two points.

Discussion

Several points with respect to the model and experimental results are to be stressed. The model uses a single dispersion coefficient for all particles sizes. This may not necessarily be the case since smaller particles tend to follow the airstream more closely than larger particles and hence are carried longer distances. This may result in higher concentration of fine dust downstream than predicted by the model. But, large particles have greater inertia and will tend to be less affected by flow fluctuations. Hodkinson and Leach[13] present data that show considerable difference between theoretically predicted dispersion coefficients and values determined from experimental data. Research is needed on determining the influence of density and size of particulate matter on dispersion.

The deposition data collection and analysis procedures ensure more accurate results than those used for ambient concentration data. The latter is influenced by several factors such as pumping rate, cross-section concentration variation and flow velocity fluctuation. In practice, high coefficients of variation have been reported. In addition, the model uses the deposition data and predicts the concentration at the following station using mass-balance whereas the experimental data will include any reentrainment which may occur between two stations. Since the forces required to entrain a deposited particle back into the airstream is dependent on particle size, smaller particles will have a higher propensity to enter the airstream thereby resulting in higher levels of ambient respirable concentration, especially at higher velocities. Also, re-entrainment from the sides and roof may be higher primarily because of the noninfluence

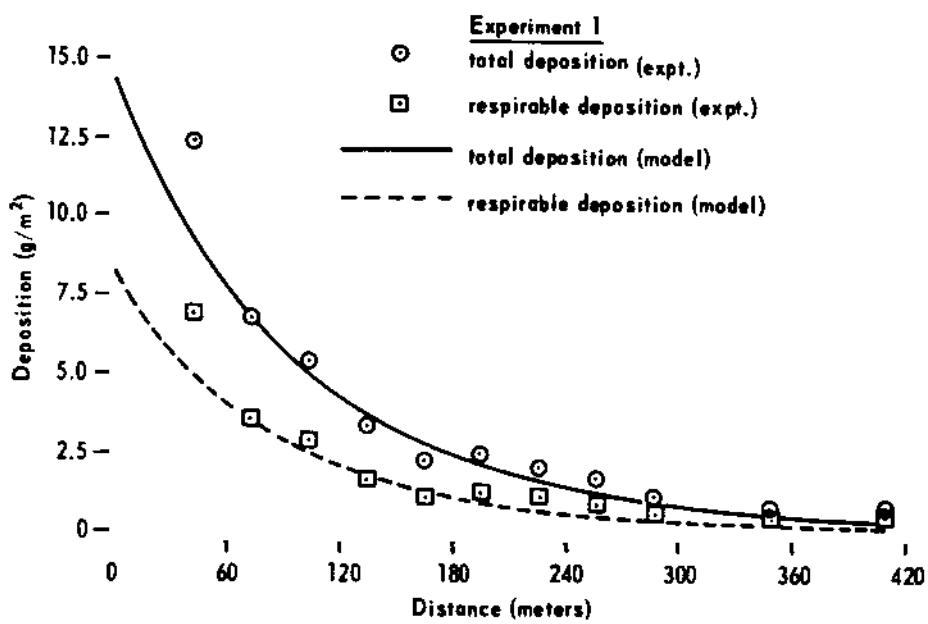


FIGURE 10. Comparison of model predicted floor deposition with experimental data (Experiment 1).

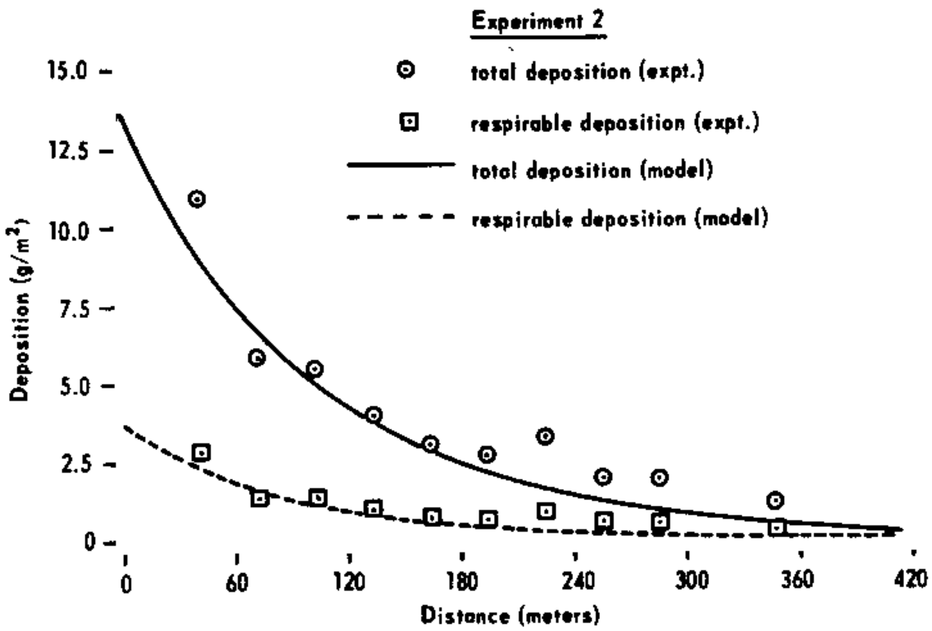


FIGURE 11. Comparison of model predicted floor deposition with experimental data (Experiment 2).

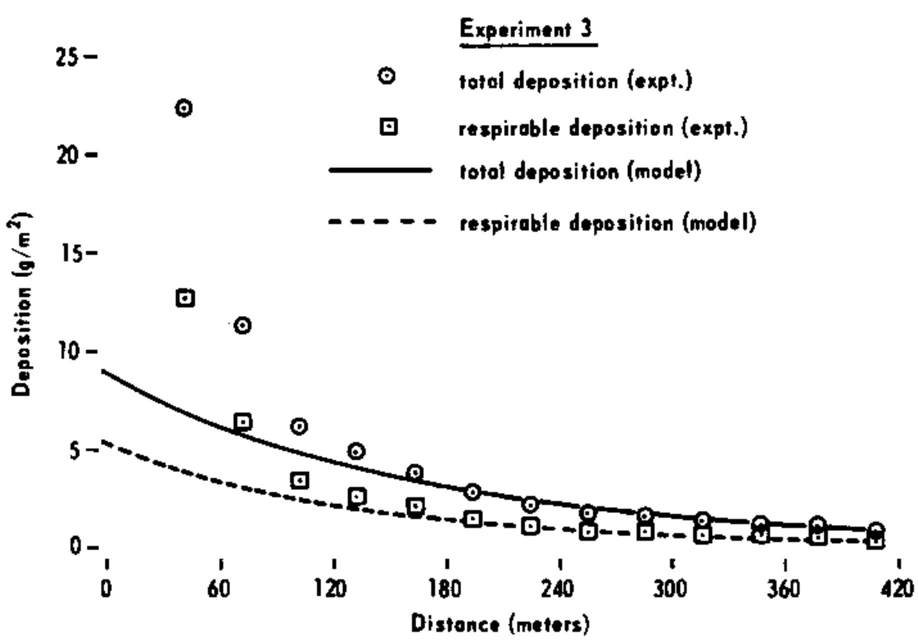


FIGURE 12. Comparison of model predicted floor deposition with experimental data (Experiment 3).

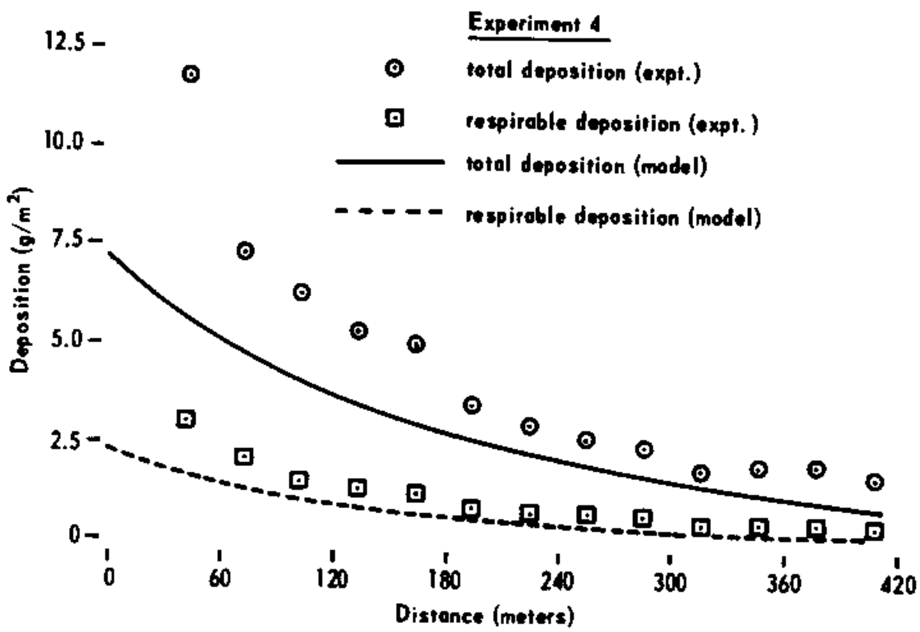


FIGURE 13. Comparison of model predicted floor deposition with experimental data (Experiment 4).

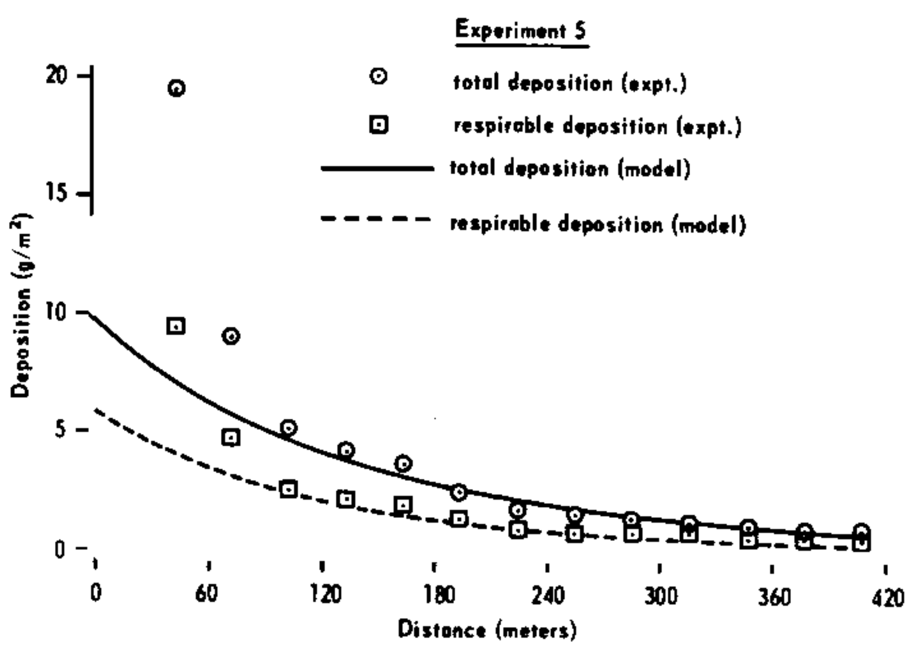


FIGURE 14. Comparison of model predicted floor deposition with experimental data (Experiment 5).

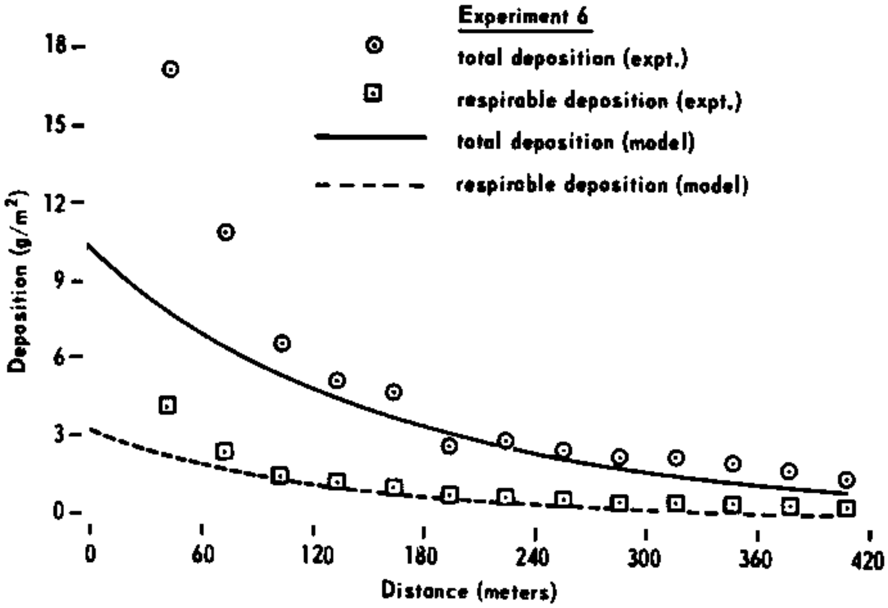


FIGURE 15. Comparison of model predicted floor deposition with experimental data (Experiment 6).

and positive influence of gravity respectively in dislodging the adhering particles.

A preliminary examination of the ambient concentration and deposition data reveals that for each size class as measured by the Microtrac Small Particle Analyzer, the deposition rate, i.e., deposition ($mg/m^2/sec$) to ambient concentration (mg/m^3), for all sizes is highest at the first station and decreases nonlinearly with decreasing concentration. In the model, deposition rate for a particular size is assumed a constant for a set of experimental parameters.

Summary and Conclusions

This paper has presented the results of a study into the spatial and temporal behavior of dust in mine airways using both theoretical and experimental studies. A mathematical model was developed to predict the ambient concentration and deposition in a mine airway as a function of the characteristics of the dust source mine airway and airflow. Six experiments were designed and conducted in a mine airway to study dust transport and deposition phenomena as well as to generate data to examine the conceptual and computational aspects of the model.

The results of the comparative analysis are as follows:

1. The model predicted deposition is in good agreement with experimental data in both the respirable and total size range.

2. The model appears to predict total concentrations better at lower velocities of flow.

3. At distances farther from the source the prediction is better for the total size range than for the respirable size range.

4. The model appears to predict respirable concentration closer to the source better than at distances farther from it.

The experimental data reveals that the deposition rate may be a function of concentration and that reentrainment may be contributing to the ambient dust concentration. The effect of these mechanisms, as well as others, on particle behavior in mine airways, particularly in the respirable size range, needs to be further examined.

Acknowledgments

The cooperation of the staff of the Ventilation Group, Pittsburgh Research Center, U.S. Bureau of Mines, the staff at the Lake Lynn Laboratory, and the Department of Mineral Engineering is gratefully acknowledged.

The research reported in this paper was supported under the Mineral Institutes Program by Grant No. G1135142 from the Bureau of Mines, U.S. Department of the Interior, as part of the Generic Mineral Technology Center for Respirable Dust.

References

1. **Hall, D.A.:** Factor Affecting Airborne Dust Concentrations, with Special Reference to the Effect of Ventilation. *Trans. Inst. Min. Eng. 115*:245-269 (1955-56).

2. **Bradshaw, F. and A.L. Godbert:** The Deposition of Dust in Return Airways. *Research Report No. 92*, SMRE:37 (1954).

3. **Bradshaw, F., A.L. Godbert and E. Leach:** The Deposition of Dust on Conveyor Roads. *Research Report No. 106*, SMRE:62 (1954).

4. **Dawes, J.G. and A. Slack:** Deposition of Airborne Dust in a Wind Tunnel (Interim Report). *Research Report No. 105*, SMRE:41 (1954).

5. **Ford, V.H.W.:** Experimental Investigations Into the Dispersion and Transport of Respirable Dust in

Mechanized Coal Mining, Ph.D. Thesis, University of Newcastle upon Tyne, pp. 227 (June 1971).

6. **Hwang, C.C., G.E. Geiger and P. Radulovic:** *Dust Concentration Simulator forMine Ventilation Systems for Coal Mines,* pp. 186-238. NTIS PB 213833 (1972).

7. **Courtney, W.G., J. Kost and J. Colinet:** Dust Deposition in Coal Mine Airway. *Technical Progress Report 116:*15. U.S. Bureau of Mines (1982).

8. **Owen, P.R.:** *Dust Deposition from a Turbulent Airstream. Aerodynamic Capture of Particles,* pp. 3-24. E.G. Richardson, Ed. Pergamon (1960).

9. **Bhaskar, R. and R.V. Ramani:** Behavior of Dust Clouds in Mine Airways. *SME Preprint 85-154*, accepted for publication in *SME Trans:10* (1985).

10. **Bhaskar, R., R.V. Ramani and R.A. Jankowski:** Experimental Studies on Dust Dispersion in Mine Atmospheres. *SME Preprint 11:86*-140 (1986).

11. **Skubunov, V.V.:** Tubulent Transport Coefficients for Mine Workings and Tunnels. Soviet Mining *Science 9*:402-412 (1973).

12. **Belyaev, S.P. and L.M. Levin:** Techniques for Collection of Representative Aerosol Samples. *Aerosol Sci. 5*:325-338 (1974).

13. **Hodkinson, J.R. and S.J. Leach:** The Longitudinal Dispersion of Pulses of Respirable Dust on Gas in Ventilated Mine Workings, studied by a Radioactive Tracer Technique. *Trans. Inst. Min. Engr. 117*:683-702 (1957-58).

Determining the Size Distribution of Coal/Diesel Aerosol Mixtures with the Microorifice Uniform Deposit Impactor

KENNETH L. RUBOW, Ph.D. and
VIRGIL A. MARPLE, Ph.D.
Particle Technology Laboratory, Mechanical Engineering Department, University of Minnesota

Introduction

As a consequence of the increased usage of diesel powered equipment in underground coal and noncoal mines, there is greater interest in finding an instrument or measurement technique to quantify the contribution of diesel particles to the overall respirable aerosol concentration. The use of mobile, diesel powered mining equipment is widespread in noncoal mines and is being increasingly employed in coal mines. The exhaust from these diesel engines contains particles which, along with the nondiesel particles, become the aerosol to which the miners are exposed. Since the diesel particles are rather small, typically 85 percent to 95 percent submicrometer diameter,[1,2] they can contribute significantly to the quantity of respirable matter. This contribution can be as high as 60 percent to 90 percent of the respirable mass to which workers are exposed.[3,4]

One procedure for reducing the quantity of respirable particles to which miners are exposed is to control the emissions at the source. However, what is not readily known is the contribution of the diesel particles to the overall respirable aerosol. Thus, a sampling method or instrument which selectively measures the quantity of diesel particles in the respirable size range is needed.

The University of Minnesota, under contract to the Bureau of Mines, has investigated the feasibility of using the microorifice uniform deposit impactor (MOUDI) to measure the size distribution of aerosols containing various mixtures of coal and diesel aerosols. The objective of the work was to determine if the relative mass concentration of diesel particles in an airborne mixture of coal dust and diesel particles could be determined on the basis of the size distribution of the two aerosols. In general, the mass of diesel particles is in the submicrometer size range while that of the coal lie in the larger size ranges.

With the MOUDI the particle distribution is determined with the diesel and coal particles separated on the basis of their aerodynamic equivalent diameters. This parameter is important from the standpoint of human health effects.

This study involved measurements conducted in both the laboratory and in several underground coal mines. The primary emphasize of the laboratory tests were to ascertain if the diesel particles could be separated from the coal, regardless of mass fraction of the diesel particles in the total aerosol mixture. The field tests were aimed at verification of the laboratory findings.

Microorifice Uniform Deposit Impactor

The MOUDI is a versatile cascade impactor designed to collect size fractionated samples of particles. This impactor is essentially the same as a conventional cascade impactor with the exception of two unique features. These are small nozzle diameters and a rotation feature which allows for a uniform particle deposit to be obtained. As a result of the small nozzle diameters, very small particles can be collected. Cutsizes as small as 0.024 um have been obtained. The two unique features, microorifices and the uniform deposit, have been developed and patented by this laboratory.

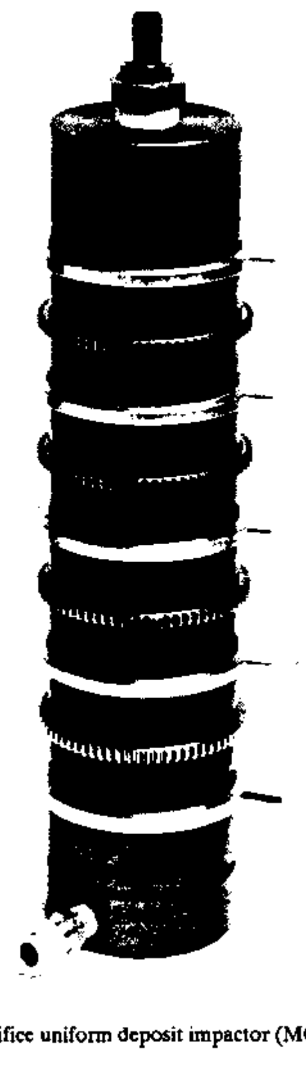


FIGURE 1. Microorifice uniform deposit impactor (MOUDI).

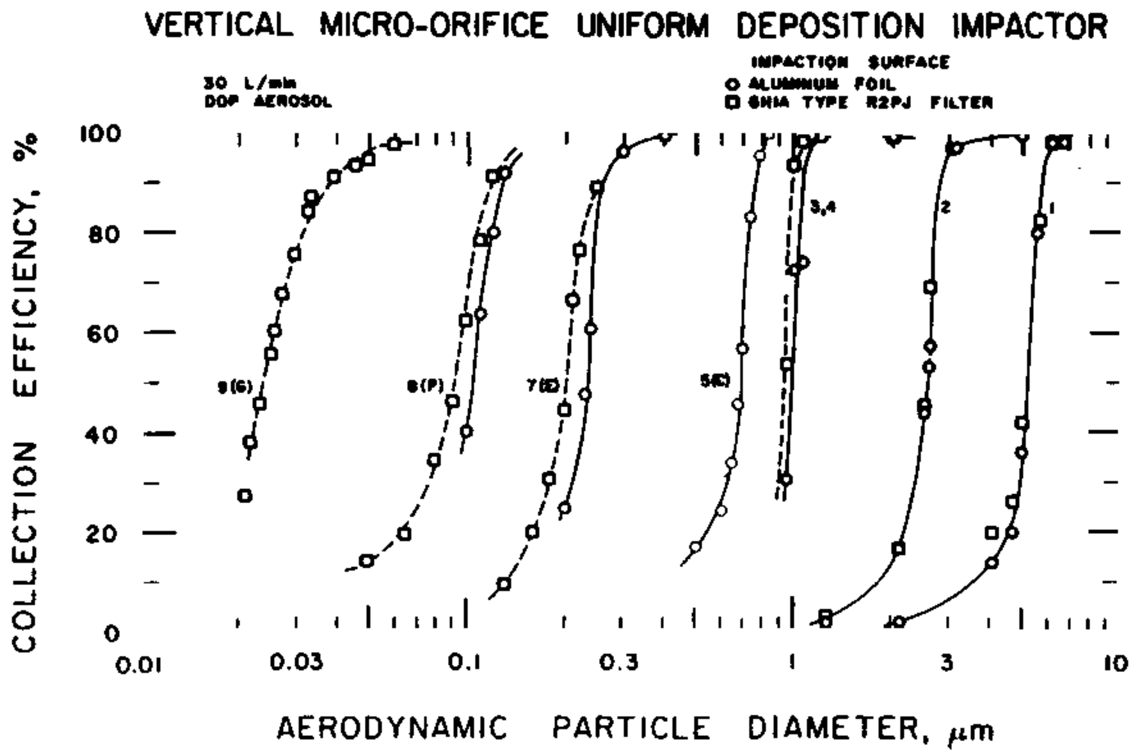


FIGURE 2. Calibration data for several stages of the MOUDI.

A seven-stage version with particle cutsizes ranging from 0.10 to 10 um is shown in Figure 1. The details of the impactor design parameters are presented in Table I. Typical efficiency curves for several of the impactor stages are shown in Figure 2. The flow rate through this impactor is 30 liter per minute (lpm). At the lowest cutsize, 2000 nozzles of approximately 50 um diameter are utilized. Marple and Rubow[5] describe, in more detail, the impactor and the particle calibration. Marple *et al*[6] and Marple and Rubow[7] describe an earlier version of the impactor.

An important feature of this impactor is that it can be used to obtain a uniform deposit of particles upon the impaction surface by rotating the nozzles relative to the impaction plates. A uniform deposit reduces the problem of particle bounce and, at any degree of loading, increases the accuracy by increasing the ratio of particle mass collected to the substrate mass.

As shown in Figure 1, the gears on alternate stages of the impactor allow the stages to be rotated to obtain the uniform deposit. A special rotation device has been developed for this purpose. The impaction stages, which do not have gears, have rings with hooks so that they cannot rotate.

In operation, the drive shaft with four spur gears is turned by an electric motor. These spur gears mesh with the four gears on the alternate stages of the cascade impactor and rotate these stages relative to the four stationary stages. Since each stage contains a nozzle plate plus the impaction plate for the stage above, as shown in Figure 3, the rotation of every other stage rotates every impaction plate relative to its impaction plate. By properly placing the nozzles at radial distances about the center of rotation of these stages, a uniform deposit is obtained on the impaction plate.

The rotation of the microorifice impactor is not necessary in order to obtain a size distribution. The impactor can be used in a conventional nonrotating manner, the same as any cascade impactor, and the mass of particles on the substrate analyzed gravimetrically or analyzed by other techniques dictated by the test program.

TABLE I

MOUDI Design and Operating Parameters

Stage	Number of Nozzles	Nozzle Diameter (um)	Cutsize (um)
1	3	8650	10.00
2	10	3410	4.90
3	10	2170	2.60
4	10	1170	1.00
5	80	467	0.70
6	900	69	0.23
7	2000	56	0.10

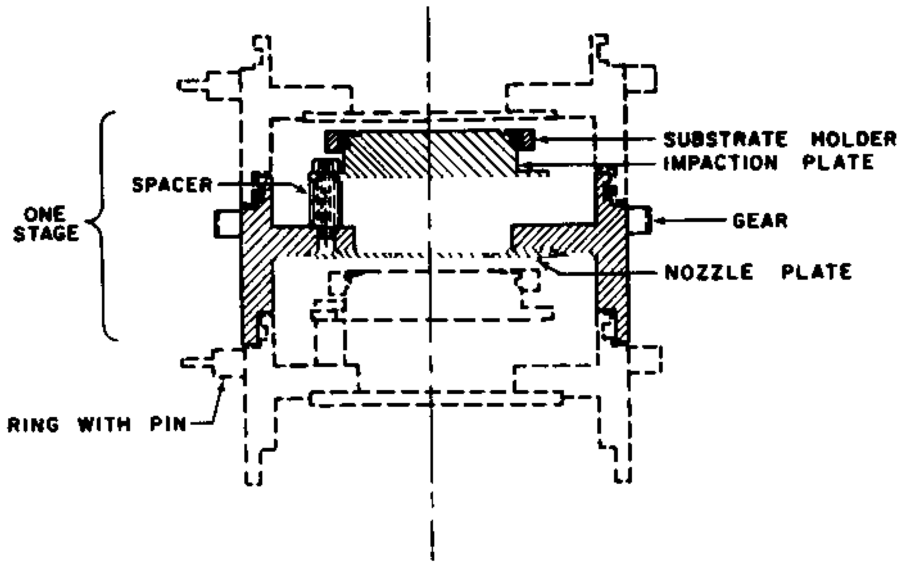


FIGURE 3. Schematic diagram of typical impactor stage.

Laboratory Experiments

The objective of the laboratory studies was to determine the feasibility of using the MOUDI to separate the diesel particulates and coal dust fractions from a mixed aerosol. A special test apparatus was constructed and tests were performed over a wide range of diesel and coal mixtures.

The test setup used in the combined diesel/coal aerosol experiments is shown in Figure 4. The system consists of four primary components, namely, a Caterpiller Type 3304 NA diesel engine, a TSI Model 3400 Fluidized Bed Aerosol Generator, a dilution system, and the aerosol sampler. Diesel exhaust, at a flow rate of 16 lpm, was extracted from the engine exhaust manifold and combined with the coal dust aerosol. The coal dust was generated with the fluidized bed aerosol generator at a flow rate of 9 lpm. For each engine operating condition, the ratio of the diesel to coal aerosol concentration was adjusted by varying the coal dust concentration. The combined aerosol was then injected into a 7.6cm diameter, dilution tunnel. Room air, at a flow rate of 800 lpm, was drawn into the tunnel and through a flow meter, a charcoal bed filter and a HEPA filter prior to the diesel/coal aerosol injection point. The diesel exhaust, coal dust and dilution air were turbulently mixed in the dilution tunnel where the aerosol dilution ratio was 33 to 1. A sample of the diesel/coal aerosol was isokinetically drawn from the tunnel at a flow rate of 30 lpm. The size distribution of this sample was obtained using the MOUDI.

With this system, the diesel aerosol concentration, at a given engine operating condition, is kept constant while the concentration of the coal dust aerosol varied to obtain different diesel particulate to coal dust mixture ratios. The diesel particle mass concentration was typically 3 mg/m^3. Classified coal dust containing no particles greater than 10 um was used as the feed material in the fluidized bed dust generator.[8] This coal dust was selected in an attempt to simulate the respirable fraction of a coal dust aerosol.

The MOUDI was used to measure the size distributions of the diesel/coal aerosol mixtures. For these laboratory tests, a six-stage version was used. The cutsizes of the stages were 0.12, 0.18, 0.7, 1.0, 2.5, and 4.9 um. For the size distribution analysis, additional interval boundaries of 0.05 and 15 um were assumed for the smallest size of the diesel particles and the largest size of the coal dust particles. Modal analysis

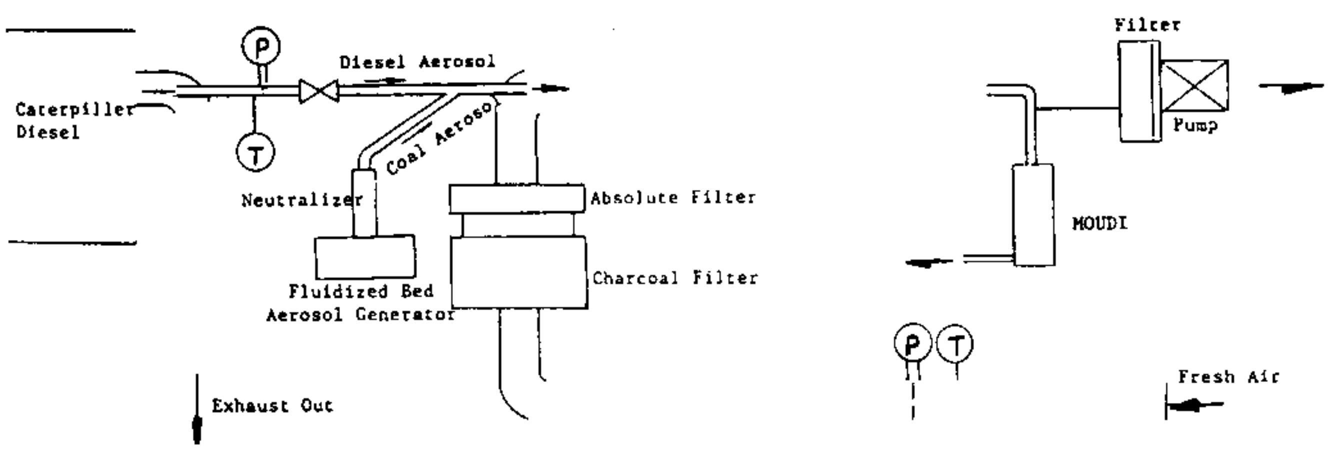


FIGURE 4. Schematic diagram of test setup used in the diesel/coal aerosol experiments.

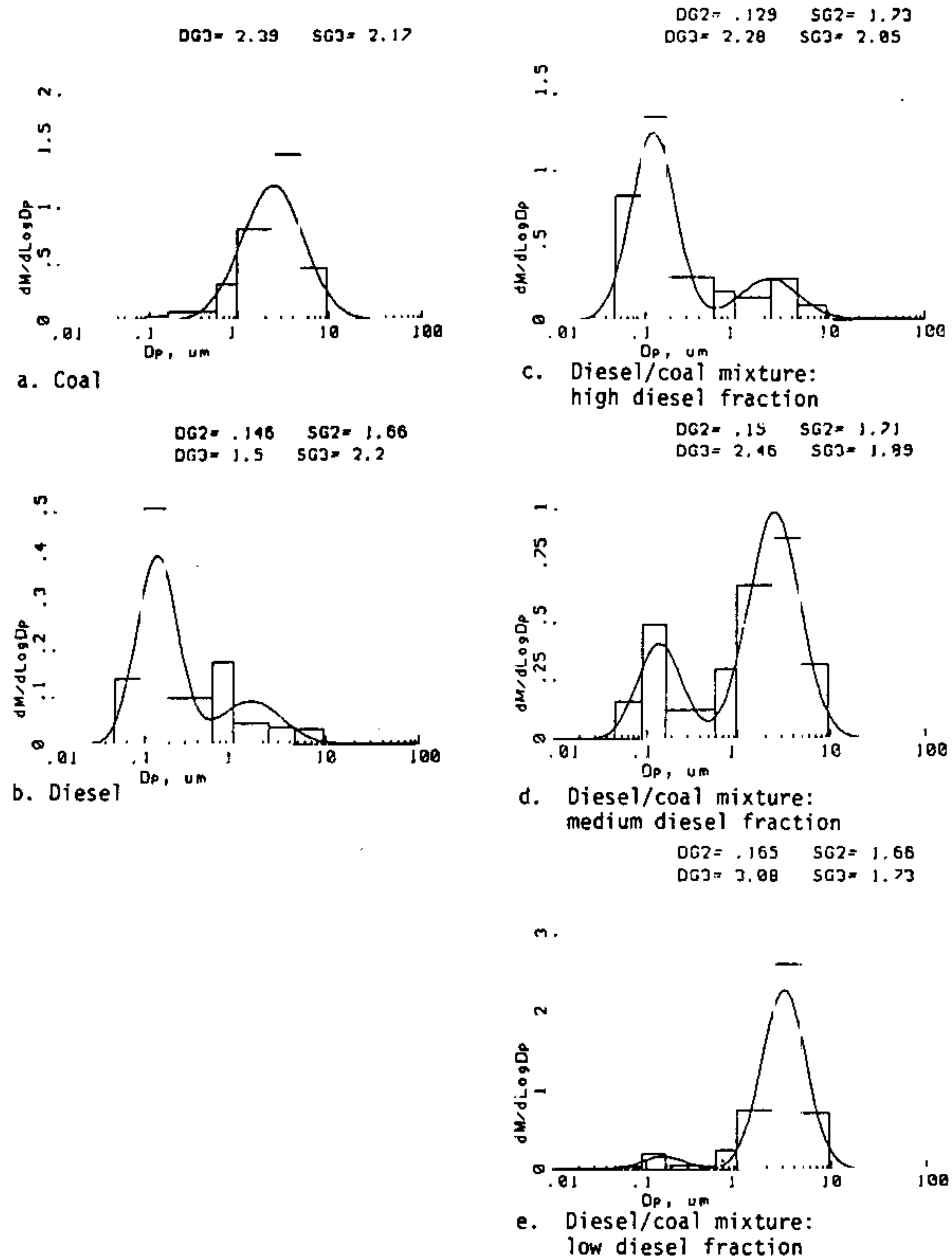


FIGURE 5. Measured and fitted size distributions for pure coal dust, pure diesel particulates and three mixtures of the two aerosols.

was then used to obtain the lognormal size distribution of these aerosols.

A series of five typical mass size distributions are presented in Figure 5. Distributions are presented for pure coal and diesel aerosols plus three diesel/coal aerosol mixtures. For the pure coal aerosol experiments, diesel particulates were removed in a filter placed upstream of the point of mixing. Thus, the equivalent flow conditions were maintained to minimize differences in particle loss.

The histograms in the graphs represent the experimental data. The lognormal size distribution curves were obtained by using "DISFIT," a size distribution fitting program. The mass medium diameter (MMD) and geometric standard deviation (og) for each mode are presented above the graph. DG2 and DG3 are the MMDs for the submicrometer and supermicrometer modes respectively. SG2 and SG3 are the corresponding og's. The measured MMD and og for the diesel aerosol were found to range from 0.13 to 0.16 um and 1.66 to 1.73, respectively. For the coal dust, the MMD and og were found to vary from 2.3 to 3.1 um and from 1.7 to 2.2, respectively.

The data in Figure 5 were obtained with the diesel engine operating conditions of half load at 1400 RPM. The mass fraction of material less than 0.7 um was 5 percent and 71 percent for the pure coal and diesel aerosols, respectively. For the combined aerosol tests, mass fractions less than 0.7 um were 78 percent, 26 percent, and 6.5 percent. Regardless of the diesel/coal aerosol mix, the data shows two distinct modes with a minimum occurring in the 0.7 to 1.0 um size range.

Field Studies

Tests were performed in three underground coal mines. Two utilized diesel powered equipment while the third exclusively used electric power. The third mine was included as a control to obtain the submicrometer size distribution of coal and rock dust without the presence of diesel particles. The three mines are identified as 1, 2, and 3 with mines 1 and 2 utilizing diesel powered equipment. The two diesel mines are located in the western U.S. while mine 3 was an eastern mine.

Schematic diagrams of the test sections in each of the three mines are presented in Figure 6. Each diagram shows the location of the working faces, feeder breaker, beltway, and pathway of mine ventilation airflow. All three test sections were in the continuous mine sections of developments for future longwall operations.

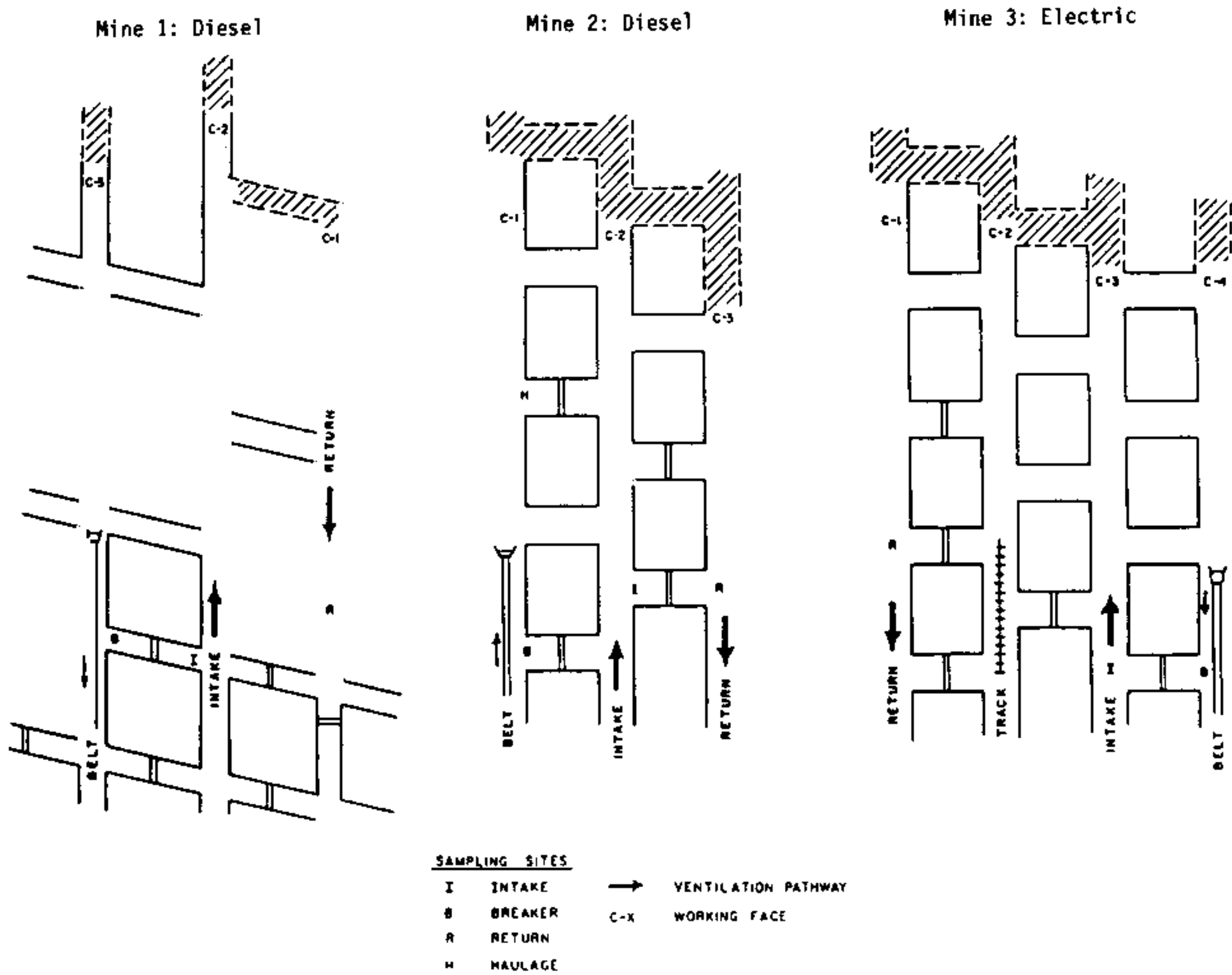


FIGURE 6. Schematic diagram of the test sections in the three mines.

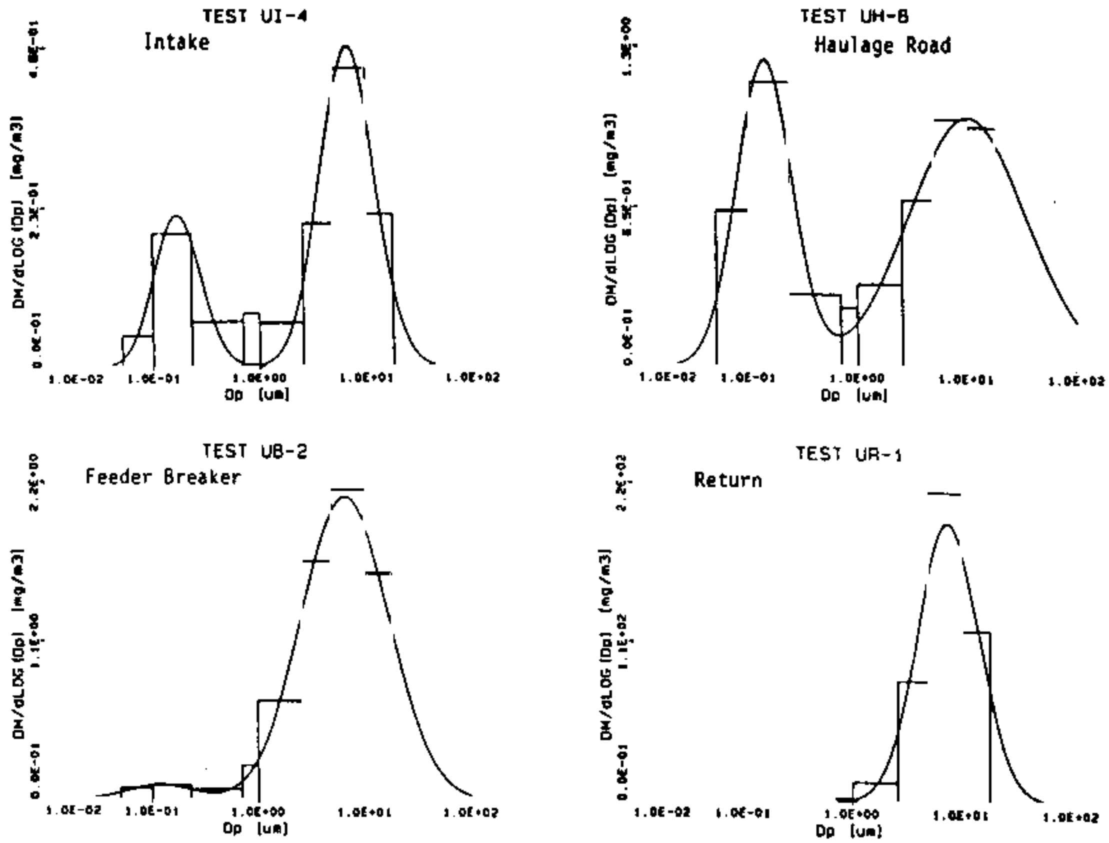


FIGURE 7. Typical particle size distributions measured at several locations in mine 2, a mine using diesel powered equipment.

The sampling sites in all three mines are also shown in Figure 6. Four sites were used, namely the intake (I), the primary return (R), along the beltway (B), and adjacent to the main haulage way (H). The beltway sites were located 30 m from of the feeder breaker. In mines 1 and 3 the beltway was located in the secondary return. The beltway was in the secondary intake for mine 2. Sampling in the return was performed with and without rock dusting occurring at the face.

Tests were performed in a wide variety of mining conditions in order to obtain a wide variation in the diesel aerosol fraction and overall aerosol mass concentrations. In particular, samples were obtained in the return airway to determine if the diesel aerosol mode would be obscured by a very high fraction of coal or rock dust. Duplicate tests were conducted to determine the variability in the aerosol size distribution.

Two types of experiments were conducted. The first utilized the MOUDI to obtain the overall size distribution of the diesel and dust aerosols. The second involved collecting aerosol sample for neutron activation analysis.

Size Distribution Results

The measured size distributions were analyzed using a lognormal size distribution fitting program. Each mode of the resulting bimodal size distribution was analyzed using DISFIT, a size distribution fitting program, to obtain the MMD and σg of the mode.

Typical size distributions measured in mine 2, a diesel powered mine, are presented in Figure 7. Data are shown for sampling sites in the primary intake and return, along the beltway, and in the main haulage way. The overall mass concentrations for these four tests were 0.40, 127.0, 1.93, and 1.68 mg/m^3. The ratio of the mass of material less than 0.7 um to the total mass was 30 percent, 1.2 percent, 4.7 percent, and 45 percent, respectively. The extremely high concentration in the return was obtained during a rock dusting operation. These results show that, regardless of the sampling location, the mass concentration, or ratio of sub 0.7 um mass to total mass, there is a clear separation between the two modes. The minimum exists in the 0.7 to 1.0 um size range.

Typical size distributions measured in mine 3 are presented in Figure 8. This mine exclusively utilized electric powered equipment. Data are presented for sampling sites located in the intake, the return and along the beltway. These size distributions show that essentially no mine generated aerosol is in the sub 0.7 um size range. The aerosol in this size range measured in the intake is most likely the background aerosol found in the outdoor air used for mine ventilation.

A composite graph showing typical size distributions as measured near the beltway and haulage way is presented in Figure 9. A typical size distribution from each of the three mines is also presented. The coarse particle modes, i.e., the coal dust mode, are nearly identical for the three mines. Furthermore, the diesel particle modes are nearly identical. The size distribution from the electric mine clearly shows the absence of any mode in the submicrometer particle size range.

These results show that, regardless of the fraction of diesel exhaust in the aerosol, the aerosol size distribution is bimodal. Furthermore, the diesel mode is clearly separated from the dust particle mode, with the minimum between the two modes occurring in the 0.7 to 1.0 um size range.

Neutron Activation Results

Chemical mass balance (CMB) model source apportionment analysis is being developed for application to the mining environment by Dr. Bruce Cantrell of the Twin Cities Research Center (TCRC). This analysis will serve as a reference analysis method to validate the findings of the MOUDI measurements, i.e., diesel and coal dust can be separated on the basis of particle size. The CMB requires measurements of the chemical and elemental components of both source and aerosol materials. These measurements were provided by instrumental neutron activation analysis.

The second set of experiments involved collecting size fractionated particle samples for elemental analysis. For each test two samples were obtained. The first consisted of respirable particles greater than 0.7 um and the other particles less than 0.7 um. Quantitative elemental analysis was then performed on each sample using neutron activation analysis. The objective of these tests was to determine the fraction of coal, rock dust and diesel particle in the particle size fractions less than and greater than 0.7 um.

The sampler consisted of a respirable impactor[9-11] followed by two 0.7 um cutsize MOUDI stages and an afterfilter. The particle cutsize was 0.7 um for both stages. The second stage was used to collect those particles larger than 0.7 um which may not be collected on the first stage. Thus, two samples were obtained, one consisting of respirable particles greater than 0.7 um and the other consisting of particles less than 0.7 um.

In addition to the aerosol samples, samples of the coal, rock dust and diesel fuel were also submitted for analysis.

Preliminary results of the neutron analysis support the findings of the MOUDI measurements. Typically, less than 1 percent of the material less than 0.7 um is coal or rock dust and less than 1 percent of the respirable material greater than 0.7 um is diesel particulates. The results from these three field trips will be reported by the TCRC in a separate publication.

Summary

The MOUDI has been successfully shown to separate coal and diesel aerosols. A clear separation between the two modes exists in the 0.7 to 1.0 um size range with a saddle point in the vicinity of 0.8 um. This primary finding is supported by test results from both laboratory and field sampling. In both cases the aerosol size distribution was found to be bimodal with the MMD of the diesel (accumulation) mode at approximately 0.15 um and the MMD of the dust (coarse) particle mode at about 2.5 um for the laboratory aerosols and 10 um obtained in the mine. Distinct separation of the two modes was found to be independent of the relative concentration ratio of the diesel particles in the total aerosol. The separation was also found to be independent of the sampling site in the mine.

Acknowledgments

This work was supported under the Bureau of Mines Contract J0145022 through the Pittsburgh Research Center. Mr. Kenneth Williams was the Technical Contract Officer. The field tests were performed with Dr. Bruce Cantrell of the Twin Cities Research Center. The financial support of the Bureau of Mines is gratefully acknowledged.

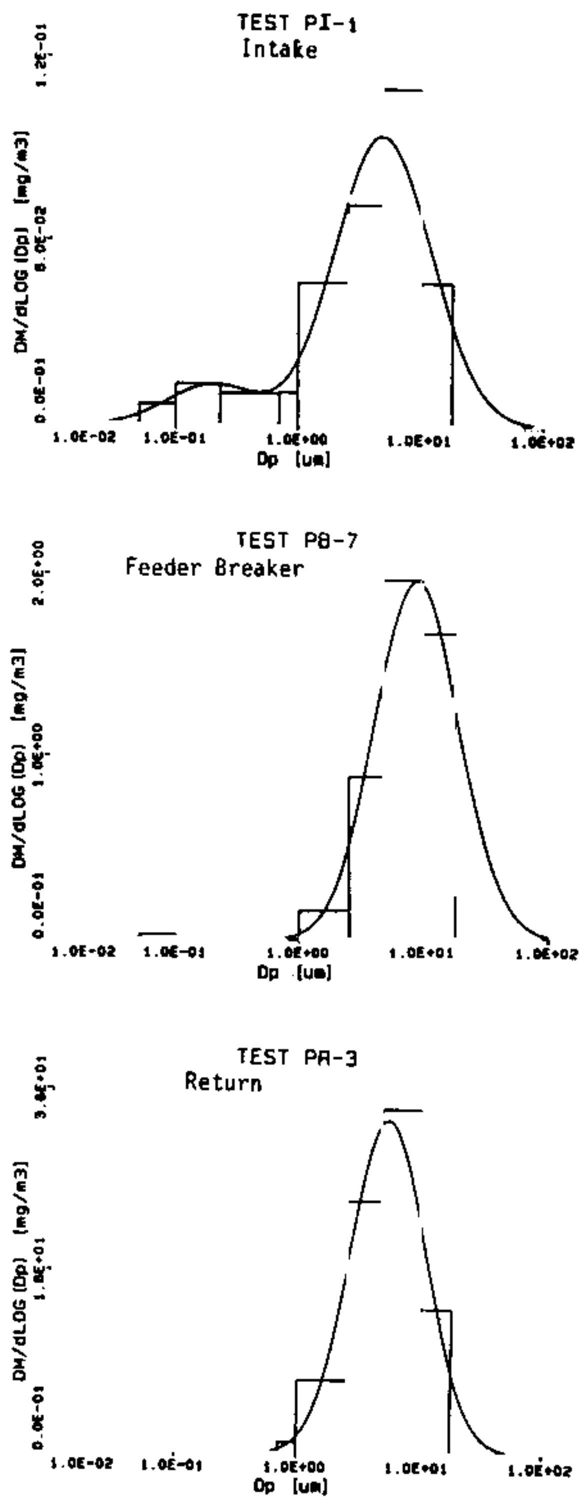


FIGURE 8. Typical particle size distributions measured at several locations in mine 3, an electric powered mine.

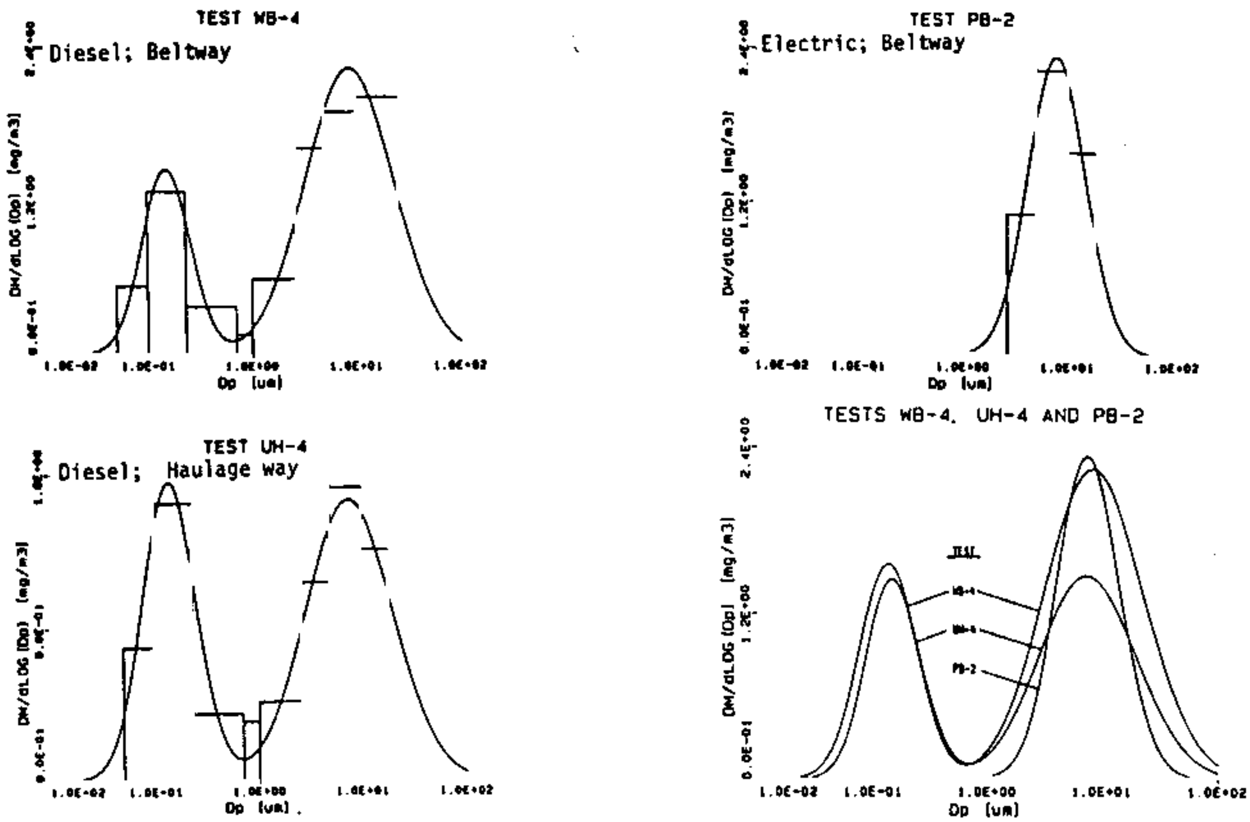


FIGURE 9. Comparisons of typical size distributions measured in two mines utilizing diesel powered equipment and one exclusively using electric powered equipment.

References

1. **Hare, C.T. and T.M. Baines:** Characterizations of Particulate and Gaseous Emissions from Two Diesel Automobiles as Function of Fuel and Driving Cycle. *The Measurement and Control of Diesel Particulate Emissions*, p. 281. Society of Automotive Engineers, Pub. No. SAE/PT-79/17 (1979).

2. **Fang, C.P. and D.B. Kittelson:** *The Influence of a Fibrous Diesel Particulate Trap on the Size Distribution of Emitted Particles.* SAE Paper No. 840362 (1984).

3. **Reinbold, E et al:** *Ambient Pollutant Concentration in Two Underground Metal Mines Using Diesel Equipment.* AIME Preprint No. 79-29 (1979).

4. **Breslin, J.A., A.J. Strazisar and R.L. Stein:** *Size Distribution and Mass Output of Particulates from Diesel Engine Exhausts.* USBM RI 8141 (1976).

5. **Marple, V.A. and K.L. Rubow:** *Development of a Microorifice Uniform Deposit Impactor*. Final report. DOE Contract No. DE-FG22-83PC61255 (1984).

6. **Marple, V.A., B.Y.H. Liu and G.A. Kuhlmey:** A Uniform Deposit Impactor. *J. Aerosol Sci. 12:*33-337 *(1981).*

7. **Marple, V.A. and K.L. Rubow:** *Calibration of Microorifice Impactor.* Final report. EPA Order No. 3D3376NAEX (1984).

8. **Marple, V.A., B.Y.H. Liu and K.L. Rubow:** A Dust Generator for Laboratory Use. *Am. Ind. Hyg. Assoc. J. 39:*26-32 (1978).

9. **Marple, V.A.:** Simulation of Respirable Penetration Characteristics by Inertial Impaction. *J. Aerosol. Sci 9:*124-134 (1978).

10. **Marple, V.A. and K.L. Rubow.:** *Respirable Dust Measurement.* Final Report. BOM Contract No. J0113042 (1984).

11. **Marple, V.A. and K.L. Rubow:** Impactors for Respirable Dust Sampling. *Aerosols in the Mininq and Industrial Work Environment*, Vol. III, pp. 847-860. V.A. Marple and B.Y.H. Liu, Eds. Ann Arbor Science Publishers, Inc., Ann Arbor, MI (1983).

GENERIZATION & CHARACTERIZATION I

Fracture Mode and Loading Rate Influences on the Formation of Respirable Size Fragments on New Fracture Surfaces

R. KARL ZIPF, Jr., and Z.T. BIENIAWSKI

Department of Mineral Engineering, The Pennsylvania State University, University Park

Researchers at The Pennsylvania State University are engaged in a project to understand the mechanics of respirable size fragment formation in coal. The project is based on the premise that a thorough understanding of the fundamental mechanics of fine fragment formation may lead to techniques for reduction and better control of coal dust problems in mines. Presently, it is believed that the mode of fracture propagation which can range from pure tensile to pure shear or any mixed mode in between and the loading or displacement rate can influence the amount of respirable size fragments that are generated on new fracture surfaces during the fracture propagation process The essence of any coal cutting process is one of mixed mode fracture propagation. To study the crack propagation process, a unique mixed mode testing rig was designed and fabricated. This rig is capable of applying loads to a prenotched test specimen that range from pure Mode I (tensile mode) to nearly pure Mode II (shear mode) or many mixed mode loading combinations. It is also possible to apply different loading or displacement rates to the test specimen. With this rig, it is possible to create new fracture surfaces via the different fracture modes and under various loading conditions.

These new fracture surfaces are examined with a scanning electron microscope (SEM) to characterize the amount of structural damage and respirable size fragment formation that occurs during the fracture process. Initial observations suggest that the amount of fine fragment formation and the new fracture surface appearance is related to the fracture initiation conditions, particularly the fracture mode and the loading rate. Mode II loading and higher loading rates seem to generate more structural damage and respirable size fragment formation that Mode I loading at slower rates.

With the mixed mode test rig, the mechanics of fracture initiation for a single crack can be controlled to better understand its influence on respirable size fragment formation. Such understanding may lead to methods which characterize the tendency of specific coal seams to produce undesirable fine fragments during the fracture process, or it may lead to rational recommendations and design guidelines or coal mining machines which inherently produce less dust.

Introduction

As part of a larger effort to reduce the incidence of coal workers pneumoconiosis (black lung) in coal miners, researchers at The Pennsylvania State University are engaged in a project to understand the fundamental mechanics of fine fragment formation in coal. This project is part of a comprehensive research effort within the Generic Mineral Technology Center for Respirable Dust which is jointly administered by The Pennsylvania State University and West Virginia University.

The principal source of the coal dust in underground mining is the cutting operation. The U.S. Bureau of Mines (USBM) and various European research organizations have conducted investigations into the mechanics of coal cutting for many years. These studies of airborne respirable dust (ARD) formation have concentrated on empirical studies of the various cutting parameters and their effect on ARD formation. The parameters study include depth of cut, cutting speed and bit spacing.[1,2] Other studies investigated the effect of symmetric and asymmetric bit wear and various bit geometries and designs.[3-5] Roepke[6] summarized the principals of proper coal cutting to minimize dust formation by recommending to "cut at maximum depth (maximum advance rate) at all times, at minimum RPM, with the fewest possible bits, having the lowest possible included tip angle." Most coal in the U.S. is mined with the continuous mining machine which inherently cannot meet these design recommendations.[3]

It is recognized that respirable size dust particles are formed and/or liberated by a fracture process. One extremely interesting and useful study performed very early in the USBM dust research effort determined the amount of respirable dust of 0.9 to 10 micrometer size adhering to the surfaces of various coals.[7] They found that the number of particles ranged from 10^{11} to 10^{12} particles per pound or from 20 to 60 x 10^6 particles per square centimeter of fracture surface. These numbers are evidently independent of the average fragment size. Fortunately, much less than one percent of the respirable particles formed ever become airborne.[1]

In a recent study sponsored by the National Academy of Sciences (NAS)[8] these observations and empirical correlations raised certain key questions regarding the mechanical events that occur immediately after particles are produced and the quantity of particles that actually become airborne. Moreover, one should know the nature of the particles that become airborne versus those that remain behind on the new fracture surface. A further question raised by the NAS study is whether the majority of the dust is liberated from the crush zone near the bit tip, from the newly created surfaces during

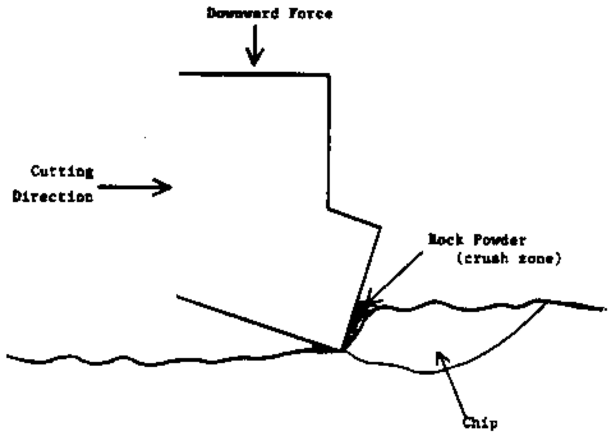


FIGURE 1. Basic coal cutting model.[11]

fracture, or from the new surface because of falling. Little work has been done on these fundamental problems.

Coal Cutting Models and Dust Formation Mechanics

Several rock cutting and rock failure theories have been proposed in the past, but it is only very recently that fracture mechanics concepts have been successfully applied to the study of rock cutting mechanics. All of these cutting models seek to predict the cutting forces and the cutter geometry necessary to cause rock breakage and chip formation given some fundamental mechanical properties of the rock. The models have wide applications in drilling, tunnel boring and mining problems.

The indentation type of models[9] consider a rock loaded by a wedge. A crushed zone is postulated around the wedge tip and interfacial friction between the bit and the rock is included. Failure or chip formation occurs when the unconfined compressive strength of the rock is exceeded. The analysis is based on plasticity theory and the size of the chip formed is determined by the size of the plastic zone around the wedge tip. In another indentation type model, a Mohr-Coulomb failure criteria is applied along an assumed failure path.[10] The cutting force is determined when the failure criteria is exceeded.

Only one model successfully analyzes rock cutting using fracture mechanics concepts. Saouma and Kleinosky,[11] model the action of a drag bit cutter with a special purpose finite element program that simulates mixed mode crack propagation based on linear elastic fracture mechanics. The problem analyzed is shown in Figure 1. This model is identical to one used by the USBM for coal cutting.[6] The cutter moves across the rock where a chip was previously removed until it engages the rock ahead of it. A new crack is propagated under mixed mode loading conditions until a new chip is removed.

The cutting model used by the USBM and analyzed by Saouma and Kleinosky[11] serves as a basis for postulates of fundamental mechanisms for ARD production. The basis for these postulates is recent work by researchers at the Southwest Research Institute[10] and additional modifications at The Pennsylvania State University. The fundamental mechanisms for dust production may include:

1. Crushing, grinding and scraping by the tool tip.
2. Energy dissipation in the fracture process zone.
3. Explosive disintegration during chip formation caused by violent release of stored elastic strain energy.
4. Preferential detachment of impurity particles during fracture due to their differing elastic moduli.

In addition to the production mechanisms, further mechanisms have been proposed for subsequent entrainment of the dust particles, but they will not be discussed here.

The relative importance of the above mechanisms and the factors which influence their relative importance are not well understood. Many regard the crushing mechanism as most important although experimental evidence for this contention is conflicting and sparse. For instance, the decrease in specific ARD with deep cutting is supportive of the contention since presumably, the size of the crush zone and the amount of grinding and scraping are not greatly affected by increased depth. On the contrary, it is known that using dull and worn bits does not effect the specific ARD. Assuming that dull and worn bits increase the amount of crushing,

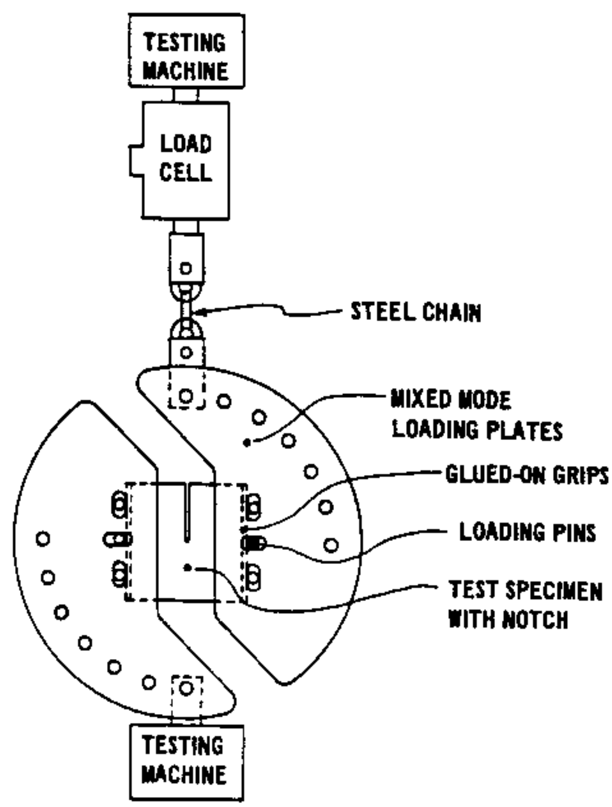


FIGURE 2. Mixed mode fracture toughness test fixture.

grinding and scraping, one should expect higher specific ARD.

Our present research thus focuses on the energy dissipation mechanisms that occur in the fracture process zone during a crack propagation event and the various mechanical properties that influence the amount of energy dissipation and the resulting fine fragment formation. It is known that when a crack propagates through a material including coal, it rarely produces a smooth, clear, well-defined surface. Microcracks are opened up all along the newly created surfaces and successful or unsuccessful attempts at crack bifurcation may occur. The material on either side of the new crack surface is affected by the "fracture process zone" (FPZ) which surrounds the propagating crack tip. Energy supplied to the crack tip by various external loads is largely dissipated in the FPZ and relatively little is consumed as free surface energy. When loading conditions are such that the crack tip is provided with excess energy for crack propagation, it responds by dissipating that energy through additional microcracking and crack bifurcation within the FPZ. As a result, new fracture surfaces may exhibit rougher appearances and increased structural damage which in turn may correlate with an increased tendency to produce unwanted fine fragments. Two approaches have been advanced to understand and quantify the fracture process as it relates to fine fragment formation: one is based on theoretical models of the size of the FPZ; and the other is based on relationships between crack tip stress intensity and new fracture surface appearance as seen under a scanning electron microscope.[12]

Experimental Methods

The present experimental work aims to provide the necessary mechanical properties data to quantify the energy dissipation processes that occur during coal cutting and which may lead to unwanted ARD production. Of central importance are fracture toughness measurements in coal as a parameter controlling unstable crack growth and fracture velocity measurements. The last aspect is a novel concept based on the observation that crack bifurcation occurs above some critical velocity. This leads to the hypothesis that when crack bifurcation does occur, fine fragments of coal material are generated which leads to increased dust formation.

Relative to other materials, few studies exist, on the fracture toughness of rock[13] and even less on coal. Considerable controversy remains regarding test procedures and the fracture strength for various coals. Table I[12] presents a compilation of the existing Mode I fracture toughness measurements of coal by various researchers in the

TABLE I

Summary of Coal Fracture Toughness Test Results

Source	Coal	Specimen Type	Specimen Size	KICMPa m	Deviation of Mean	Standard No. of Tests
Advani et al[15]	Pittsburgh	SEND-3PB	15 cm x 3.8 cm	0.0281	86%	2
	Waynesburg	SEND-3PB	x 1.9 cm	0.156	36%	3
	Bedstone	SEND-3PB		0.0348	60%	6
Powell et al[16]	Pittsburgh	SEND-3PB	15 cm x 3.8 cm	0.0629	37%	15
	Pittsburgh	SEND-3PB	x 1.9 cm	0.0472	34%	25
Bhagat[17]	Lower Freeport	SEND-3PB	20 cm x 3.8 cm	0.0283	35%	10
	Redstone	SEND-3PB	x 1.9 cm	0.0474	72%	20
	Waynesburg	SEND-3PB		0.121	48%	5
	Sewickley	SEND-3PB		0.267	19%	9
Szendi-Horvath[18]	Black Coking Coal	DMC	1.6 to 3.8 cm	0.219	13%	12
	Black Steaming Coal	DMC		0.435	12%	6
	Semi-Anthracite	DMC		0.132	11%	6
	Black Coking Coal	SEND-3PB	4 to 7 cm	0.321	11%	12
Bassim and Hsu[19]	Coal A	SEND-3PB	up to 8 cm	0.020 to 0.225	–	11
Klepaczko et al[20]	Coal A	WLCT	3.8 x 3.8 cm	0.154	25%	4
	Coal B	WLCT	x 3.2 cm	0.181	3%	3
	Coal A	WLCT-dynamic		2.014	11%	4
Bieniawski and Mark[13]	Bone Coal	DMC	1.6 cm	0.220	25%	11
	Kitt Mine	SEND-4PB	up to 3 cm long	0.346	17%	3
	Coal Kitt Mine	DMC	1.6 cm	0.150	19%	4
	Anthracite	DMC	1.6 cm	0.296	32%	11
	Rushton Mine	SEND-4PB	up to 3 cm long	0.172	42%	4
		DMC	1.6 cm	0.032		2

U.S., Canada, Australia, and at Penn State. The fracture toughness for coal can range over an order of magnitude for different coals and the standard deviation for individual coals can reach 30 to 50 percent. The primary reason for the variability is the highly asisotropic, non-homogeneous, and discontinuous nature of coal. Because of its nature, only the strongest, most durable coal samples are ever tested which tends to produce very suspect fracture toughness test data.

Existing data for the fracture toughness of coal is for Mode I only. From a general review of the rock mechanics literature, relatively little test work has been completed under mixed mode conditions[14] and only relatively recently has such testing become important in other materials such as metals and ceramics. Since the coal cutting mechanism is indeed one of mixed mode crack growth, it was necessary to design, analyze, and calibrate a special mixed mode testing rig in order to study the crack growth mechanism and its effect on fine fragment formation. A schematic of the test fixture is shown in Figure 2. It can subject a 0.1 meter, pre-notched test specimen to pure mode I loading, a nearly pure mode II loading or various mixed mode loadings. Figure 3 shows three plaster of paris test specimens that were fractured in the test rig for calibration purposes. The specimen in the front was fractured by a mode I loading, the one in the rear by a mode II loading, and the one in the middle by a mixed mode loading. The increasing angle of crack growth observed as the amount of mode II loading is increased is as expected from theoretical considerations.

In conjunction with the fracture toughness testing, determination of related coal material properties is essential. The properties include the unconfined compressive strength, the direct tensile strength, the point load index, the Schmidt hardness, the NCB indenter hardness and the Young's Modulus and Poisson's Ratio. Determination of these coal material properties enables more complete characterization of the various coals and also provides useful cross checks and correlations for the fracture mechanics properties.

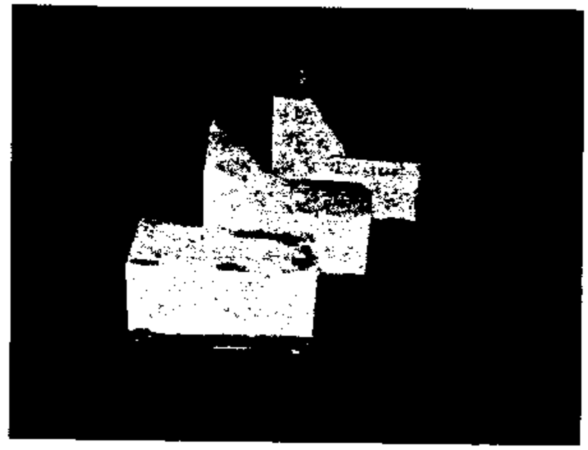


FIGURE 3. Calibration specimens fractures by mixed mode test rig.

Table II shows the design of the mechanical properties test program presently underway. The program is basically designed to supply input data to the models of fracture process zone size and the relationship between crack tip stress intensity and new fracture surface appearance as seen with the scanning election microscope. Tests are conducted under various mixed mode loading conditions at different

TABLE II

Mechanical Properties Tests for Each Coal Seam

Test Type	Perpendicular to Bedding Planes	Perpendicular to Face Cleat	Perpendicular to Butt Cleat	Total
Mixed Mode Fracture Toughness Tests				
slow load rate	7	7	7	21
middle load rate	7	7	7	21
fast load rate	7	7	7	21
Tensile Strength Tests	5	5	5	15
Unconfined Compressive Strength Tests	5	5	5	15
Dynamic Moduli Tests	10	10	10	30
Point Load Index Tests	10	10	10	30
Schmidt Hardness Tests	10	10	10	30
NCB Indenter Tests	10	10	10	30

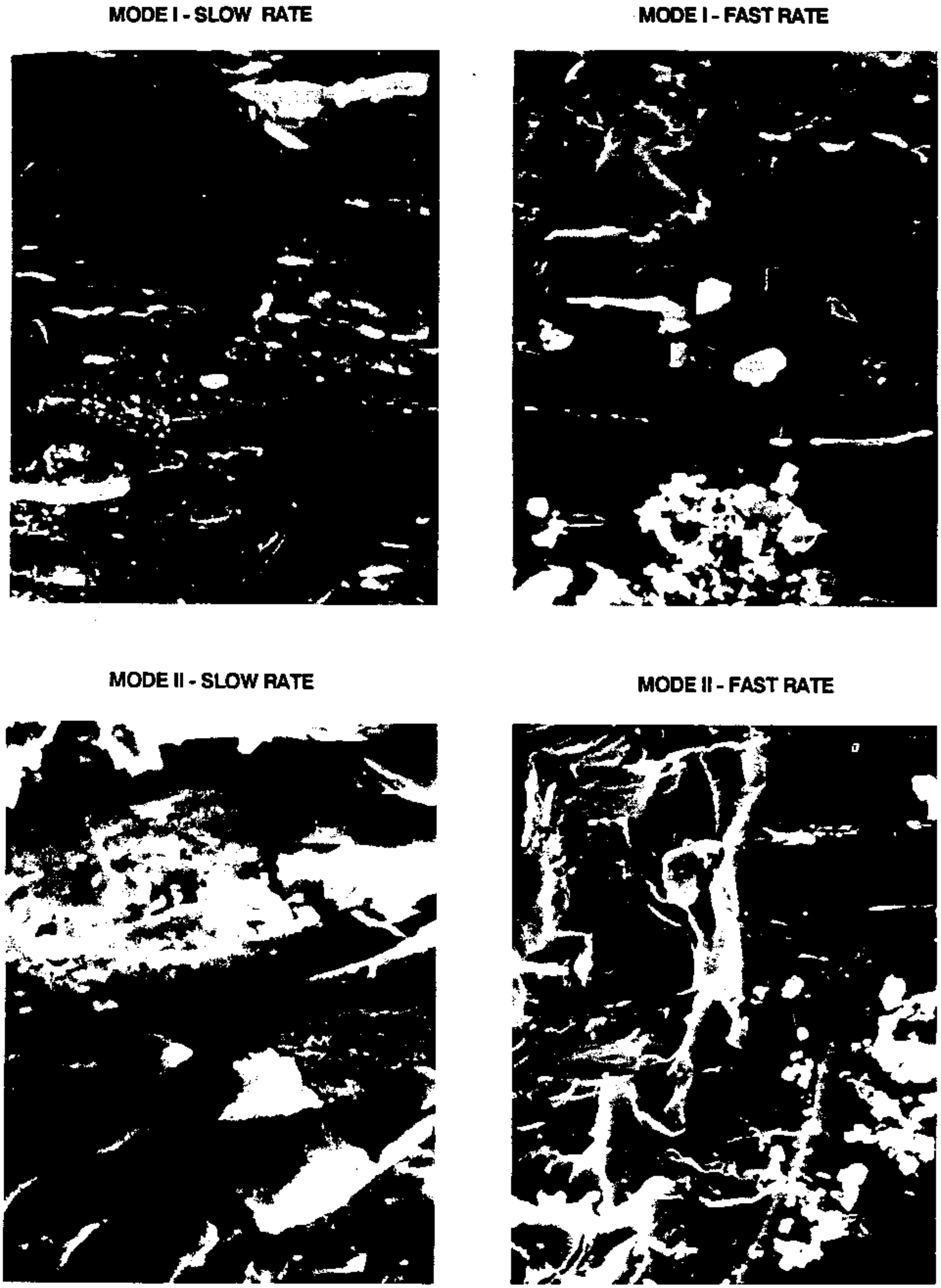


FIGURE 4. SEM micrographs of coal fracture surfaces along the face cleat at 1000x — Scale 0.820 Cm = 10 micros.

loading rates and at different orientations relative to the natural structure of coal.

Successful preparation of these specimens required use of delicate, low energy preparation equipment. The laboratory at Penn State has acquired a horizontal bandsaw, diamond bandsaw, and a belt/disc sander for this purpose. In addition, fresh coal is stored in a chamber at 100 percent relative humidity at all times to prevent drying and shrinkage cracking. Preparation of specimens has been extremely successful. In order to obtain better, more meaningful cross correlations between tests, specimens for a mixed mode test, compressive strength test, tensile strength test, and the other tests are cut from the same lump of raw coal. With the existing preparation equipment, sample preparation has been extremely reliable. It is estimated that it has been possible to successfully prepare fracture toughness test specimens from over 75 percent of the coal lumps collected in the field. This leads to laboratory fracture toughness data that is indeed more representative of the *in situ* coal.

To demonstrate the effect of fracture mode and loading rate on the formation of respirable size fragments on new fracture surfaces, a small number of pre-notched cubes of Pittsburgh coal were fractured by dominantly Mode I or dominantly Mode II loading conditions at both slow and fast loading rates. Fracture was also propagated in various directions either parallel to the bedding planes, the face cleat or the butt cleat. The newly created fracture surfaces are then examined under the scanning electron microscope at 1000X magnification.

Under the SEM, respirable size fragments on the fracture surfaces appear quite readily as lighter areas or white spots. This contrast is due to charging by the electron beam because the particles are detached. Four SEM micrographs are shown in Figure 4 for

1. Mode I cracks under slow loading conditions.
2. Mode I cracks under fast loading conditions.
3. Mode II cracks under slow loading conditions.
4. Mode II cracks under fast loading conditions.

In comparing these images, we make the following observations:

1. The least amount of structural damage and fine fragment formations occurs under slow loading conditions in Mode I.
2. Increasing the loading rate or changing the loading condition from mode I to Mode II can increase the structural damage and fine fragment formation.

Conclusion

A scientific rationale and an approach to investigating the fundamental mechanics of fine fragment formation in coal has been developed. When a crack tip is supplied with excess energy, it responds by dissipating the energy through increased structural damage to the new fracture surface and crack bifurcation which leads to larger amounts of fine fragment formation. Since the coal cutting process is best considered as a mixed mode crack propagation problem, a special mixed mode test rig was constructed to study crack growth in coal under mixed mode loading conditions and to determine its influence on fine fragment formation. A thorough mechanical testing program is well underway to determine fracture toughness and other related mechanical properties for several coals under different fracture mode and loading conditions and at different orientations relative to the natural structure of coal. Preliminary SEM studies show that higher loading rates and different fracture modes induce differences in the amount of structural damage and fine fragment formation on the new fracture surfaces.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142

References

1. **Strebig, K.C. and H.W. Zeller:** *Effect of Depth of Cut and Bit Type on the Generation of Respirable Dust.* USBM RI 8042, 15 pp. (1975).

2. **Roepke, W.W., D.P. Lindroth and T.A. Myren:** *Reduction of Dust and Energy During Coal Cutting Using Point-Attack Bits.* USBM RI 8185, 53 pp. (1976).

3. **Roepke, W.W. and B.D. Hanson:** *Effect of Symmetric Bit Wear and Attack Angle on Airborne Respirable Dust and Energy Consumption.* USBM RI 8395, 24 pp. (1979).

4. **Roepke, W.W. and B.D. Hanson:** *Effect of Asymmetric Wear of Point Attack Bits on Coal-Cutting Parameters and Primary Dust Generation.* USBM RI 8761, 16 pp. (1983).

5. **Roepke, W.W. and B.D. Hanson:** *Testing Modified Coal-Cutting Bit Designs for Reduced Energy, Dust, and Incentivity.* USBM RI 8801, 31 pp. (1983).

6. **Roepke, W.W.:** General Methods of Primary Dust Control During Cutting. *Mining Engineering 26(6)*::636-644 (June 1984).

7. **Cheng, L. and P.P. Zukovich:** *Respirable Dust Adhering to Run-of-Face Bituminous Coals.* USBM RI 7765, 10 pp. (1973).

8. **Cook, N.G.W. et al:** *Measurement and Control of Respirable Dust in Mines,* 405 pp. National Academy of Sciences, Washington, DC (1980).

9. **Pariseau, W.G. and C. Fairhurst:** The Force-Pentration Characteristic for Wedge Penetration into Rock. *Int. J. Rock Mech. Min. Sci. 4*:165-180 (1967).

10. **Stecklein, G., R. Branstetter, R. Arrowood et al:** *Basic Research on Coal Fragmentation and Dust Entrainment.* USBM Contract No. J0215009, 121 pp. South West Research Institute (May 1982).

11. **Saouma, V.E. and M.J. Kleinosky:** Finite Element

Simulation of Rock Cutting; a Fracture Mechanics Approach. 25th U.S. Symposium on Rock Mechanics. Evanston, Illinois. (1984).

12. **Zipf, R.K. and Z.T. Bieniawski:** Mixed Mode Testing for Fracture Toughness of Coal Based on Critical-Energy-Density. *27th U.S. Symposium on Rock Mechanics,* pp. 16-23. Tuscaloosa, Alabama (1986).

13. **Bieniawski, Z.T. and C. Mark:** A Fracture Mechanics Study of Crack Propagation Mechanism in Coal. *First Annual Report,* Grant No. G1135142, 70 p. The Pennsylvania State University (October, 1984).

14. **Ouchterlony, F.:** Review of Fracture Toughness Testing of Rock. *Solid Mechanics Archives* 7:131-211 (1982).

15. **Advani, S.H., Y.T. Lin, F.D. Gmeindl and W.R. Powell:** Coupled Roof Fracture Response and Surface Subsidence Evaluations Elated to Underground Coal Gasification. *Proceedings of the 4th Underground Coal Conversion,* pp. 507-5!4. (1978).

16. **Powell, W.R., S. Khan, D.G. Remsey and F. Gmeindl:** Fracture Mechanics Model for Pittsburgh Coal. *Paper 81-Pet-16.* American Society of Mechanical Engineers, Petroleum Division. (1981).

17. **Bhagat, R.M.:** *Fracture Toughness of Coal: Variability Between Seams and Correlation with its Grindability and Chemical Characteristics.* M.S. Thesis, 55 pp. West Virginia University (1981).

18. **Szendi-Horvath, G.:** On the Fracture Toughness of Coal. Australian *J. Coal Mining and Technology and Research* 2:51-57 (1982).

19. **Bassim, M.N. and T.R. Hsu:** Fracture Behavior of Coal. *Fifth Canadian Fracture Conference,* pp. 239-247. Winnipeg, Pergamon Press (1982).

20. **Klepaczko, J.R., M.N. Bassim and T.R. Hsu:** Fracture Toughness of Coal Under Quasi-Static and Impact Loading. *Eng. Fracture Mechanics 19(2):*305-316 (1984).

Correlation of Fragment Size Distribution and Fracture Surface in Coal Cutting Under Various Conditions

A. WAHAB KHAIR and W.M. DEVILDER

Department of Mining Engineering, West Virginia University, Morgantown

This paper presents an analysis of fragment size distribution and characterstics of fracture surface in coal cutting using a rotary coal cutting simulator. Coal cutting by a drum type continuous miner was simulated in the laboratory. A series of tests along both the face and butt cleat direction of coal under different operating and *in-situ* conditions were performed. In each experiment the cut surface was photographed microscopically and the coal cuttings were collected and sized. Data were used to show how and to what extent various parameters effect size distribution of the coal cutting and how this correlates with the characteristics of the fracture surface. This study resulted in establishing a number of distinct correlations between the size distribution and fracture surface. These correlations were primarily based on the degree of interaction between adjacent bits and the amount of bit-coal interaction taking place on the cutting path. Some of the major results of this study are as follows.

Zones of bit-coal interactions proved vital toward understanding the effect the conical bit has on the fragmentation process. This in turn led to the identification of areas which are responsible for the production of fines and generation of respirable dust.

The various parameters employed in the coal cutting experiments which showed a strong effect on the coal fragment size distribution were: bit type, bit spacing, depth of cut, *in-situ* stresses, and cleat orientation. Bit angles and cutting head velocity exhibited the least effect and no correlation was established.

From this study it is obvious that the key to achieving efficient coal fragmentation is to limit the degree of bit-coal interaction that takes place throughout the bit path while causing maximum interaction between adjacent bits. Accomplishing this not only increases the percentage of large fragments produced but limits the amount of secondary crushing that takes place in the bit path thus resulting in decreasing fines and consequently, the amount of respirable dust generated.

Introduction

Over 2000 continuous mining machines (introduced in the 1950s) equipped with conical bits or point attach bits account for well over half of the United States' production from underground coal mines. Today, competition in the coal industry has increased, due mainly to coal market conditions and legal restrictions, thus placing an emphasis upon increasing production, efficiency and health/safety of the workers. Mine operators are always interested in finding the most efficient performance of continuous mining machinery to produce the largest amount of size of coal at the lowest cost. An increase of fine material sent to the cleaning plant can seriously overload the plant to the extent that plant efficiencies deteriorate significantly.[1] Also, the difficulty and expense of cleaning very small particles often cannot be done economically and thus, thousands of tons of coal are sent to the refuse pile because of costly or ineffective cleaning facilities. It has been said "the efficient extraction of coal or rock implies breakage into a size range that contains a minimum quantity of very small sizes."[2] All known fragmentation theories concur that more fragmentation requires more energy.[3] So, the importance of reducing fines is already evident from an outlook upon efficiency. Now, let's consider another viewpoint, dust generation.

The Federal Coal Mine Health and Safety Act of 1969, with revisions in 1977, was enacted to insure more healthful and safer working conditions for miners. The Act of 1969 established initially the respirable dust standard for coal mining operation as 3.0 mg/m^3. The 1969 Act further reduced this standard to 2.0 mg/m^3 in 1973. The impact of respirable dust on miners health and economy of the coal industry is obvious. Since 1970 the federal government has paid over $11.7 billion to more than 470,000 miners with black lung diseases and their survivors.[4] Also, the coal mining industry considers respirable dust to be the greatest obstacle to achieving the full-production potential of current mining equipment. The following was stated: "it has been concluded that the amount of dust produced is approximately in proportion to the degree of fragmentation and to reduce the production of respirable dust, the fragmentation process must be better understood."[5] Accordingly, it is most important to develop extraction technology that reduces the production and release of particles in the small size, even though only a small fraction of the fine particles produced by coal cutting become airborne. By better understanding the coal fragmentation process and how various parameters effect this process, it may be possible to reduce unwanted fines and respirable dust generation. This may be accomplished by shifting the size distribution to a higher percentage of larger fragments, thus reducing the percentage of fines. If the top sizes of coal are low, it is generally true that the portion of extremely small sizes is correspondingly high.[2] By reducing the amount of fines, this will tend to shift the size distribution, improving cutting efficiency, thus reducing bit and machine related costs and those associated with handling, and cleaning those unwanted fines. This will also aid in decreasing the amount of respirable dust generated

Considerable effort has been expended in the last 30 years on laboratory experiments and in the mine investigations of the cutting process applied to coal and rock cutting machines. Most of the early work by many authors has been summarized by Rad and provides a good reference.[6] From these studies, inconsistencies and discrepancies were revealed. Some of the most basic studies done try to understand the fracturing process involved in indentation of a rigid wedge or bit into a brittle material.[7-10] With the continuing development of more sophisticated mining equipment, the need to understand the fragmentation process was becoming more important. This led to the undertaking of many more research projects to evaluate the effect of operating, *in situ* and geologic parameters on the cutting process in hopes of aiding in the design of more efficient mining machinery, reducing dust generation and improving the overall fragmentation process.

There are three basic types of research which have been done to evaluate the effects of various parameters in coal cutting. The three types are: 1) linear cutting in the laboratory using single or multiple bits; 2) rotary laboratory or in the mine cutting using single or multiple bits; and 3) in the mine tests on actual production equipment. Investigators for the U.S. Bureau of Mines have done and are currently doing extensive work in all three areas. In the Bureau of Mines Research Plan for Coal Mine Health and Safety during fiscal years 1979-1983, the most important study area was fragmentation.[5] A detailed review of the above three types of research and the work done prior to 1980 is given some place else,[11] due to relevant interest of this paper emphasis will be on rotary type coal cutting.

Recent review of research on the measurement and control of respirable dust prior to 1980 concluded the following:[5] "It has long been recognized that deep cutting coal mining machines produce larger fragments and less respirable coal mine dust than do machines that take only shallow cuts. Apart from this general observation, however, significantly diverse experience exists on the effects of cutting speed and cutting-pick or bit design. This situation is clear evidence that the mechanics of fragmentation are not understood adequately. It has been concluded that those disparities reflect the incomplete nature of many experiments. It has been also concluded that such questions and similar questions related to cutting speed, pick design, and other cutting parameters as well as dust generation, can only be answered by cutting experiment in which more attention is give to the actual process of fragmentation." No tests were available that completely evaluated the point-attack bit so broadly accepted by the U.S. mining industry; in fact most published cutting research has been done using chisel-type tools. Most of the past work with rotary cutting machines was done in the area of rock cutting.[12] However, to better understand the process of rotary cutting and the factors that effect the fragmentation of coal and dust generation process a unique rotary coal cutting simulator was designed and developed at West Virginia University.[13] Correlation of the fragment size distribution and characteristics of fracture surface in coal cutting under various parameters is a part of the research program entitled "An Experimental and Analytical Approach to Study the Mechanisms of Respirable Dust Generation and Entrainment in Underground Coal Mining" sponsored by the U.S. Bureau of Mines through the Generic Center for Respirable Dust to be presented here. It is believed that a major source of respirable dust is the intensely crushed material produced at the tip of the cutting tool.[5,14] Therefore this paper emphasizes microscopic analysis. Using microscopic photographs to better analyze the area of bit-coal interaction (bit path analysis) for better understanding the effect of the conical bit on the coal fragmentation process in relation to areas that contribute to the production of fines and generation of dust.

Background

A continuous mining machine removes coal from the seam by a fracturing process consisting of forcing a conical bit into the coal face. In the removal of coal and rock from the face, tensile and/or shear failure is induced by the cutting machine, through the compressive action of the bit as it is forced into the coal. This compressive stress, which is transmitted primarily through the carbide tip, produces a high degree of crushing or pulverizing of the material at the bit tip which leads to the generation of a very fine dust. This compressive stress initiates fracture propagation into an area where the combination of tensile or shear stress fields and existing cracks creates the most favorable conditions for fracturing; thus failure of the material results and a chip or fragment is produced. As the strength of the coal or rock increases, so does the compressive stress required to initiate failure; the fragments are released more explosively from the face, causing greater dispersion of the crushed material and hence higher entrainment.[3,5,6,14,15]

The major portion of the primary dust generated occurs in the crushed zone around the tip of the tool. This portion of primary dust generation does not vary with depth, but does vary with bit geometry.[16] The total dust will increase with the depth of cut, but the increase is small compared to that produced in the crushed zone and will vary as the fracture length to the free surface varies.[17] However, under deeper cut more material is broken per bit and the amount of dust produced becomes a smaller proportion of the total produce removed.[18] Investigators are in complete agreement with the fact that the amount of fines and airborne dust is directly proportional to the amount of specific energy used in cutting the coal.[2,19-22] Increasing the depth of the cut reduces the specific energy used to fragment the coal. If the broken coal is not cleared from the cutting element, the material will become subjected to secondary degradiation by the bit in the bit path. Also, if insufficient interaction occurs between adjacent bits the coal boundary between them may be left intact. If this occurs excessive crushing and grinding action will be present between the bit body and the coal surface causing dust generation and entrainment. It is very important to break the coal boundary and remove the chips bounded before energy is wasted grinding and regrinding the chips, fragments and the sides of the bit path.[3,5,14,21,23] By increasing the depth of cut the spacing can be increased and still maintain breakage of the coal boundary. The optimum spacing to depth of cut ratio falls in the range of 0.5 to 0.3.[2,3,21,24]

The crescent-shaped cutting action is a significant part of the dust problem. When the top cutters start to recover coal, all the broken coal must be transported through the remaining arc of the drum. The transport of already recovered coal through the cutting zone of the rotary head makes it also a rotary grinder. The potential effect on dust generation by this secondary grinding may be at least as much as that produced by primary fragmentation.[17]

Any time fractures through the coal dust is produced. However, the amount of dust which is produced along fracture lines is very small as compared to that generated by the cutting tool. By breaking off larger fragments this will reduce the total surface area produced and thus the dust created along fracture lines.[3,21]

Another area where dust is generated during the cutting process is that of crushing action by the drum and bit blocks. This regrinding or rubbing action can arise from several sources. First, if the cut material is not removed from this area it may be forced into the cutting head causing regrinding of the material. Another cause is if the coal is not broken between bit paths the bit blocks may come into contact with the solid coal generating dust. Any time the coal is not removed from the cutting area there will be excessive fragmentation in one form or another in this area. Due to the motion of cutter head, dust is more likely to become airborne.[14,21,25]

Experimental Program

The overall objectives of this research program are to study the mechanisms of respirable dust generation and entrainment in underground coal cutting by continuous miner and how these mechanisms will be affected by important factors such as operating parameters, coal properties and *in-situ* stresses. However, this paper deals with the analysis associated with bit-coal interaction and coal cutting size distribution as affected by the above mentioned factors. Therefore, a number of monitoring facilities and experimental procedures will be described here which may not be directly related or essential to carry out the segment of research which is the subject of this paper.

Laboratory Facilities

A thorough discussion of coal cutting and monitoring facilities used in the current studies is given elsewhere.[13,26] Therefore, only a brief outline of the facilities will be discussed here.

The main component of the testing facilities is an automated rotary coal cutting simulator (ARCCS) as shown in Figure 1. The ARCCS was designed with the capability to study the different machine and *in situ* parameters that influence the fragmentation of coal and the resulting dust generation. The ARCCS operates under simulated mining conditions with equivalent *in situ* horizontal and vertical stresses applied to a coal block of 18 in. x 15 in. x 6 in. (45.7 cm x 38.1 cm x 15.2 cm) located in a specifically designed confining chamber (Figure 1a). The cutting drum (8 inches in diameter and 12 inches wide) has the capability of rotating from 1 to 50 rpm and can be stopped after a predetermined number of revolutions or a certain depth of cut. The

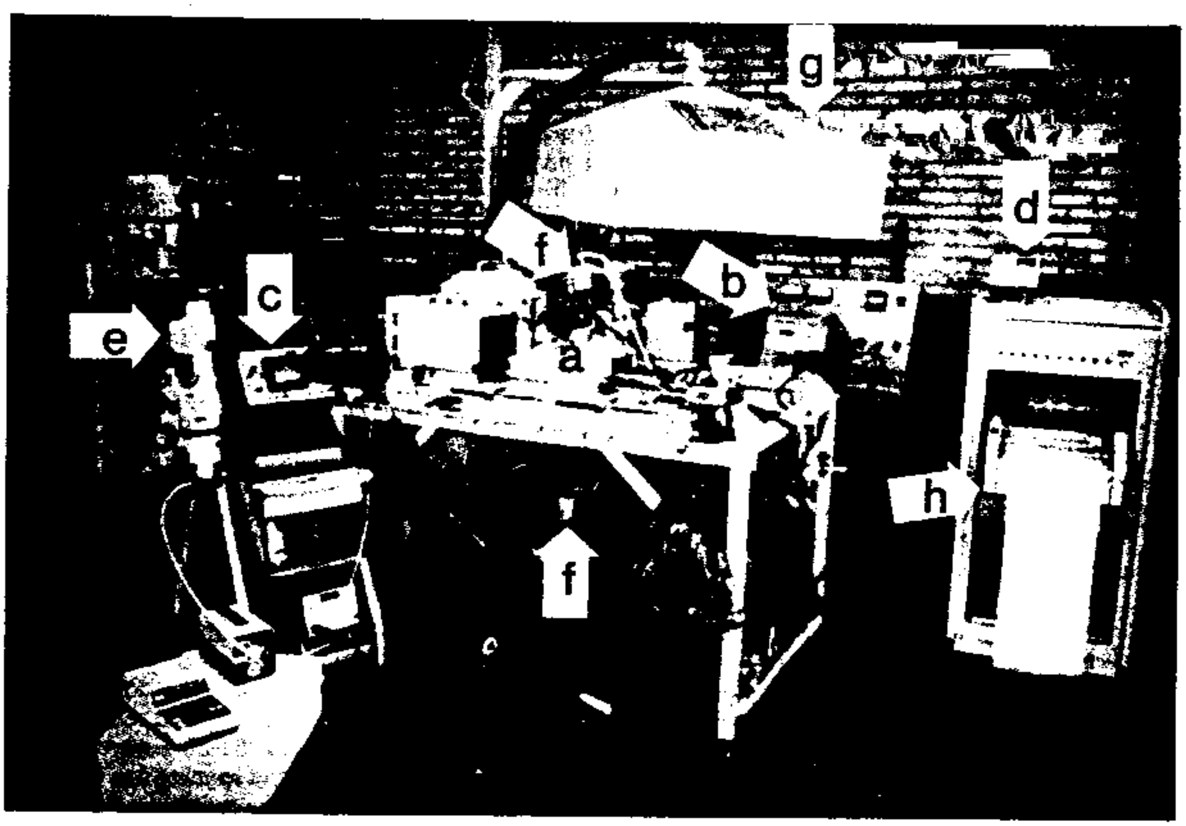


FIGURE 1. Test and monitoring equipment facilities (a) automated rotary coal cutting simulator, (b) programmable control and monitoring unit, (c) sonic testing unit, (d) acoustic emission, (e) microscope and the attached camera unit, (f) cascade impactors, (g) hood and air current generating unit and (h) data acquisition and recording unit.

bits can be mounted on the drum at four different angles 15, 30, 45, and 60 degrees and spacings of 1.5 in. (3.81 cm) to 3 in. (7.62 cm). A maximum of seven bits can be mounted on the drum in a echelon pattern. The ARCCS can be controlled manually or automatically through the use of a programmable control unit (Figure 1b). Figure 1 also shows some of the testing and monitoring facilities used in this research. They are sonic testing unit (Figure 1c) to measure fracture extension, acoustic emission (A.E.) monitoring unit (Figure 1d) to measure fracture propagation and fracturing characteristics, microscope and attached camera unit (Figure 1e) for analysis of fractured surface, 6-stage cascade impactors (Figure 1f) for collecting airborne dust, hood and air generating unit (Figure 1g), and data acquisition and recording unit (Figure 1h). In addition to this, linear variable differential transformers (LVDTs), pressure transducers, flow meters, flow controls and drum rpm indicator were some of the other monitoring devices. LVDTs were used to monitor the displacement of the coal block as well as the depth of cut. Pressure transducers were used to monitor the changes in pressure both due to the thrust and due to the intermittent cutting nature of the rotary cutting. Flow controls were used to run the drum at a particular rpm and to provide a specific rate of advance. U.S. sieve series/ASTM specification E-11-61 was used in conjunction with the Ro-Tap Testing sieve shaker to size the fragments (settled) from 0.742 in. (1.885 cm) to –0.0015 in. (–0.0038 cm) or –400 mesh (–37 microns). Allen Bradley Sonic Sifter, model L3P, Series A was used to size the product from 37 microns to –10 microns.

Experimental Procedure

Large blocks of coal were obtained from a surface mine in the Waynesburg coal seam. The coal blocks were then cut in the laboratory to an approximate dimension of 16 in. x 13 in. x 6 in. (40.0 cm x 33.0 cm x 15.2 cm) with respect to the intended cutting direction (i.e., against face or butt cleat). The specimen was molded into plaster of paris mixture to a perfect dimension of 18 in. x 15 in. x 6 in (45.7 cm x 35.6 cm x 15.2 cm) which was essential to avoid stress concentrations in the specimen when confining pressures were applied. The molded specimens were allowed to dry a week before testing. The molded specimen was placed in the confining chamber, the test conditions were set, and the *in situ* and operating parameters were marked on the mold at the top of the specimen. Using the following nomenclature: #41-test number, III-bit type, 7-number of bits, 30-bit attack angle, 1.5-bit spacing (inches), 1/32-depth of cut per revolution (inches), 25-cutting head velocity (rpm), F-face cleat (B-butt cleat), S_v and S_h – equivalent vertical and horizontal *in situ* stresses (confining pressures). Note if Sv and Sh are not specified, the confining pressures are negligible. A sonic test was done by which the stress wave travel time through the coal sample was recorded. Then predetermined confining pressures (equivalent *in situ* stresses) were applied to the coal block. Some of the tests were done without any significant confining pressures; however, a small amount of pressures were used to keep the specimen in the confining chamber. The confining pressures were applied through the use of two sets of hydraulic jacks consisting of two jacks in a set (one set for horizontal pressure and one set for vertical pressure) each connected in parallel to a hand pump. A 1.0 inch (2.54 cm) thick steel plate was positioned between the sample and hydraulic jacks in order to distribute the pressure uniformly over the whole surface of the specimen. Before the test, the operating parameters such as velocity of the cutting drum and advance rate were adjusted to predetermined values. Then bit blocks of specific attack angle were mounted at a particular spacing and pattern. Conical bits of a specific make were inserted into the bit block and kept in position by a screw in a way as to allow symmetric bit wear. An acoustic emission transducer was mounted on top of the specimen on the mold. Then a canvas was hooked to the main frame of the machine and a plastic sheet was spread on it to collect the coal fragments after each experiment. Six-stage cascade impactors were prepared (according to the instruction manual provided by Andersen Samplers, Inc.). A set of four impactors were then mounted on the specially designed arms at fixed positions with respect to the rotating drum. The number of rotations by the cutting head was set in the counter unit in the control module and then the machine was started to execute the program in continuous or counter mode. The counting of the number of rotations started when the hydraulic pressure was increased, due to the cutting process, or when the cutting head traveled to a preset distance measured mechanically and by the LVDT. After the executive of the predetermined number of rotations, the cutting head retreated and stopped. After each experiment the canvas was unhooked and the coal fragments were collected in the Ziploc bags and the vacuum bag with the help of a vacuum cleaner. This product was sieved into different sizes. A standard square root of 2 series was used from 0.742 in. (1.885 cm) to 0.187 in (0.475 cm), then the screens were used alternativey, meaning that the previous screen size was divided by square root of 2 to get the net size. From 0.187 in. (0.475 cm) to 0.0029 in. (0.0074 cm) every other sieve size was used or a ratio of 2 between screen sizes. The –0.0029 in. (–0.0074 cm) sizes were screened with the square root of 2 series again. This method of screening was used to reduce the number of screens, thus reducing the amount of fines lost in the 0.187 in. (0.475 cm) to 0.0029 in. (0.0074 cm) range. This method also distributes irregularities at both ends of the size range. After the screening was completed, the material retained on each screen size was weighed. Then the percent of weight retained on each screen was plotted on three cycle, semi-log graph paper at

TABLE I

Physical Properties of Waynesburg Coal

Properties		
Moisture (%)	–	0.0 – 1.5
Ash (%)	–	13.5 – 13..7
Sulfur (%)	–	2.03 – 2.06
Rank	–	hbBv*
HGI**	–	50.43
Specific gravity	–	1.42

* High Volatile B Bituminous

** Hardgrove Grindability

TABLE II

Mechanical Properties of Waynesburg Coal

Cleat/Bedding Plane Orientation	Compressive Strength psi (kPa)	Young's Modulus psi (kPa)	Poisson's Ratio	Indirect Tensile Strength psi (kPa)	Direct Shear Strength psi (kPa)
Face Cleat	3289 (473.6)	5.1×10^5 (7.3×10^4)	0.25	154 (22.2)	204 (29.4)
Butt Cleat	3459 (489.1)	4.7×10^5 (6.8×10^4)	0.31	205 (29.5)	180 (25.9)
Bedding Plane	4912 (707.4)	4.6×10^5 (6.6×10^4)	0.32	146 (21.0)	180 (11.5)

the corresponding opening size. In general, there are two dips that appear in the size distribution curve that are due to the transition from screens in the square root of 2 series to those of the 2 series and back. The dips occur because the screens that start the change in a series receives more material than it would have in a straight series. The bump occurring at the 0.0015 in. (0.0038 cm) or 400 mesh size is natural and is characteristic of the material and not related to screening. The sizing from 400 mesh (37 microns) to –10 microns was done by the sonic sifter. All the sized products were then weighted up to 0.1 gm by Sartorius Type 2351, mechanical balance with analog readout and the percent weights retained were then calculated.

Following the completion of the tests, the tested coal block was removed from the confining chamber. It was photographed using a Nikon 35 mm camera and auxiliary lights to give overall pictures of the fractured surface of each test specimen. The bit paths were then photographed using a camera attached to an optical microscope. The pictures were taken of the center bit path approximately 1 inch from the bit entry, middle of the coal block, and 1 inch from the bit exit. In general, these pictures were taken using 0.66 and 1.5 zoom settings, given a total magnification of 3.5 and 8 times, respectively. In some instances more detailed pictures of the bit path and the particles trapped in this area where taken in order to understand what happens in the zone of bit-coal interaction. These pictures were used to help categorize and correlate the fracture surface characteristics with the size distribution and other parameters involved in the coal cutting process.

Results and Discussion

Most of the coal used in this study is part of the Waynesburg coal seam. Presently, only limited tests have been completed on the Pittsburgh coal seam. The physical and mechanical properties of the Waynesburg coal were determined in the laboratory and are presented in Tables I and II. However, the properties of the Pittsburgh coal seam are not available at the present time. There have been a total of 43 individual tests completed and detailed analysis has been presented elsewhere.[11] However, only brief analysis of the results will be discussed here. It should be noted that due to the extended scope of the study and involvement of a large number of parameters/factors a limited number of tests have been documented under a specific set of parameters. Therefore, if the results may not be clear it is probably due to the inhomogeneous nature of the coal. To compare the size distribution results of different tests, it is first necessary to define the size limits used in this study. Two types of particle analysis were made. The first type includes the settled particles and the second type is airborne particles. In the first type, large fragments are defined as fragments greater than 0.0937 in. (0.238 cm), fine fragments between 0.0937 in. (0.238 cm) and 0.0015 in. (0.0038 cm) or 400 mesh, and dust

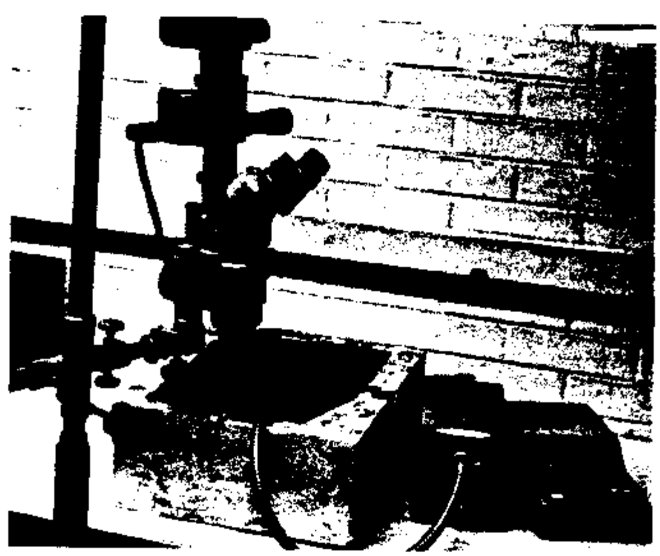


FIGURE 2. Illustrates facilities used in microscopic photography of the fractured surface of the tested specimen.

is defined as the material below 0.015 in (0.038 cm). In the second type particle size distributions were made based on the standard sizes associated with cascade impactor.

This paper deals with the analysis of the appearance of fracture surface after a test has been completed. An optical microscope was used (Figure 2) to investigate the area of the bit path and to determine what happens in the area of contact between the bit and coal from the resulting traces left on the fracture surface by the bit. The four different types of conical or point attack bits used in this study are shown in Figure 3a. The corresponding manufacturer's specifications giving bit dimensions and angle of carbide tip (degree of sharpness) are shown in Figure 3b. The bit types are known as: pencil bit with medium carbide tip, Type II; plumbob with large carbide tip, Type III; sharp/slender bit with fins to aid in bit rotation and sharp carbide tip, Type IV; plumbob bit with medium carbide tip, Type V. Tests conducted to evaluate the effects of bit spacing, depth of cut, bit angle, drum velocity confining pressure, and face/butt cleat direction of cutting were all done using the Type IV bits.

Bit Path Analysis

In analysis of zone of bit-coal interaction, it was found that there are two extreme cases. Test #10 and Test #41 are typical tests that represent Case 1 and Case 2, respectively shown in Figure 4. In Case 1 fracture surface shows only interaction of the carbide tip and the coal surface as evident by a shiny line in the center of the bit path. However, the Case 2 fracture surface involves not only interaction of the carbide tip but also that of part of the bit body and the coal surface. The zone of interaction of the carbide tip and coal surface was formed to have the same general characteristics in all tests, although, the size and shape were found to vary with bit type.

To characterize interaction of bit-coal, it is necessary to define the zones of the bit which correspond to distinct zones in the bit path. Figure 5 illustrates three distinct Zones 1,2, and 3, which correspond to the carbide tip, transition between the carbide tip and the bit body (appears as an offset or gap), and the bit body, respectively. The corresponding zones in the center of the bit path are indicated in Figure 6

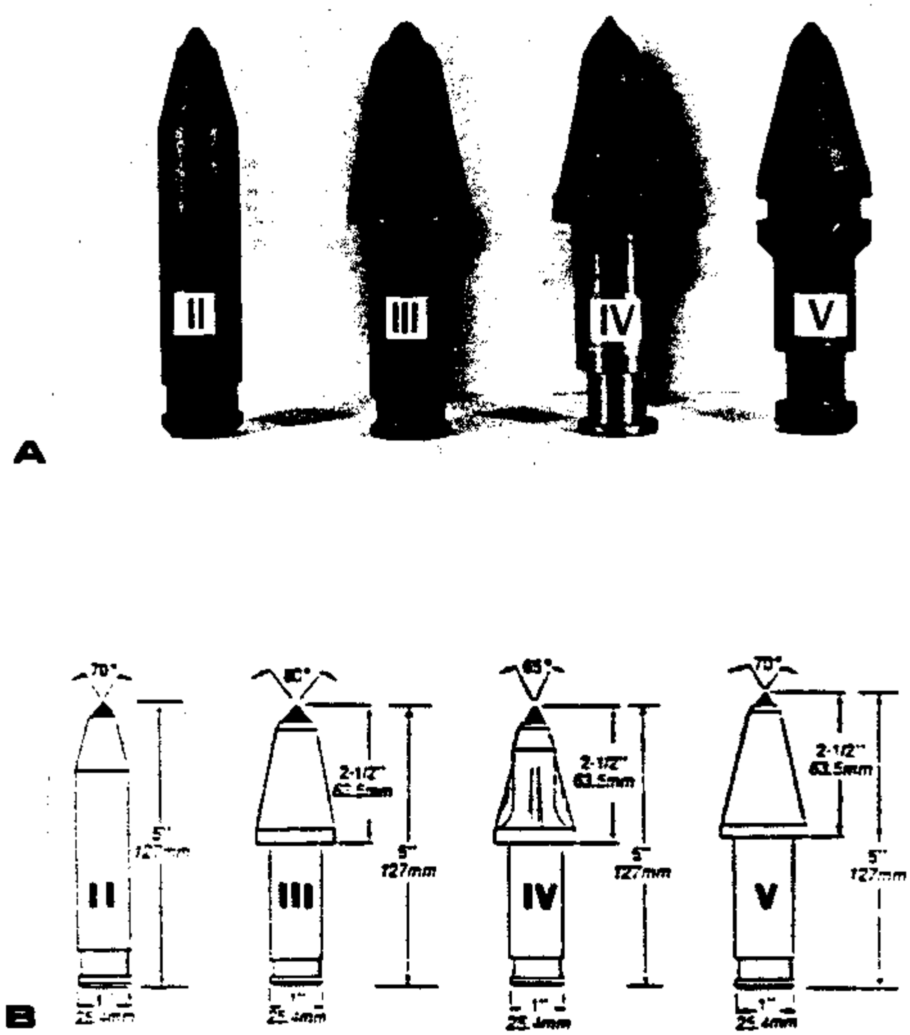


FIGURE 3. Illustrates four types of bits: (a) Type II, pencil bit with medium carbide tip; Type III, plumbob bit with large carbide tip; Type IV, sharp/slender bit with fins and sharp carbide tip; Type V, plumbob bit with medium carbide tip. (b) corresponding manufacturers' specifications showing bit dimensions and angle of carbide tip.

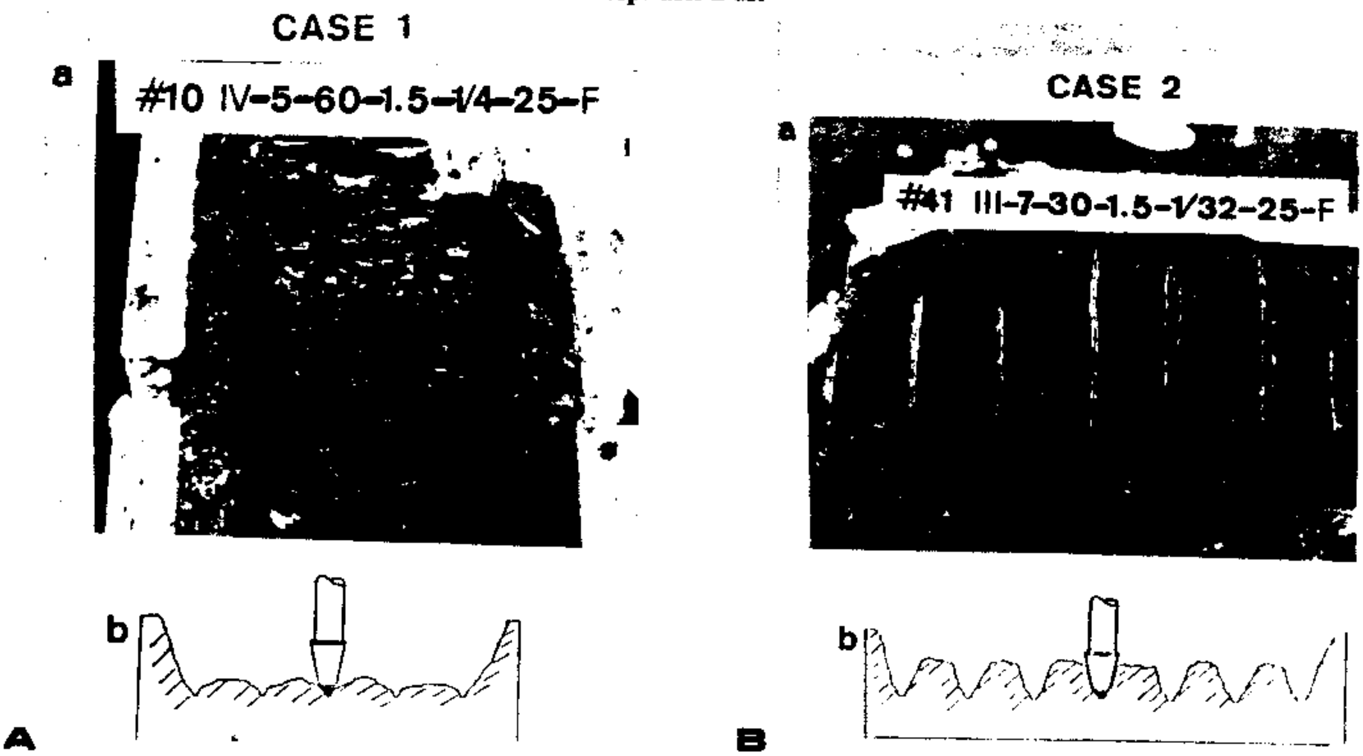


FIGURE 4. Illustrates two types of fractured surfaces: A — Case 1, B — Case 2 (a — photographs of typical test representing each case, b — general cross-section corresponding to each case).

while for the top (one inch from the bit entry) in the same bit path are shown in Figure 7. Within these three zones, there are three notable microscopic fractures (denoted by A, B, and C). Feature (A) representing the shiny or black areas, Feature (B) the light brown areas, and Feature (C) areas of solid intact coal which have not been scared by bit action. Feature (A) is formed as the bit passes through the bit path causing excessive crushing or grinding of loose and/or intact material between the bit and the solid coal surface along the bit path. Frictional heat generated by the abrasive action between the bit (body and carbide tip) and coal surface tend to liquify part of the crushed material causing it to fuse together leaving a shiny almost metallic looking surface with small microscopic ridges on its surface (Figure 8a). These ridges ran parallel to the direction of the bit travel. This shiny surface tended to break in a platy fashion. Along the breakage, small dust size particles of irregular shape were produced. Further, breakage of the platy particles resulted in a production of very fine dust size particles thus giving the area shown in Figure 8b. Further analysis indicated that beneath this shiny surface at Zone 1 a pocket of crushed material was trapped. The size, shape and depth of this pocket varied with the size/shape of the carbide tip with typical depth of approximately between 1/64 and 1/16 of an inch. It was noticed that the shiny surface and associated crushed material appeared to be charged (or became active by a chemical of electro static means) because it was attracted to the metal tool and any other metallic object (knife, tweezer). Crushing of these materials resulted in very small dust size particles of irregular shape which were attracted to each other and grouped in small clusters, agglomerated (see center of Figure 8b). It should be noted that the material in Figure 8b is from the side of the bit path and appears similar and exhibits the same characteristics of that in the center of the path (Figure 8a). However, in general the shiny material on the sides of the bit path did not have quite as much crushed material beneath it. Speaking in relative terms, this suggests that more crushed material was produced by the carbide tip as opposed to the bit body. This can primarily be attributed to the high compressive stresses imposed ject (knife, tweezer). Crushing of these materials resulted in very small dust smaterial is slightly compacted and deposited (Figure 7b). Note the large platy particles are from the black areas and the finer particles are from the brown areas. The intermittent shiny and dark areas (Feature (C)) represent freshly exposed intact coal.

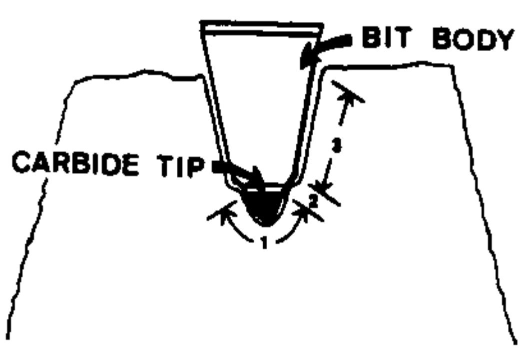


FIGURE 5. Shows the three zones of the bit which correspond to three distinct zones of the bit path.

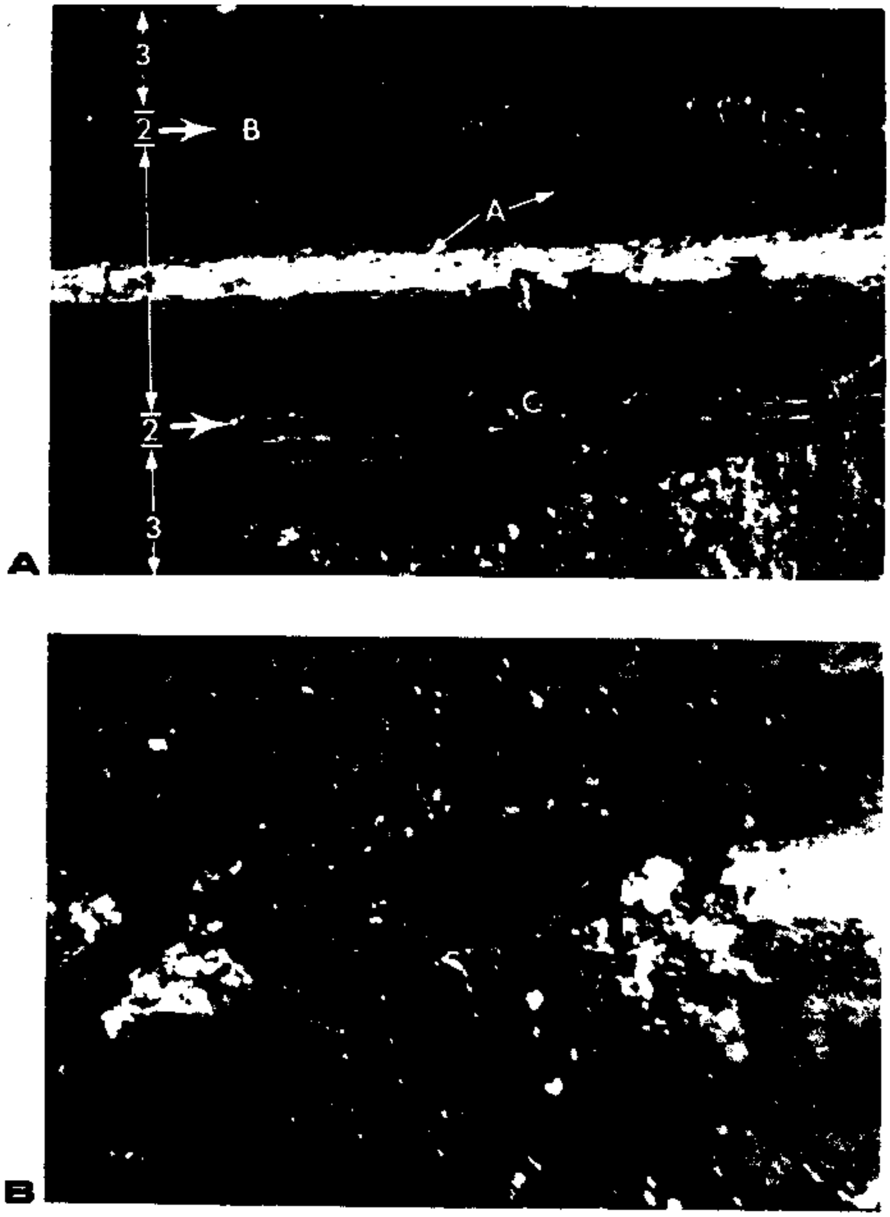


FIGURE 6. Microscopic pictures of the center bit path taken in the middle of the coal block (test #41). (a) Indicates the three zones of the bit path (1,2,3) and the three features within these zones (A,B,C) taken with a .66 zoom setting; (b) shows the same material created upon disturbing the shiny surface taken with a 1.5 zoom setting.

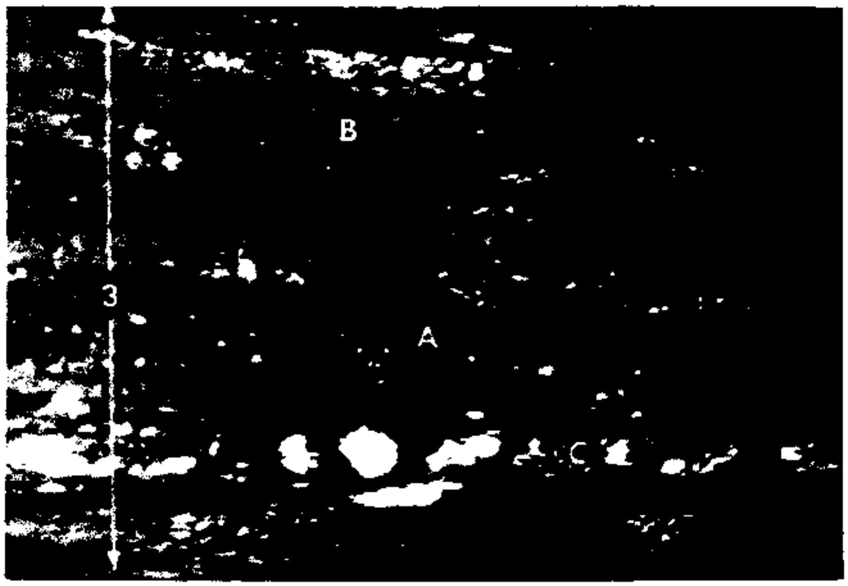
Any or all of these features may be presented in any one zone. However, Zone 1 mainly consisted of a shiny or black surface that was produced from frictional contact with the carbide tip, also some brown deposits of crushed material may be present. Zone 2 consisted of freshly exposed intact coal and brown deposits of crushed material depending on the gap (offset) between the bit body and carbide tip. In general, the larger the gap (Zone 2) resulted in a clean fracture with little or no crushed material. Zone 3 consisted generally of all these features. The extent of each zone was largely dependent upon the degree of fracturing and the amount of frictional contact between the bit and solid coal. The particles deposited in the brown areas appear much larger than those produced by breakage of the black or shiny areas.

Effect of Bit Type

A series of tests were conducted, using seven bits mounted in an echelon pattern, to evaluate the effects of the four bit types. The test parameters used were: 30 degree attack angle, 1.5 inches bit spacing, 1/32 inches depth of cut per revolution, 25 rpm drum velocity, negligible confining pressure and cutting was made along the face cleat. Observation of the fracture surface indicated that all four tests were representative of Case 2. That is, there were traces left on the fractured surface by all three zones of the bit. The height of the coal boundary left between the bit path fell in the range of 0.75 to 1 inch for the specimen which were cut using bit Type III, V, and II and 1 to 1.5 inches using bit Type IV. In general, bit type seems to have no significant effect on the degree of breakage of the boundary between the bit paths. Although it was observed that for each bit type fracturing may initiate at different points in the bit path breaking material away from the bit as it proceeds through the coal. This tends to widen the groove but has little effect on the overall breakage of the coal boundary.

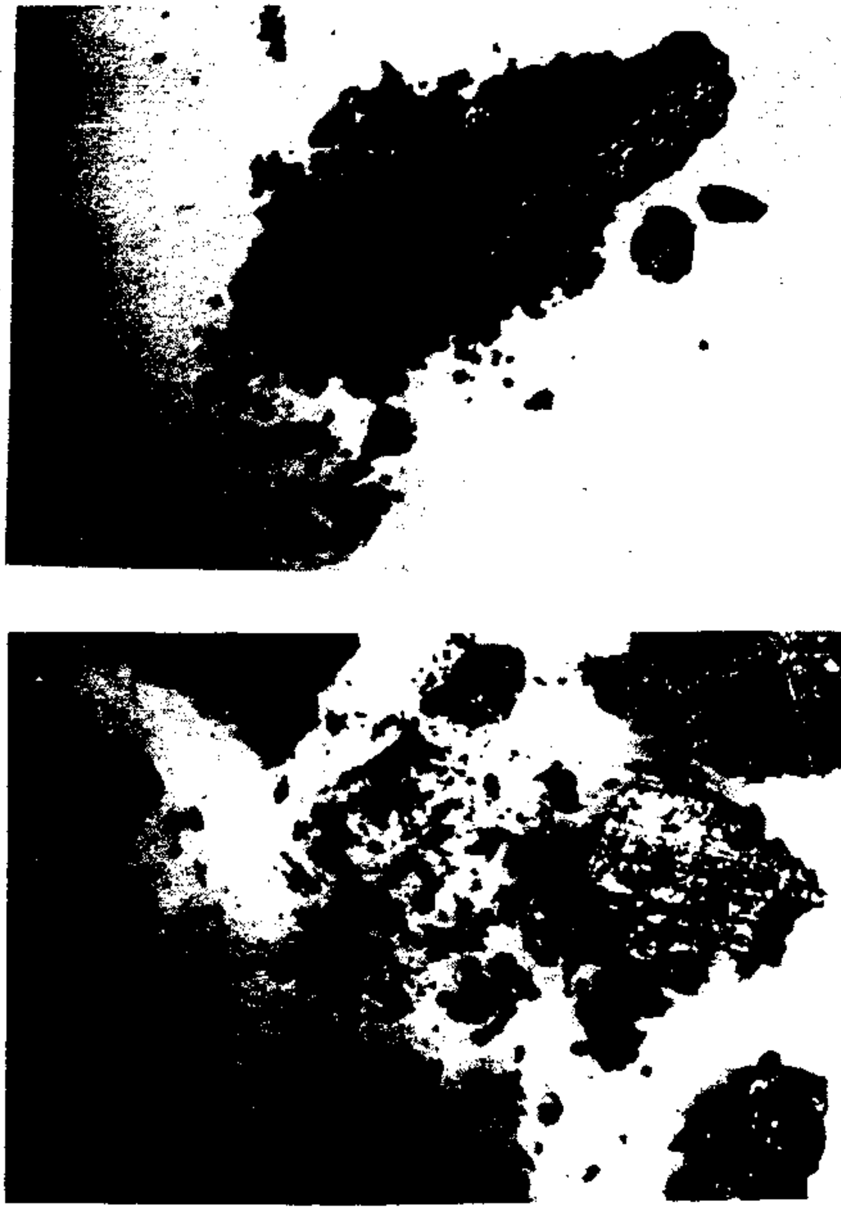
Figure 9 shows the corresponding microscopic photographs of the specimen using the above four types of bit. It is obvious that Zone 1 is the largest using Type III bit with the large carbide tip (Figure 9a). Zone 1 is virtually the same size using Type V and Type II bits with a medium carbide tip, shown in Figures 9b and 9c, respectively. The smallest of Zone 1 was produced using bit Type IV with sharp carbide tip (Figure 9d). The relative size and shape of the pocket of crushed material using different types of bit is illustrated in Figure 10. The depth of the crushed material shown in Figure 10 varied from approximately 1/64 to 1/16 of an inch. The intermittent brown areas in Zone 1 in essence did not change the general shape of the pocket of crushed material but where these areas occurred, the pocket was slightly deeper than indicated in Figure 10. The Type III bit by far trapped the most crushed material, due to the bluntness of the carbide tip. This material was of uniform thickness throughout Zone I tapering off at the edges. Type IV bit trapped the least material because of the sharpness of the carbide tip. The trapped material was very shallow throughout Zone 1, whereas, Type V and Type II bits fell somewhere in between, trapping most of the crushed material at the edge of Zone 1 (due to offset of carbide tip and bit body). There was little material trapped directly under the carbide tip. Zone 2 is by far the largest for the Type II bit because of the large offset between the bit body and carbide tip. This offset provided a relief for fractures to propagate from Zone 1 to Zone 3, leaving a freshly exposed ridge of intact coal which was not scarred by bit action (Figure 9c), whereas, Zone 2 for Types V and IV bits ap-

A



B

FIGURE 7. Microscopic pictures of Zone 3. (a) Indicates the three features (A,B,C) in Zone 3 taken with a .66 zoom setting; (b) shows Zone 3 after lightly brushing the surface.



A

B

FIGURE 8. Microscopic pictures of the shiny surface and related material. (a) Typical piece of material removed from the area of contact with the carbide tip (Zone 1) and resulting pocket of crushed material beneath it; (b) typical piece of material removed from the side of the bit path (Zone 3) note the clustering of the very fine material, magnified 11 times.

peared as small thin ridges of exposed coal with intermittent dust pockets, brown areas (Figures 9b and 9d). The transition between the bit body and carbide tip is gradual compared to Type II (small gap) leaving a small ridge across Zone 2. For the Type III bit, there is a small line which runs between Zone 1 and Zone 3 and represents the very small gap between the bit body and carbide tip (Figure 9a). Zone 2 in Figure 9a is mostly filled affected by the degree of bit-coal interaction in Zone 1, by the carbide tipof bit, a smooth transition occurs between the bit body and carbide tip. Zone 3 consisted of a small band of shiny platy material with intermittent areas of compacted fines. The amount of crushed material trapped behind the areas of frictional contact (shiny areas) was less than that associated with Zone 1 for all bit types. Type II bit had by far the least amount of bit coal interaction in Zone 3 as compared to the other bits. Zone 3 was much wider meaning more interaction, larger area of contact, occurred for the Type V bit as compared to Type II. The Type III and IV bits by far showed the most bit-coal interaction in Zone 3. In the case of the Type III bit, Zone 3 extends beyond that captured in the microscopic photograph (Figure 9a) and is made up equally of black and brown areas. In other words, almost half of the total area has been subjected to frictional contact producing black areas, whereas, for the Type IV, Zone 3 was slightly wider as would have been expected because it had the highest coal boundary left between the bit path and almost entirely consisted of areas of frictional contact, black (shiny areas) with few areas of deposited fines (Figure 9d).

An attempt was made to correlate bit-coal interaction with product size distribution. The results/correlation were obviously within certain ranges, however, in some ranges

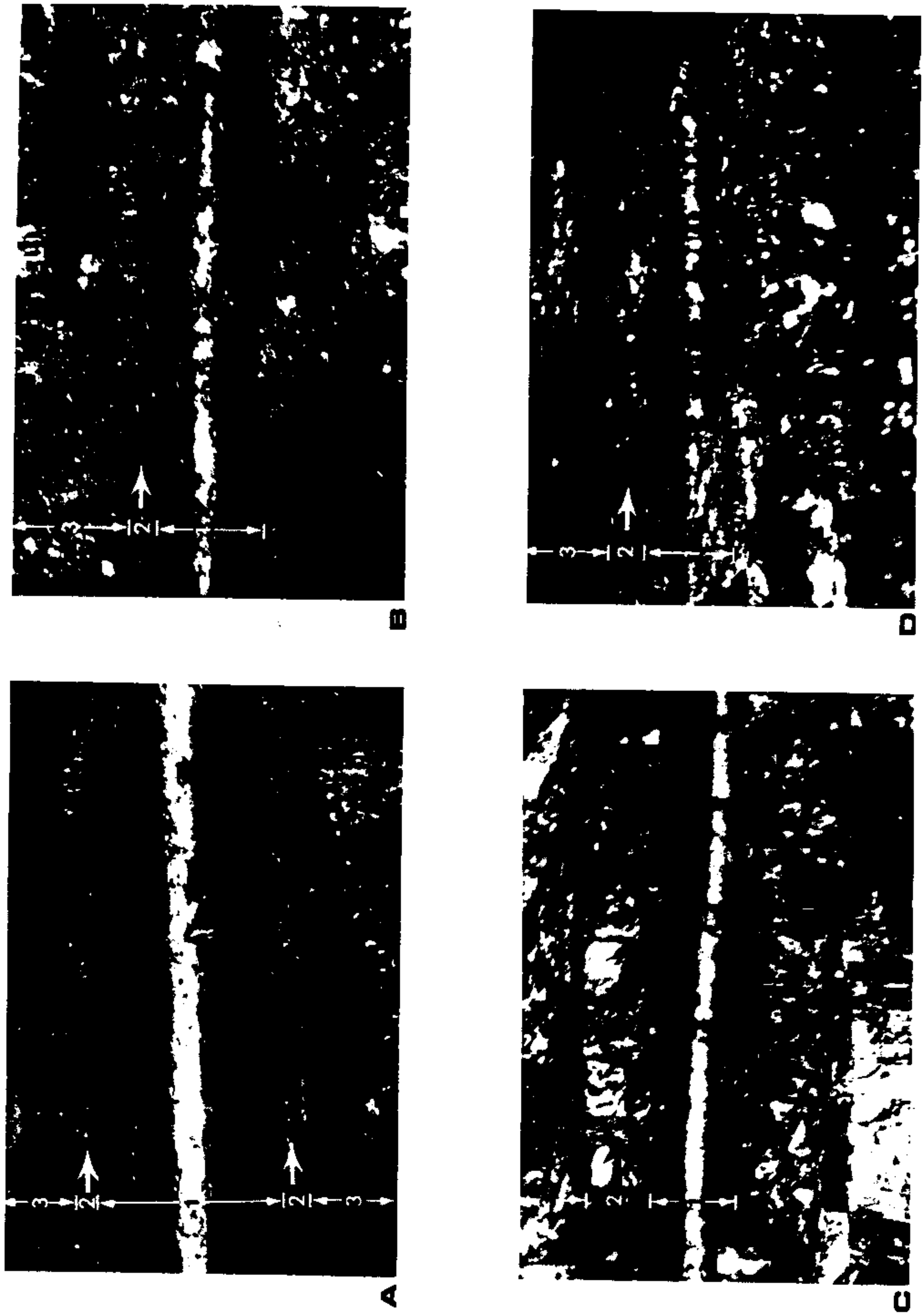


FIGURE 9. Shows the corresponding microscopic photographs in the center bit path taken with a .66 zoom setting in the middle of the coal block. The three zones (1,2,3) are appropriately labeled. (a) Test #41, Type III bit; (b) Test #43, Type V bit; (c) Test #36, Type II bit; (d) Test #35, Type IV bit.

they became less conclusive. Figure 11 shows the fragment size distribution associated with the four bit types for Case 2 fracture surface. The fine range of the size distribution (-0.007 inches) is affected by the degree of bit-coal interaction in Zone 1, by the carbide tip. the Type III bit being the most blunt of the four bits produced the most crushed material in Zone 1, part of which is trapped by bit action and the remaining undoubtedly released during cutting. This pocket of crushed material which was produced by each pass of the bit will be released upon the next cutting cycle. Thus, the Type III bit produced the highest percentage of material

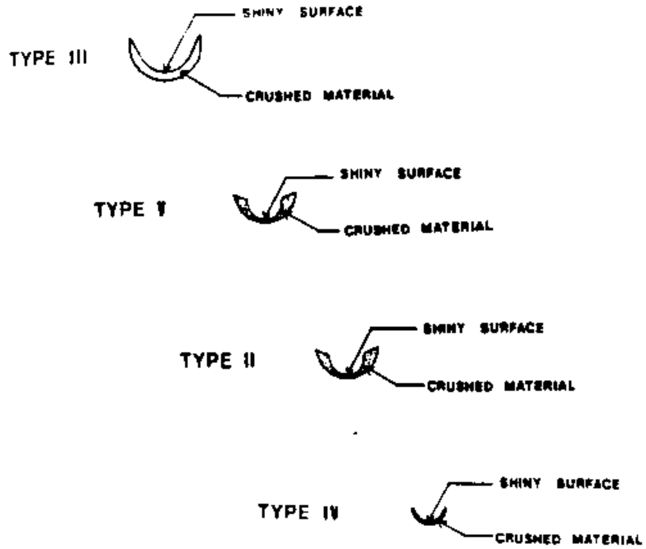


FIGURE 10. Shows the relative size and shape of the pocket of crushed material in Zone 1 for each bit type (not to scale)

in the fine range (-0.007 inches) of the size distribution. Next, the Type V and II bits which have the same size carbide tip produced virtually the same amount of crushed material in Zone 1, resulting roughly in the same percentage of fine material (-0.007 inches), whereas, the Type IV bit being sharper produced the least amount of crushed material in Zone 1 and reflected in the size distribution by having the lowest percentage of material in the fine range (-0.007 in-

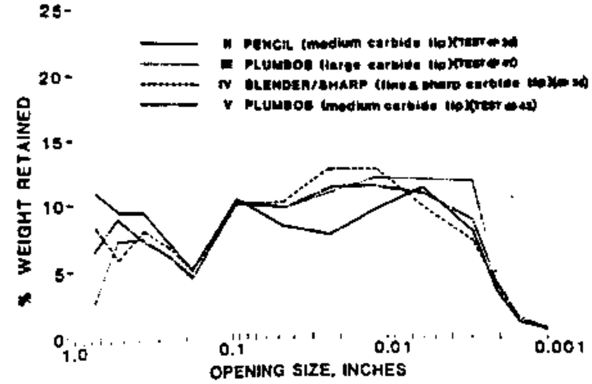


FIGURE 11. Opening size vs. percent of weight retained as a function of bit type when cutting against the face cleat (representative of the Case 2 fracture surface).

ches). The size distribution from 0.09 to 0.007 inches is affected by the degree of bit-coal interaction in Zone 2 and Zone 3. The larger area of frictional contact resulted in excessive crushing and grinding of loose material in the bit path as well as that of intact coal. For this reason, Type IV bit produced the highest percentage of fine material in the range of 0.09 to 0.007 inches of size distribution. In contrast, the Type II bit had the least amount of fractional contact. Also, because fracturing occurred across Zone 2 (ridge remains due to offset to bit tip and bit body), the bit did not trap broken material. However, these ridges may be subjected to secondary crushing by the bit body in subsequent cycles and will reflect the production of dust size particles. Figure 11 shows that the Type II bit produced the lowest percentage of fines in the range of 0.09 to 0.007 inches. Zone 3 for the Type III bit was large but only partially had areas of frictional contact, thus accounting for a slightly higher percentage of fines than Type V bit for which Zone 3 was much narrower and had correspondingly less total area of frictional contact. To further evaluate the effect of bit type on fragment size distribution another series of experiments are presented here. The test parameters used were: four bits mounted in an echelon patter, 30 degree attack angle, 1.5 inches bit spacing, 1/5 inch depth of cut per revolution, 15 rpm drum

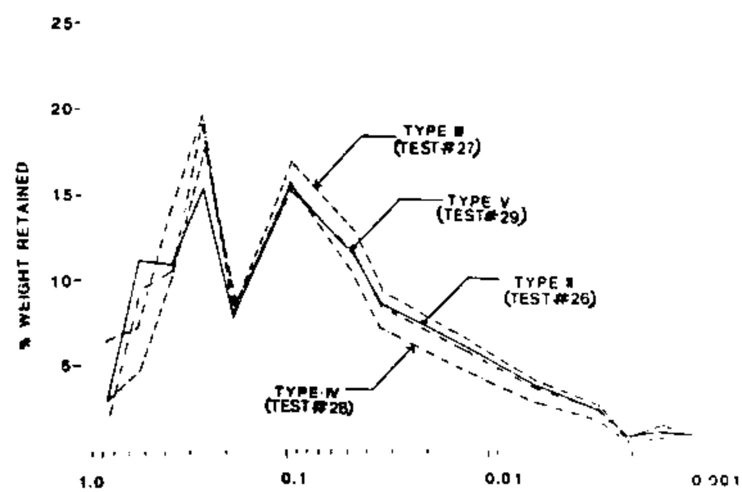


FIGURE 12. Opening size vs. percent of weight retained as a function of bit type when cutting against the face cleat (representative of the Case 1 fracture surface).

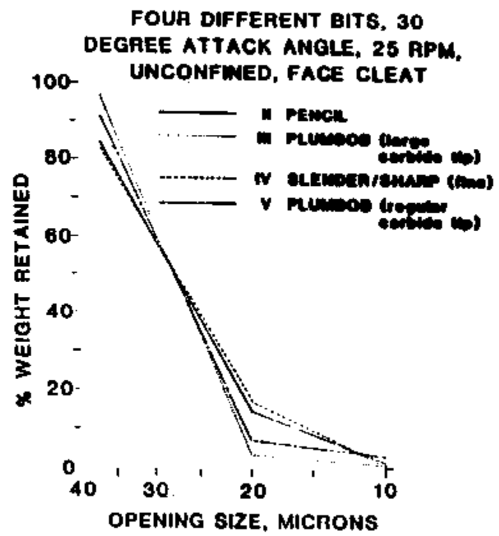


FIGURE 13. Mesh size versus percent of weight retained as a function of bit type, dust size distribution from 37 microns (400 mesh) to -10 microns.

velocity, 512 psi vertical and 300 psi horizontal confining pressures and tested along the face cleats. The fractured surface of the tested specimen were representative of Case 1, indicating breakage occuring between bit paths and only the resulting trace left by the carbide tip (Zone 1) remains on the fractured surface. Furthermore Zone 1 had the same general size/shape and characteristics associated with it as in the previous tests. The size distribution of these experiments is presented in Figure 12. Figure 12 shows that the

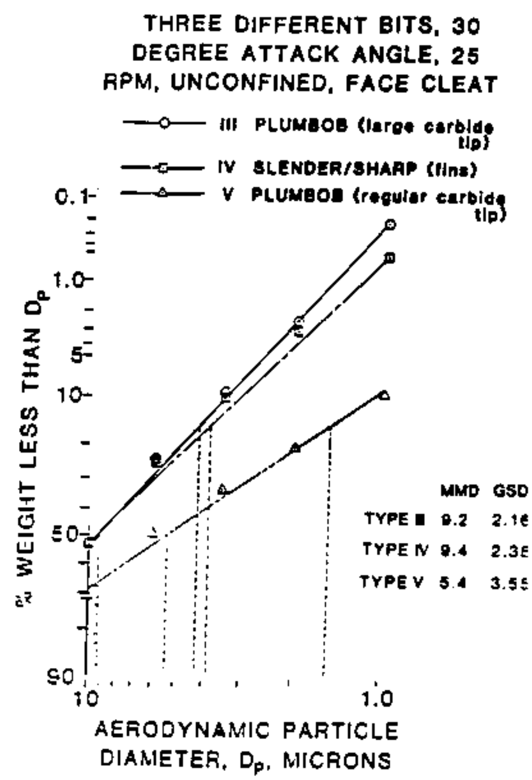


FIGURE 14. Particle size distribution of the respirable coal dust sampled by cascade impactors, while cutting coal with different types of bits.

Type IV bit produced the least percentage of fines and that the Type III bit produced the most. The Type IV bit had the sharpest carbide tip and produced the smallest frictional contact in Zone 1, whereas, the Type III bit having the largest carbide tip produced the largest frictional contact in Zone 1. Size distribution for the Type V and II bits fell between that of the Type III and IV bits mainly due to the size and shape of their carbide tips and associated frictional contact in Zone 1.

It is difficult to identify any correlation in the large range (+0.0937 in.) size distribution. Mainly, due to the bit type having no significant affect on breakage of the boundary between bit paths. Similarly on the dust range (–0.015 in.) there is no obvious correlation. The size distribution graph between 40 to 10 microns crossing each other at approximately 27 microns and has a natural dip at 20 microns (Figure 13). Between 20 and 12 micron sizes, bit Type IV produced the

TABLE III

Respirable Mass Fraction Sampled by Impactors While Cutting with Different Bit Types (Face Cleat)

Bit Type	Concentration	Particle Size (um) 10.0 x 6.0	6.0 x 0.6
III	A. Weight* (mg)	7.69	10.61
	N. Weight + (mg)	8.35	11.53
	Percent	42.00	58.00
IV	A. Weight* (mg)	8.61	11.28
	B. Weight + (mg)	8.61	11.28
	Percent	43.30	56.70
V	A. Weight* (mg)	2.95	9.45
	B. Weight + (mg)	4.72	15.17
	Percent	23.70	76.30

* Actual weight sampled.

\+ Normalized with the highest weight in series.

highest percentage, but Type II second, bit Type V third and bit Type III the lowest. Furthermore the size distribution curves for bit Types V and II shows similar characteristics with crossing each other at 27 and 12 micron size, similar curves for Type V and III with only crossing each other at 27 micron size. This irregularity could be due to the characteristics of coal and bit-coal interaction and possibly may have been affected by the sieving process where further breakage of the fragments may have resulted in various production of dust size particles. An important feature to note in Figure 13 is the sharp decline in size distribution curve for bit Type IV between 20 and 10 micron sizes, where the percentage weight retained at 10 microns is the lowest for bit Type IV than others indicating possibly the least production of respirable size dust.

Particle size distribution of the entrained dust sampled by 6-stage cascade impactors was plotted on log-probability

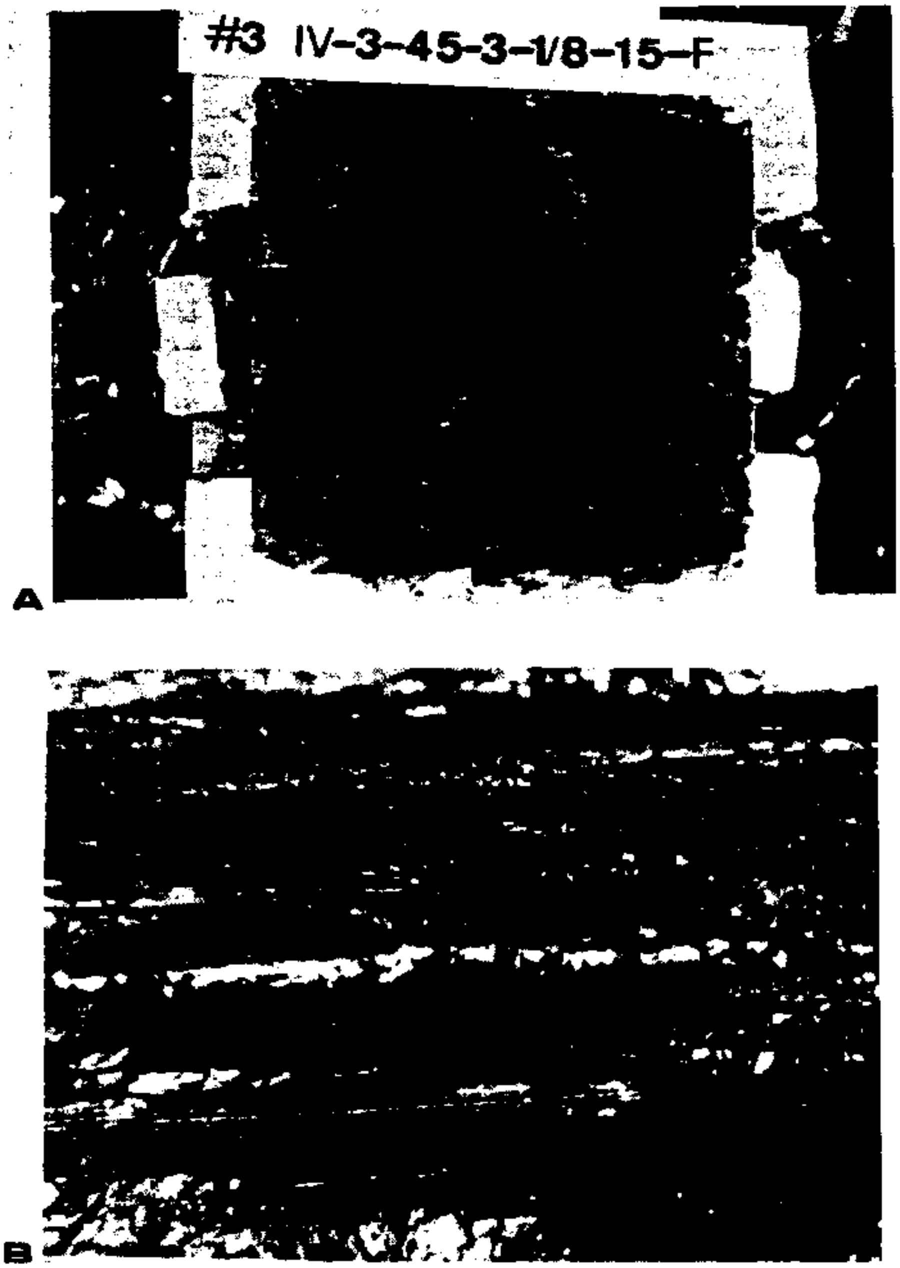


FIGURE 15. (a) Photograph of the coal block of test #3 after cutting against the face cleat; (b) microscopic photograph taken approximately 1.5 inches from the entrance of the center bit with .66 zoom setting.

graphs (Figure 14). Most distribution functions like this require two parameters, one that identifies the location or center of the distribution and the other that characterizes the width or spread of the distribution. Location of center of the distribution here is identified by mass median diameter (MMD). MMD is defined as the diameter for which half the mass if contributed by particles larger than the MMD and half by particles smaller than the MMD. The geometric standard deviation (GSD) is a measure of the spread of the particle size distribution. It is defined as the ratio of MMD and the particle size at 16 percentile. If GSD = 1, all the particles are of the same size, i.e., the entrained dust is "monodisperse."[27] The MMD and GSD for bit Type V are 5.4 and 3.55, respectively. They are considerably different when compared to the bit Types III and IV for which the MMDs and GSDs are consistent between 9.2 and 9.4 and 2.16 and 2.38, respectively. Table III shows the weight and percent of respirable size mass divided into 10.0 x 6.0 microns and 6.0 x 6.6 microns. Table III confirms with the MMDs and GSDs where in the bit Type V produced 76.3 percent of the mass in the 6.0 x 0.6 micron size range while bit Types III and IV produced only 58.0 and 56.7 percent in the same size range respectively. At 10.0 x 6.0 micron size range the order of highest production reversed resulting in 23.7, 43.30, and 42.00 percent for bit Types V, IV, and III, respectively.

In analysis of bit coal interaction for these experiments, as it was described before, largest of Zone 1 and least of Zone 3 occurred by bit Type III opposed to the bit Type IV, and bit Type IV and bit Type V showed characteristics somewhat in between the two. This bit-coal interaction reflected in size distribution curves shown in Figures 11-13. Geometrically bit Type V has somewhat common characteristics with both types of bits III and IV. Its plumbob shape, small head and large base make the bit body sharper than the Type III bit which has the largest of all three. This small carbide tip caused a rough surface feature on the bit and left a large gap around the carbide tip as the extension of the head (body) of the type V bit. This gap provided a trap zone for the crushed material and left ridges (Zone 2) in the bith path (Figure 10), which was further subjected to crushing and grinding in subsequent cutting cycle resulting in production of higher respirable dust sizes (Figure 14 and Table III). It was mentioned before, breakage of ridges and fine particles (shiny surface, black area, and algormerated crushed material) produced dust size particles, therefore any bit type which produces rough surfaces and large percentage of fine particles, excessive fractured surface area, will also produce the larger percentage of respirable size dust. From Figures 11–14 it could be concluded that the bit which has a carbide shape and tip-head arrangement of bit Type IV and the body of bit Type V is more effective in less production of fine and respirable dust size particles. A sharp and larger carbide tip for bit Type V would have given a smooth transition between the tip and body of the bit. This would improve the cutting efficiency of the bit by having least bit-coal interaction and resulting in less regrinding and fractional contact at all three zones, thus producing less respirable dust.

Effects of Bit Spacing

A series of experiments were run to study the effect of bit spacing on fragment size distribution and to see how this may relate to the overall and microscopic appearance of the fracture surface. The tests were conducted using 1.5 and 3 inch spacing. The appearance of the coal blocks after cutting for 1.5 inch spacing resembled Figure 4 and for a typical test with 3 inch spacing is shown in Figure 15a. Despite varying the cutting head velocity, bit type, bit attack angle and confining pressures within the depths of cut used in this study, the boundary walls between the bit paths remained intact with

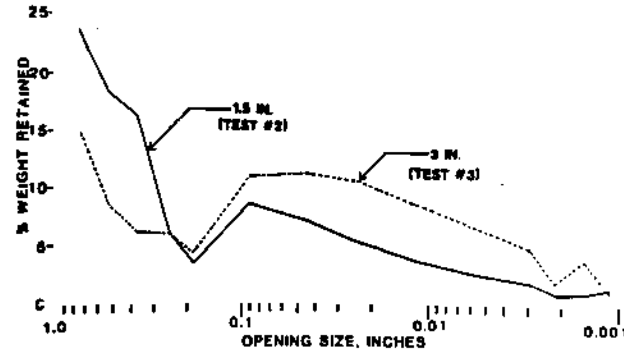


FIGURE 16. Opening size vs. percent of weight retained as a function of two different bit spacings when cutting against the face cleat.

the least interaction between each bit. The fractured surface represented the extreme end of Case 2 indicating a high degree of bit-coal interaction and frictional contact as shown in Figure 15b. For the reasons mentioned above, the 3 inch spacing produced, percentage wise, far less large size and more fine size particles than did the 1.5 inch spacing as shown in Figure 16.

Effect of Depth of Cut and Cleat Orientation

A series of experiments have been performend both along the face and butt cleat direction keeping the other parameters constant while chaning the depth of cut. Four tests representing general characteristics of this series of experiments are selected for discussion here. Tests #11 and #35 were performed along the face cleat, while #21 and #40 was performed along the butt cleat. Test #11 represents a 1/4 inch depth of cut per revolution with five bits mounted in an echelon pattern (Figure 17a). Test #35 represents a 1/32 inch depth of cut per revolution with seven bits mounted in an echelon pattern (Figure 18a). Test #11 indicates the breakage of the boundary wall between the adjacent bit

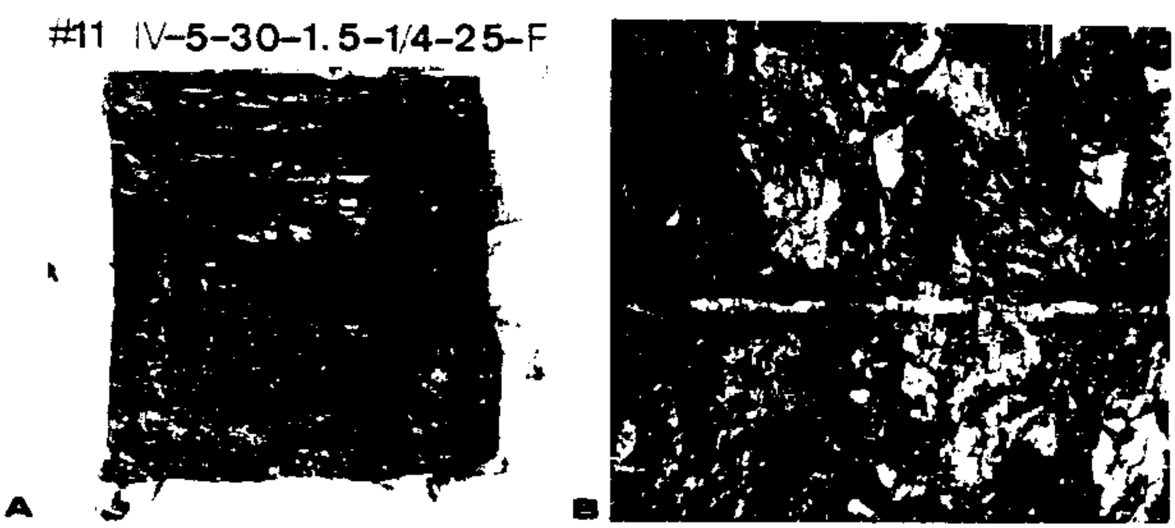


FIGURE 17. (a) Photograph of the coal block of test #11 after cutting along the face cleat; (b) microscopic photograph taken of the center bit path in the middle of the coal block with a .66 zoom setting.

paths. The height of the boundary lift is in the range of 0 to 1/2 inche (average of 1/4 inch) measured from the center of the bit path and the fractured surface here represents case 1. However, test #35 indicates a much lesser degree of interaction between the adjacent bit paths leaving a much larger boundary between them as shown in Figure 18a. The height of the boundary is in the range of 1 to 1.5 inches (averaging a 1.25 inches) and the fractured surface represents Case 2. In deep cut (Test #11) only a small trace of the carbide tip on the fractured surface lift (Figure 17a) and indicating less bit-coal interaction as shown in Figure 17b. However, shall depth of cut caused excessive bit-coal interaction and frictional contact as shown in Figure 18b.

Fracture initiates at the zone of highest stress concentrate or where the stress exceeds first the strength of material. In coal cutting fracture initiates under the bit tip. This feature continues to propagate as long as the above conditions are met or the fracture reaches to a free surface. Generally the depth or length of crack depends on the magnitude of stress at the time of fracture initiation. Increasing the depth of cut requires a higher stress level and causes more complete interaction between the bit paths; coal is broken away from the test specimen so the bit is not enclosed by the bit groove which causes the production of fines as shown in Figure 19. When the depth of cut is increased, the cracks, which were produced from the compressive stresses induced on the coal by the bit, must propagate further to a free surface to allow breakage, thus causing larger fragments to be formed and more coal broken per pass. Not only were larger fragments produced with a deeper depth of cut per revolution but there was less contact between the carbide tip and coal surface in removing the same volume of material versus that of a shallow cut, thus reducing the amount of crushed material produced at the bit tip for the same volume of coal removed. When the depth of cut is decreased, the cracks have much less distance to travel to reach a free surface producing smaller fragments and allowing the boundary wall to be built up between the bit paths.

The fractured surfaces for the specimens tested along the butt cleats (tests #21 and #40) was much rougher and broke

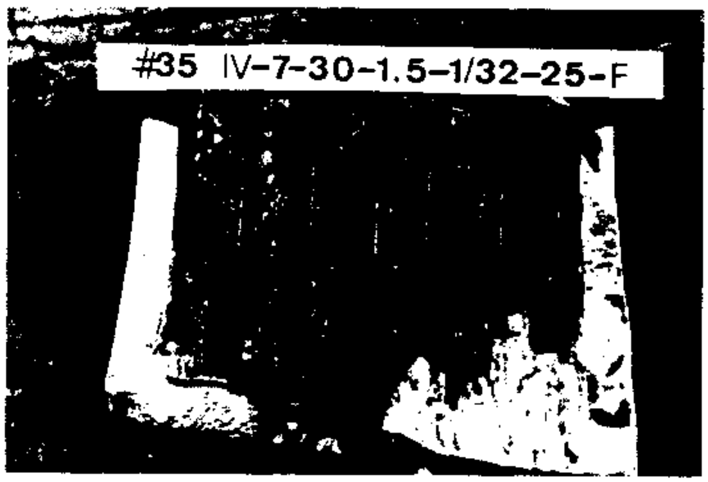


FIGURE 18. (a) Photograph of the coal block of test #35 after cutting against the face cleat; (b) microscopic photograph of test #35 taken of the center bit path near the middle of the coal block with a .66 zoom setting.

irregularly. The figure associated with these tests is not included here due to limited space. The cutting resistance along the butt cleat was much higher than those tested along the face cleat under the same set of parameters. This higher resistance attributed to a 5.2 percent higher compressive and 33 percent higher tensile strength of coal in the butt cleat direction (See Table II). This in turn led to different failure characteristics in the butt cleat direction especially at deeper cuts. For example the average height of the boundary wall between the bit path for test #21 along the butt cleat was 3/4 inch which was much greater than that of test #11 along the face cleat direction (averaging 1/4 inch) for the depth of cut of 1/4 inch. This resulted in more bit-coal interaction and caused more frictional contact between the coal and bit for the case of cutting along the butt cleat. Comparing the same depth of cut, along the face and butt cleat, percentage-wise more larger size fragments and fewer fines are produced when cutting along the face cleat (Figure 19). However, this difference become negligible when depth of cut was reduced (i.e., 1/32 inch) especially at the lower end of the fine size (dust). The latter claim was substantiated by the analysis of

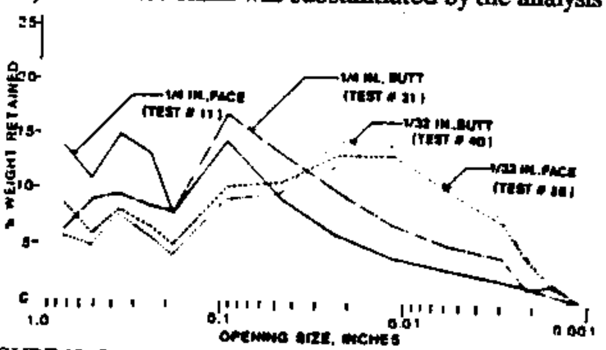


FIGURE 19. Opening size vs. percent of weight retained as a function of two different depths of cut per revolution and cleat directions.

respirable dust collected by cascade impactors as shown in Figure 20. In Figure 20, respirable dust in both experiments having the same mass median diameter (MMD = 9.4) with less difference between their spread of the particle size distribution, GSD of 2.38 and 2.16 for face and butt cleat respectively. One of the reasons for this lack of difference in particle size distribution, when testing along face cleat versus buttcleat at very shallow depth of cut probably the characteristics of coal itself. Under shallow depth of cut, cutting stress will be very low, fracture length will be small, consequently coal will break along its natural imperfection which is rather constant for these specimens (because of being all prepared from the same block of coal) and has not been affected by the cutting direction.

Effects of Cutting Head Velocity

During coal cutting the velocity of cutting head is not uniform rather it is cyclic due to the intermittent nature of the fracturing process. When cutting head exerts peak dynamic force on the coal its velocity reduces to its lowest value and meanwhile causes fracture initiation and propagation. During fracture propagation resistance offered by the coal is low and also due to the back up pressure the cutting head accelerates and its velocity reaches its peak value. In

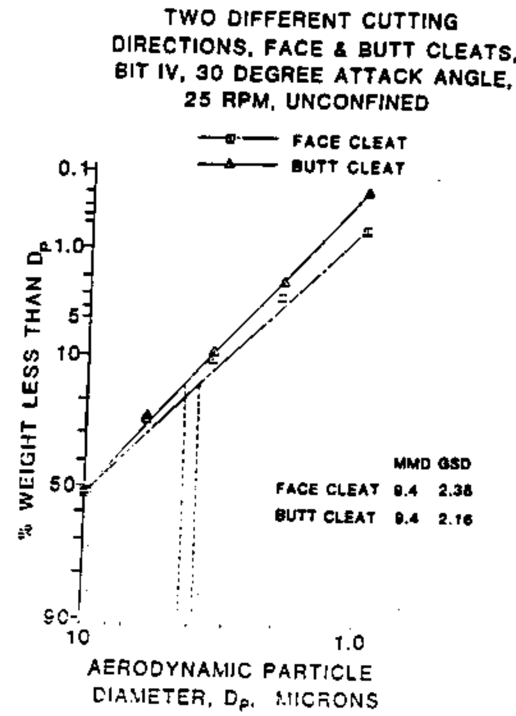


FIGURE 20. Particle size distribution of respirable coal dust sampled by cascade impactors while cutting coal with different cleat orientations.

this period of the cycle the cutting head grades the cutting path. Higher peak dynamic stress causes longer/deeper fracture; however, it also increases the length of the grading surface. The higher the velocity of cutting head and resistance offered by the coal,the higher peak stress and more fluctuation is observed in the velocity of the cutting head, consequently increasing the grading period.[26] The higher the cutting velocity the higher the required cutting force is observed as shown on in Figure 21. However, the specific energy might be the same because under a higher rpm the bit spends little time cutting coal. Analysis of both microscopic and overall appearance of the fractured surface for this series of tests showed no significant differences due to changing drum velocity. However, change in rpm of drum

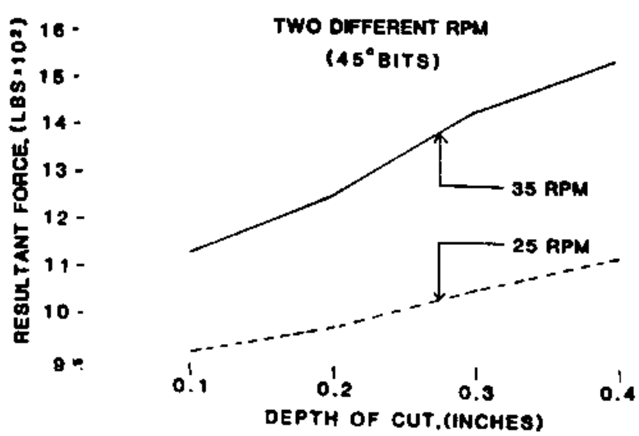
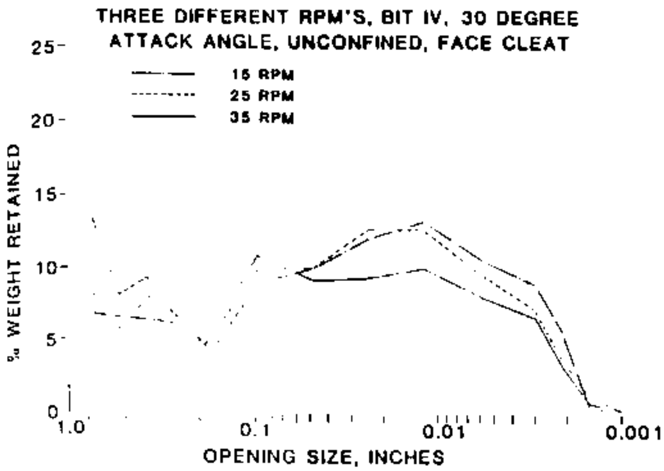


FIGURE 21. Resultant force vs. depth of cut as a function of rpm (face cleat direction).

has been reflected on fragment size distributions as shown in Figure 22a-b. The higher rpm produced a higher percentage of large and a lower percentage of fine size material. There is an exception where the size distribution curve for 15 rpm experiment lies between 35 and 25 rpm in range of 20-10 microns (Figure 22b). This could be due to the characteristics of coal or due to the limited number of tests with orthotropic and nonhomogeneous material. Analysis of



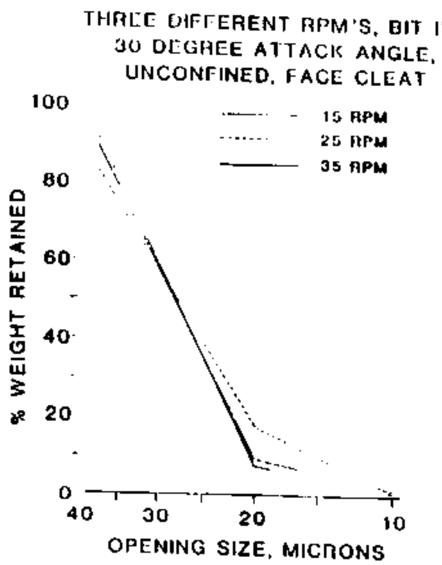


FIGURE 22. Mesh size versus percent of weight retained as a function of cutting head speed (rpm) for face cleat orientation, (a) fragment size distribution from 1.885 cm (0.742 in.) to 0.0038 cm (0.0015 in.) or 400 mesh and (b) dust size distribution from 37 microns (400 mesh) to –10 microns.

respirable dust for this experiment indicated similar results with less differences in production of respirable dust as shown in Table IV. However, the aerodynamic particle size is smaller for 35 rpm cutting head speed than 25 rpm as shown in Figure 23.

Increasing the cutting head velocity under a constant depth of cut imposed more energy on the coal during dynamic loading (fracturing) producing more large and

TABLE IV

Respirable Mass Fraction Sampled by Impactors While Cutting at Different Drum Speeds (Face Cleat)

Drum RPM	Concentration	Particle Size (um) 10.0 x 6.0	6.0 x 0.6
25	A. Weight* (mg)	8.61	11.28
	N. Weight + (mg)	8.76	11.47
	Percent	43.3	56.70
35	A. Weight* (mg)	8.99	11.24
	B. Weight + (mg)	8.99	11.24
	Percent	44.40	55.60

* Actual weight sampled.

\+ Normalized with the highest weight in series.

deep fractures in the coal resulting in more large and less fine fragments. The higher velocity will also tend to enhance crack propagation allowing a greater distance to be traveled before reaching a free surface, thus detaching a larger fragment. Increasing the velocity will increase the kinetic energy of the fragmented material which will help in removal from the bit path and reduce secondary degradation (reducing fines) but will undoubtedly increase dust entrainment. That is to say, it increases the airborne dust in expense of settled dust. Also coal is "weaker under a higher rate of loading (impact) making it easier to fracture, thus giving larger fragments."(6) The only drawback for higher speed would be increasing grading period of cutting process and secondary fracturing of the crushed material due to high impact result-

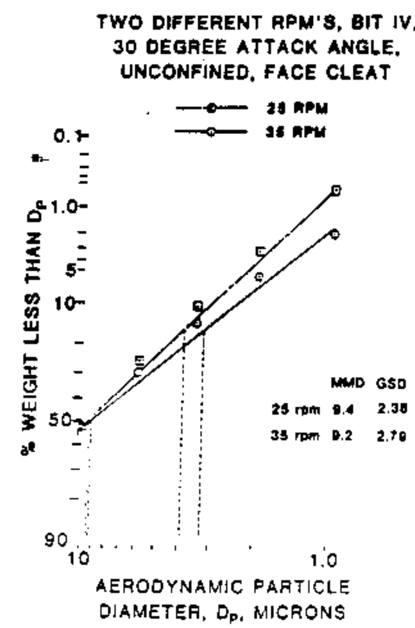


FIGURE 23. Particle size distribution of respirable coal dust sampled by cascade impactors while cutting coal with different cutting head speeds (rpm).

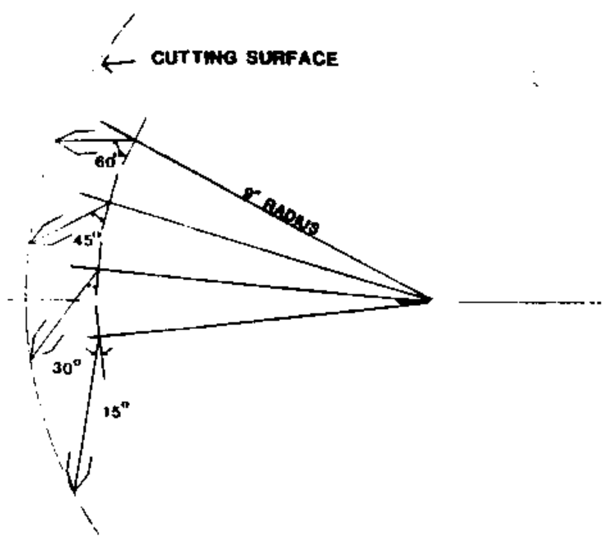


FIGURE 24. Illustrates the cutting surface and the area of contact between the cut surface and bits mounted at various attack angles on the cutting head.

ing in smaller size particles. Even though the total airborne dust might be less under the high speed cutting bit the total number of dust particles might be high as it is shown by the GSD of 2.79 for 35 rpm as compared to 2.38 for 25 rpm. This substantiates the possibility of increasing airborne dust in expense of settled dust under higher drum speed.

Effects of Bit Attack Angle

The point of contact for bits along the cutting path changes from entry to exit for any attack angle. At the entry of the cutting path the front portion of the bit tip will make contact mostly with the coal, at the center of the path almost the tip of the bit tip (depending on the angle of attack) and at the exit position the back of the bit tip as shown in Figure 24. However, the tip of the bit is semispherical where its curvature slightly changes from the tip to the sides which might affect the required force to cut the coal. Figure 25 shows the resultant forces (resultant of cutting and thrust forces) for the depth of cut for the four types of attack angles. Figure 25 shows that a 30 degree bit attack angle required the least force to cut the coal for a given depth of cut where a 15 degree attack angle required the highest. The fragment size distribution for these tests are shown in Figure 26. From Figure 26 it is obvious that a 30 degree attack angle is producing more large and less fines compared to the other three. However, the trend based on force requirement for a depth of cut for the other attack angles are not exhibited on fragment size distribution. This suggests that directional properties of coal highly influence the cutting force and fragment size distribution. That is to say coal breaks easily and

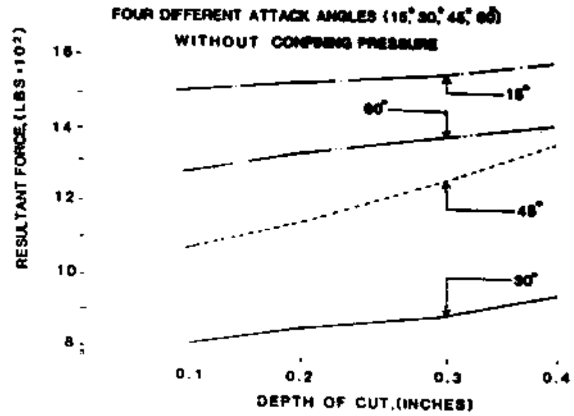


FIGURE 25. Resultant force vs. depth of cut as a function of bit attack angle (face cleat direction) (1 lb = 0.45 kg; 1 in. = 2.54 cm).

produces larger size fragments when it has been cut at a certain angle. Analysis of the fractured surface indicated no significant apparent differences for the different bit attack angles and the bit traces were very similar. Even though the 30 degree attack angle which produced substantially more large fragments, it was expected that there may be more interaction between the bit paths but this was not evident. In fact, all four tests showed almost the same degree of interaction, leaving a very small boundary between the paths. However, the 30 degree attack angle may break off larger

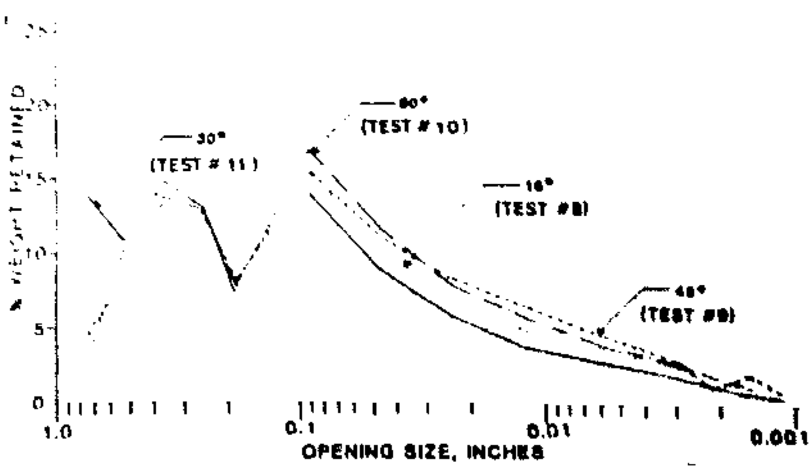


FIGURE 26. Opening size vs. percent of weight retained as a function of four different bit attack angles when cutting against the face cleat.

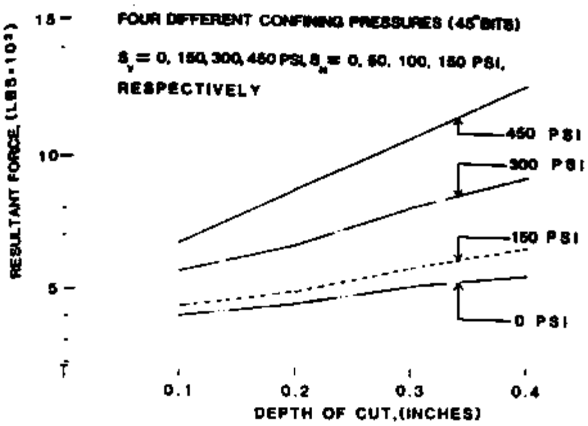


FIGURE 27. Resultant force vs. depth of cut as a function of equivalent in situ pressures (face cleat direction). (1 psi = 0.144 KPa).

fragments during the cutting process which may not always be evident by the appearance of the fracture surface after cutting.

Effect of Confining Pressure

A series of tests were performed both along the face and butt cleat directions at various equivalent *in-situ* stresses. The fractured surface definitely has a different appearance than that of the unconfined situation. Along the face cleats the fracture surface was very rough and irregular in appearance as though the coal provided a very high cutting resistance. This was clearly indicated in resultant force required to cut a specific depth as shown in Figure 27. The higher the equivalent in-situ stresses (horizontal stress = 1/3 vertical stress) the higher required cutting forces. Under the confining pressure, no longer was the splitting type fracture prominent between adjacent bit paths as was seen under no confining pressure. In a constrained situation, the fracture seemed to propagate in an angular almost unpredictable fashion seeking the path of least resistance giving a very rough appearance of the fractured surface. Increasing compressive strength of coal due to confining pressure makes it much more difficult for fractures to propagate directly to adjacent bit paths breaking the wall boundary of bit paths. Instead the confining pressures closes the joints causing the coal to act like a solid continuous material. When cutting the coal, crater shaped grooves were formed and ridges were left between them. In both directions (face and butt cleat), the

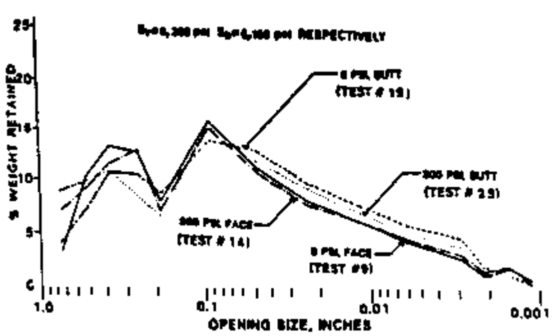


FIGURE 28. Opening size vs. percent of weight retained as a function of in-situ stresses and cleat directions (30 attack angle).

coal offered more resistance to cutting, giving a rougher fractured surfaces. Microscopic photographs of these tests indicated that, in general, the only trace left by the bit was that due to the carbide tip, no excessive contact was evident. The trace left by the carbide tip was more intermittent than those tested without confining pressures. Larger gaps occurred between traces (shiny lines) left by the carbide tip through the bit path and are indicative of the harder cutting and irregular fracturing. Furthermore, fractures propagated in a step-like manner toward the coal face deviated by the confining pressure before breaking across the wall boundary of the bit path in an irregular fashion.

The effect of confining pressures on size distribution for the tests done (using 30 attack angle) is less conclusive as shown in Figure 28. Increasing the confining pressure in the butt cleat direction resulted in a slight decrease in the percentage of fines and increased the percentage of large fragments in the upper end of the size distribution. However, it is not quite clear what effect the increasing pressure has on size distribution, when cutting along the face cleat. In a similar test conducted along the face cleat but at the other three attack angles (15, 45, 60), it was found that the confining pressure decreased the percentage of large fragments

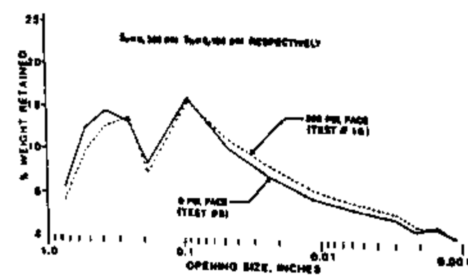


FIGURE 29. Opening size vs. percent of weight retained as a function of in situ stresses and cleat directions (30° attack angle).

and increased the percentage of fines as shown in Figure 29. In general, confining pressure has the opposite effect while cutting along the face cleat than those of butt cleat. A possible explanation may be that the confining pressure may make the coal either easier or harder to cut, depending on the inherent characteristics of the coal in the face and butt cleat directions.

Effect of Coal Properties

A limited number of tests have been carried out on the Pittsburgh coal seam and for comparison an example is presented here. The apparent feature of the tested specimen is shown in Figure 30. The fractured surface represents Case 2 indicating higher bit-coal interaction and frictional contact resulting in production of more percentage of fines and less of large fragments as exhibited in Figure 31a-b. The analysis of airborne dust, collected by cascade impactor, indicated that smaller aerodynamic particles with higher particle size spread (MMD = 9.0, GSD = 2.77) were produced when coal specimen of Pittsburgh seam was tested under similar tests carried out on the Waynesburg seam. A comparisn between the two coal seams in the dust size range is presented in Figure 32 as well as in Table V. Table V shows 61.70 percent of respirable mass having particle size in the range of

FIGURE 30. Photograph of the test specimen prepared from Pittsburgh coal seam (IV-7-30-1.5-1/32-25-F).

6.0 x 0.6 microns for the Pittsburgh seam as compared to 56.70 percent for the Waynesburg seam.

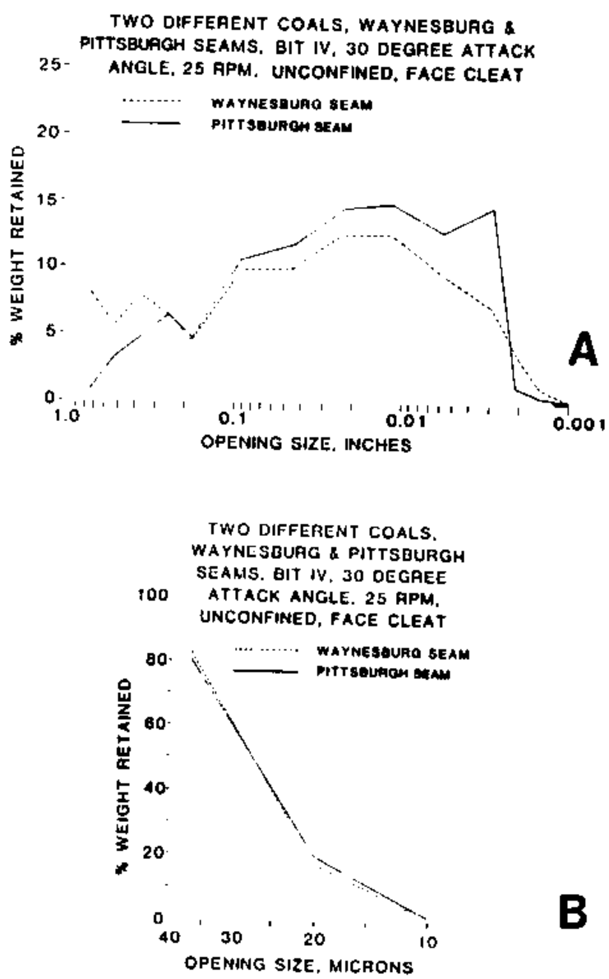


FIGURE 31. Mesh size versus percent of weight retained as a function of coal type (a) fragment size distribution from 0.742 in. (1.885 cm) to 0.0015 in. (0.0038 cm) or 400 mesh and (b) dust size distribution from 27 microns (400 mesh) to -10 microns.

Conclusions

Only a limited number of tests have been performed at a specific condition on the two types of coal to evaluate the effect of various parameters on coal cutting. However, the results of this study have yielded many distinct conclusions which can by summarized as follows:

The depth of cut and bit spacing seem to have by far the most affect on the breakage of the coal boundary between the bit paths. The results indicate that increasing the cutting head speed increased the percentage of large sized fragments and reduced the percentage of fine material produced. Of the four attach angles tested, the 30 degree, clearly gave the highest percentage of large material and the fewest fines. The effect of *in situ* stresses seems to depend

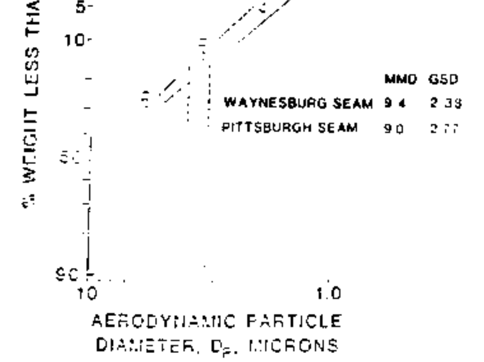


FIGURE 32. Particle size distribution of respirable dust sampled by cascade impactors while cutting two different coals.

on the cutting direction as well as the physical and mechanical properties of the coal, thus confining pressure may shift the size distribution depending upon other factors. Under the same testing conditions cutting along the butt cleat produced more fines and less large fragments as opposed to the face cleat. Also, under the same testing conditions bit type appears to only have an offset on the percentage of fines and amount of dust produced in the area of the bit path. It is evident that each coal has its own fragmentation characteristics, thus reflecting its product size distributions. More fines and dust were produced in cutting Pittsburgh coal than Waynesburg coal.

For most of the parameters studied, an apparent relationship between the size distribution and the fractured surface characteristics exist. These parameters include: bit type, bit

TABLE V

Respirable Mass Fraction Sampled by Impactors While Cutting Different Types of Coals (Face Cleat)

Coal Type	Concentration	Particle Size (um) 10.0 x 6.0	6.0 x 0.6
	A. Weight* (mg)	8.61	11.28
Waynesburg	N. Weight + (mg)	11.12	14.57
	Percent	43.30	56.70
	A. Weight* (mg)	9.83	15.86
Pittsburg	B. Weight + (mg)	9.83	15.86
	Percent	38.30	61.70

* Actual weight sampled.

\+ Normalized with the highest weight in series.

spacing, depth of cut, *in situ* stresses (confining pressure), cleat orientation and coal type the only exceptions being bit attack angle and fracture surface, one can tell how the fragmentation process has taken place with respect to the size distribution and resulting dust generation.

It appears that the key to achieving efficient coal fragmentation is to limit the degree of bit-coal interaction that takes place in the bit path while causing maximum breakage of the coal boundary (wall) between the paths. By increasing the degree of breakage of the coal boundary, it not only increases the percentage of large fragments produced but limits the amount of secondary crushing that takes place in the bit path which results in decreasing fines and consequently the amount of dust. Cutting bits having proper (carbide tip and body) shape, size and geometry (stream lined shape) will enhance further reduction of dust.

Acknowledgment

This project was funded by the Generic Mineral Technology Center for Respirable Dust Research sponsored by the U.S. Bureau of Mines Mineral Institute Program under Grant No. G1135142.

References

1. **Leonard, J.W.**: *Coal Preparation*, pp. 6-19. Port City Press, Inc. Baltimore, MD (1979).

2. **Pomeroy, C.D.**: Mining Applications of the Deep Cut Principle. *The Mining Engineer 20(6)*:506-517 (1968).

3. **Warner, E.M.**: Machine and Cutting Element Design. *Mining Congress J. 56(8)*:35-43 (1970).

4. **Newmeyer, G.E.**: Cost of Black Lung Program. *Mining Congress J. 67(11)*:74-75 (1981).

5. **National Materials Advisory Board (NMAB)**: *Measurement and Control of Respirable Dust in Mines*, pp. 1-25. National Academy of Sciences, Washington, DC (1980).

6. **Rad, P.F.**: *Mechanical Properties and Cutting Characteristics of Coal*, 66 pp. U.S. Department of the Interior, Bureau of Mines, IC 8585 (1973).

7. **Evans, I. and S. Murrell**: *Conference on Mecahnical Properties of Nonmetallic Brittle Materials*, pp. 432-450. Butterworths, London (1958).

8. **Hartman, H.L.**: Basic Studies of Percussion Drilling. *Mining Engineering 11(1)*:68-75 (1959).

9. **Paul, B. and D.L. Sikarskie**: Preliminary Theory of Static Penetration by a Rigid Wedge into a Brittle Material. *Transaction, Society of Mining Engineers 233(2)*:372-383 (1965).

10. **Lawn, B.R. and M.B. Swain**: Microfracture Beneath Point Indentations in Brittle Solids. *Manual of Materials Science 10, 22(8)*:113-122 (1975).

11. **Devilder, W.M.**: *Correlation of Fragment Size Distribution and Fracture Surface in Coal Cutting Under Various Conditions*, 117 pp. M.S. Thesis, Department of Mining Engineering, West Virginia University (1986).

12. **Barker, J.S.**: A Laboratory Investigation of Rock Cutting Using Large Picks. *International J. Rock Mechanics 1*:519-534 (1964).

13. **Khair, A.W.**: Design and Fabrication of a Rotary Coal Cutting Simulator. *Proceedings of the Coal Mine Dust Conference*, pp. 190-197. Department of Mining Engineering, West Virginia University (1984).

14. **Daniel, H.J.**: Respirable Dust Control Research -- The Bureau of Mines Program. *Proceedings of the Coal Mine Dust Conference*, pp. 1-8. Department of Mining Engineering, West Virginia University (1984).

15. **Niewiadomski, G.**: Improving Dust Control Technology for U.S. Mines. *Proceedings Symposium on Control of Respirable Coal Mine Dust*, pp. 41-73. Beckley, WV (1983).

16. **Roepke, W.W., D.P. Lindroth and T.A. Myren**: *Reduction of Dust and Energy During Coal Cutting Using Point Attack Bits*, 53 pp. U.S, Department of

Using Point Attack Bits, 53 pp. U.S. Department of the Interior, Bureau of Mines, RI 8185 (1976).

17. **Roepke, W.W., D.F. Winguist, B.D. Hanson and L.L. Sundae:** Research on Reducing Generation of Primary Respirable Dust in Cutting Coal. *Proceedings of the Coal Mine Dust Conference,* pp. 37-44. Department of Mining Engineering, West Virginia University (1984).

18. **Hamilton, R.J.:** Principles of Machine Design and Operation Related to Dust Production and Control with Particular Reference to Longwall Mining in the United Kingdom. *Proceedings Symposium on Respirable Coal Mine Dust*, pp. 160-178. Washington, DC (1969).

19. **Roepke, W.W. and B.D. Hanson:** New Cutting Concepts for Continuous Miners. *Coal Mining and Processing 16(10)*:62-67 (1979).

20. **Roepke, W.W.:** U.S. Bureau of Mines Coal-Cutting Research for Dust and Energy Reduction. *Proceedings of the European Economic Community Symposium on Reduction of Dust in Coal Mining,* pp. 12-23. Luxemburg (1983).

21. **Fuh, G.F.:** On the Determination of Cutter Bit Spacing for Optimum Coal Mining. *Proceedings 24th U.S. Symposium on Rock Mechanics,* pp. 703-712 (1983).

22. **Black, S., B.V. Johnson, R.L. Schmidt and B. Banerjee:** *Impact of Deeper Depths of Cut on Coal Mining Machines and Respirable Dust,* pp. 161-179. U.S. Bureau of Mines Unofficial Report (1976).

23. **Friedman, M. and L.M. Ford:** Analysis of Rock Deformation and Fractures Induced by Rock Cutting Tools Used in Coal Mining. *Proceedings 24th U.S. Symposium on Rock Mechanics*, pp. 713-723 (1983).

24. **Strebig, K.C. and H.W. Zeller:** *Effect of Depth of Cut and Bit Type on the Generation of Respirable Dust,* 16 pp. U.S. Department of the Interior, Bureau of Mines, RI 8042 (1975).

25. **Arentzen, R.F.:** Machine Design: State of the Art. *Proceedings Symposium on Respirable Coal Mine Dust,* pp. 178-183. Washington, DC (1969).

26. **Khair, A.W. and M.K. Quinn:** *Mechanisms of Respirable Dust Generation by Continuous Miner.* Preprint No. 85-413, 14 pp., presented at the SME-AIME Fall Meeting, Albuquerque (1985).

27. **Hinds, C.W.:** Particle Size Statistics. *Aerosol Technology, Properties, Behavior, and Measurement of Airborne Particles,* Chapter 4, pp. 69-103. John Wiley and Sons, New York, New York (1982).

Statistical Analysis of the Elemental Characteristics of Airborne Coal Mine Dust

CHANGWOO LEE AND JAN M. MUTMANSKY

Department of Mineral Engineering, The Pennsylvania State University, University Park

This paper outlines some of the work associated with a research study into the relationship between the characteristics of coal mine dust and the incidence of coal workers' pneumoconiosis (CWP). The project involves study of the chemical, mineralogical, and morphological characteristics of the dust. Early stages of the study have dealt primarily with the size analysis and elemental composition of airborne dust in continuous miner sections. This paper outlines the procedures and findings of the elemental analysis portion of the study.

Most of the previous elemental analyses of coal were made available in the quest for information on the combustibility of coal dust or on causal agents and prevalence of CWP. However, no extensive studies have been performed to date, primarily due to the limitations of the analytical methods. A review of the analytical methods for elemental characterization of coal and coal dust particles is presented. The comparisons are made based on the sample mass required, the sample preparation required, the destructivity of the test, and the capability of providing an easy multi-element analysis. The reasons for selecting the proton-induced x-ray emission spectroscopy (PIXE) method are outlined.

The PIXE method was applied to both the airborne coal mine dust and channel samples collected from seven continuous miner sections in six different mines. Channel samples of the coal, roof and floor were collected and analyzed. Airborne dust sampling was performed using multi-stage cascade impactors and permissible 2.0 l/min pumps. Sampler locations were fixed in the sections with respect to the continuous miner and roof bolter or with respect to the intake and return airways. Sampling times varied from 45 minutes to 6 hours, depending on the dust concentration.

The statistical analysis of the resulting elemental data is presented. Of particular importance are the analyses of the variation of elemental composition with size and the variation in elemental composition over the working section. One interesting finding is outlined showing the multivariate statistical analysis of the trace elements and its implications in the identification of the dust sources. The paper concludes with an analysis of the ramifications of the elemental data to related medical studies.

Introduction

The significance of coal mine dust in the development of coal workers' pneumoconiosis has long been recognized. As a result, various medical and environmental studies have been carried out in order to identify the variables of coal mine dust that are related to CWP. These studies have revealed that a wide variation in the incidence of CWP exists from coalfield to coalfield, opening the door to a number of hypotheses. Most of these hypotheses deal with geologic variables such as coal rank, organic structure of the coal and the mineral and elemental characteristics of the coal and the surrounding geologic sediments.

Although many epidemiological studies indicate that a significant positive correlation exists between the incidence of CWP and the rank of coal mined, many researchers feel that the rank is not the causal variable. Criticism of the "rank cause" hypothesis is largely centered around the possible synergistic effects of other variables and the questionable representativeness of the samples of coal workers studied. This question and the effects of free silica have drawn considerable attention from many researchers.[1]

Additional studies of the characterization of coal, coal mine airborne dust, and dust from deceased miners' lungs have showed the possible association of the elemental composition of coal to the development of CWP. Concentration of some elements have been found to vary significantly in different coalfields.[2,3] Additionally, other studies have also related the significant differences in elemental compositions with the incidence and progression of CWP.[4-7] This led to a study by the authors on the elemental composition and rank of coal in three Pennsylvania coalfields. The results showed that elemental composition varied significantly with rank and that a successful discriminant analysis was possible using the elemental compositions as a basis for the discrimination.[8]

The primary objective of this paper is to carry the study of elemental characteristics one step further by the systematic study of airborne coal mine dusts in continuous miner sections. The overall study involves determining the elemental, mineralogical, and physical characteristics of the dust but only the elemental compositions of the dust will be analyzed here. The work involves analysis of the elemental composition of the dust as a function of its size, its location in the mining section and its association with the materials being mined. The ultimate purpose for this work is to identify dust characteristics that are worthy of further study by medical personnel.

Sample Collection

In assessing the sample collection possibilities, one major concern was the necessity for determining the properties of dust as a function of the size. The second major concern was the ability to classify the particles by aerodynamic diameter with a minimum of handling or alteration. In addition, the ability to utilize permissable pumps and a reasonably small sampler size was very desirable. As a result, Sierra Model 298 eight-stage cascade impactors were used, powered by Dupont Model P2500A pumps. The pumps and samplers were first tested in an aerosol chamber for proper sampling times as a function of dust concentration and in a simulated mine tunnel to determine whether isokinetic inlets were necessary (they were not).

A standardized sampling scheme was established and applied to all the mining sections sampled. In the sections employing a double-split ventilation scheme, mine sampling locations were selected to study the affects of different dust sources and the locational variability. One sampler was placed in the intake airway, outby the effects of section activity. Two samplers were assigned to the primary dust sources, the continuous miner and the roof bolter. One of these samplers was placed in the air of the immediate intake of the machine and the other was placed in the immediate return air. Two additional samplers were used in each return airway of the two machines, one at two blocks outby the pertinent machine. In a single-split ventilation plan, it was not possible to differentiate between the returns of the bolter and the miner. As a result, only two samples were placed in the return airway, one at two blocks and one at four blocks outby the closest machine.

During the sampling operation, all samplers were fixed relative to the face equipment. As a result, the samplers were moved each time an equipment face change occurred. In addition to airborne dust samples, channel samples were taken as close as possible to the continuous miner location. These were used to correlate the coal and airborne dust properties. More complete details on the sampling scheme can be found elsewhere.[9]

The Elemental Analysis Method

Among the variety of elemental analysis methods, only a few are applicable to the elemental characterization of coal mine dust. An optical method, emission spectroscopy, has been used for the analysis of heavy metals in coal dust found in miners' lung tissue.[10,11] Spark source mass spectroscopy and the neutron activation method have been applied to respirable coal mine dust samples gathered from a mine atmosphere.[12,13] Finally, the atomic absorption method has been used with application both to coal mine dust and to coal dust in lung tissue.[11,13,14]

In selecting an elemental analysis method for airborne coal mine dust collected by cascade impactors, the most restrictive requirement was the ability to perform the analysis at a relatively low cost on very small samples. Typically, the weight of the dust sample from a properly loaded stage of an impactor is usually in the range of 0.05 to 1.0 mg while the backup filter possesses a sample of about 0.01 mg. Furthermore, except on the backup filter, a sample on each stage is divided into six or twelve submasses. Therefore, the analytical method must be capable of performing multi-element analysis on an extremely small weight of sample. Another crucial requirement in the project was that the dust samples were needed intact for later mineralogical and morphological analysis. Thus, methods requiring ashing or chemical treatments of the samples were excluded.

Our literature research indicated that a non-destructive analytical method that can perform rapid multi-element analysis of extremely small samples at nanogram sensitivity had been applied to atmospheric samples collected by cascade impactors.[15,16] This method, proton-induced x-ray emission (PIXE) spectroscopy, uses a proton beam for excitation of the atoms of a sample prepared as a thin layer (usually a thickness of less than 5 mg/cm^2). Matrix absorption of characteristic x-rays is known to be negligible in this range of thickness. In our case, the thickness of samples on the substrates of the cascade impactors has consistently been smaller than this value and thus thin-sample PIXE analysis is applicable. One advantage of the PIXE method is that the variables related to the characteristic x-ray yield are known or can be experimentally determined.[17] Therefore, it is an absolute method that does not require standard samples. The PIXE method can also be applied to thick samples if they are in standard pellet form so that compensation for the absorbed x-rays can be made.[18] Therefore, the PIXE method was applicable to channel samples if the sample was crushed, blended, ground to 200 mesh, and pressed into pellets. As a result, both channel and aerosol samples were analyzed by the PIXE method in this project. The samples were prepared by project personnel and sent to a commercial lab for analysis.

Application to Impactor Sample

In the PIXE method, the analytical instrument was capable of generating a proton beam of up to 5/8-inch diameter. As a result, the beam is capable of irradiating only one dust submass at a time. In analyzing substrates from a multi-stage impactor, the large number of substrates and submasses involved can result in very large analysis costs. As a result, the investigators decided to limit the number of substrates to which the elemental analysis procedure was applied. In choosing selected substrates, it was decided to utilize substrates that are normally loaded to an appropriate level and to span both the respirable and nonrespirable size ranges. This led us to choose the third-stage (10 to 15 um), fifth-stage (3.5 to 6 um), and seventh-stage (0.9 to 2 um) substrates for analysis. Before deciding the number of submasses to be analyzed per substrate, a statistical analysis of the submass variation was conducted.

The entire dust mass on any given substrate can be analyzed using six irradiations of the proton beam. As a measure of the variation in any given irradiation on a substrate, the coefficient of variation (CV) in the weight percentage of the elements on a given substrate was determined. The airborne dust collected in the immediate return of the continuous miner in a development section was used for this purpose. When considering the major elements (Mg, Al, Si, P, S, K, Ca, Ti and Fe), the CVs were relatively small on the third and fifth stages of the impactor with most CVs being less than 20 percent. On the seventh stage, the CVs were higher relative to the upper stages with most values being less than 50 percent. Submass-to-submass variation of the trace elements was much higher with numerous CVs above 100 percent. However, most of the trace elements with CVs greater than 100 percent had extremely low concentrations, usually less than 1 ppm by weight. This clearly leads to higher variations because some elements will be recorded as non-existent if their concentrations fall below the detection limit. As in the major elements, the submass-to-submass variation increased in the lower stages.

In addition to the relatively small variance in the data, one also obtains a strong feeling for the stability in values of the non-organic portion of the dust by studying the ratios of the major element weight percentages to that of silicon. Using this procedure, the analysis from each dust submass on a given substrate shows a remarkable resemblance as a result of the fact that the effects of the organic elements are removed. As a result of these results, it was decided by the investigators that two submasses from each substrate would be appropriate for analysis by the PIXE method.

Results of Field Studies

Data for the elemental composition studies reported here were collected in seven different continuous miner sections located in six bituminous coal mines in Pennsylvania. Five of the seven sections sampled in this portion of the study were

TABLE I

Effects of Size on the Major Element Composition

Elements[(1)]	Comparison[(2)]	Stage/Mean[(3)]
Sampling Location: CI (intake of continuous miner)		
SI	5,3 > 3,7	5/ 55.676, 3/ 41.517, 7/ 9.513
S	3,5 > 7	3/ 16.850, 5/ 13.288, 7/ 6.102
Ca	3,5 > 5,7	3/ 83.128, 5/ 46.313, 7/ 5.333
Ti	3,5 > 7	3/ 2.274, 5/ 1.567, 7/ 0.202
Fe	3 > 5,7	3/ 36.981, 5/ 14.616, 7/ 2.533
MONOVA Test		
Wilks' Lambda = 0.036	F(128,366) = 1.68	Pr > F = 0.0001
Pillai's Trace = 2.526	F(128,448) = 1.61	Pr > F = 0.0002
Sampling Location: CR (immediate return of continuous miner)		
Al	3 > 5 > 7	3/ 52.123, 5/ 30.384, 7/ 10.208
Si	3 > 5 > 7	3/ 92.256, 5/ 47.916, 7/ 14.394
P	7 > 5,3	7/ 2.090, 5/ 1.116, 3/ 1.000
S	3 > 5,7	3/ 16.538, 5/ 9.247, 7/ 6.545
K	3 > 5,7	3/ 8.939, 5/ 5.608, 7/ 3.593
Ca	3,5 > 5,7	3/ 31.507, 5/ 19.325, 7/ 6.108
Ti	3 > 5 > 7	3/ 4.391, 5/ 2.299, 7/ 0.496
Fe	3,5 > 7	3/ 19.223, 5/ 14.696, 7/ 3.040
Wilks' Lambda = 0.183	F (18, 92) = 6.84	Pr > F = 0.0001
Pillai's Trace = 0.987	F (18, 94) = 5.09	Pr > F = 0.0001
Sampling Location: RI (intake of the roof bolter)		
Al	5,3 > 7	5/ 66.296, 3/ 58.844, 7/ 17.022
Si	5,3 > 7	5/120.350, 3/116.320, 7/ 22.400
S	3 > 5 > 7	3/ 21.693, 5/ 12.183, 7/ 5.302
Ca	3,5 > 5,7	3/ 31.078, 5/ 21.509, 7/ 4.815
Wilks' Lambda = 0.106	F (18, 26) = 2.99	Pr > F = 0.0055
Pillai's Trace = 1.267	F (18, 28) = 2.69	Pr > F = 0.0093
Sampling Location: RR (immediate return of the roof bolter)		
Mg	3,5 > 5,7	3/ 2.947, 5/ 1.517, 7/ 0.574
Al	3 > 5 > 7	3/ 61.936, 5/ 41.807, 7/ 15.187
Si	3 > 5 > 7	3/113.760, 5/ 72.140, 3/ 22.070
S	3 > 5,7	3/ 19.137, 5/ 8.242, 7/ 6.397
K	3 > 5 7	3/ 14.989, 5/ 9.953, 7/ 3.323
Ca	3 > 5,7	3/ 43.562, 5/ 20.357, 7/ 5.590
Ti	3,5 > 7	3/ 4.041, 5/ 2.802, 7/ 0.799
Fe	3,5 > 7	3/ 36.894, 5/ 24.860, 7/ 6.639
Wilks' Lambda = 0.101	F (18, 50) = 5.95	Pr > F = 0.0001
Pillai's Trace = 1.269	F (18, 52) = 5.02	Pr > F = 0.0001

TABLE I (Continued)

Elements[1]	Comparison[2]	Stage/Mean[3]
Sampling Location: 2X (two crosscuts outby the face operations)		
Mg	3,5 > 5,7	3/ 1.673, 5/ 1.199, 7/ 0.294
Al	3,5 > 7	3/ 47.591, 5/ 36.000, 7/ 9.310
Si	3,5 > 7	3/ 80.187, 5/ 58.695, 3/ 13.814
S	3 > 5,7	3/ 30.219, 5/ 18.714, 7/ 7.595
K	3,5 > 7	3/ 10.292, 5/ 8.322, 7/ 1.945
Ca	3 > 5,7	3/ 42.408, 5/ 14.579, 7/ 5.182
Ti	3,5 > 7	3/ 5.626, 5/ 4.099, 7/ 0.600
Wilks' Lambda = 0.089	$F(18, 38) = 4.96$	$Pr > F = 0.0001$
Pillai's Trace = 1.370	$F(18, 40) = 4.83$	$Pr > F = 0.0001$
Sampling Location: 4X (four crosscuts outby the face operations)		
Al	5,3 > 7	5/ 35.579, 3/ 31.965, 7/ 8.143
Si	5,3 > 7	5/ 57.216, 3/ 54.495, 7/ 11.305
S	3,5 > 7	3/ 19.045, 5/ 17.081, 3/ 6.877
K	5,3 > 7	5/ 7.710, 3/ 7.249, 7/ 1.546
Ca	3 > 5,7	3/ 37.649, 5/ 17.557, 7/ 4.436
Ti	3,5 > 7	3/ 3.234, 5/ 2.983, 7/ 0.410
Fe	3,5 > 5,7	3/ 52.753, 5/ 26.702, 7/ 2.749
Wilks' Lambda = 0.010	$F(18, 26) = 12.57$	$Pr > F = 0.0001$
Pillai's Trace = 1.329	$F(18, 28) = 3.08$	$Pr > F = 0.0037$

Notes:

(1) Only the elements showing significant size effects at an alpha risk of 5 percent by ANOVA are listed.

(2) Comparisons are based upon the multiple F-test, REGW. Stages connected by a comma indicate no significant difference between them.

(3) The unit for the mean values is 102 x percent by weight.

using single-split ventilation schemes. As a result, return airway samples associated with the miner and bolter operations are not differentiated. The elemental data used in the paper are relative values expressed as weight percentages. Because of the volume of data (over 7000 values of elemental weight percentages), the data is not presented here. However, the complete data set will be available through the Generic Technology Center for Respirable Dust at The Pennsylvania State University. The study results reported here are confined to the topics of relating the elemental compositions to the size of the dust, the location of the samplers in the mine layout, and the materials being cut.

Size Dependency of Elemental Compositions

The size dependency of the elemental composition characteristics of airborne coal mine dust was tested using standard univariate and multivariate statistical methods. At each sampling location, a multiple F-test known as the Ryan-Einot-Gabriel-Welsch (REGW) test was performed along with the analysis of variance (ANOVA) procedure to compare the concentrations of the individual elements in the three size fractions that were analyzed. Then, taking into account the correlation structure among the elements, the multivariate analysis of variance (MANOVA) procedure was applied to test the significance of the differences in the overall elemental compositions of the dust samples in the three size fractions. In all of these statistical tests, the trace elements were analyzed separately from the major elements.

Tables I and II contain the elements that showed a significant size dependency at an alpha value (level of significance) of 5 percent and the results of the equality tests by the multiple F-test at each of the sampling locations. Also included are results of the MANOVA for significance of the differences in the centroids of the 9 major element and the 21 trace elements for the three different size fractions.

As shown in Table I, airborne coal mine dust samples from all the sampling locations show significant size effects in the overall composition of the major elements; however, samples from the immediate return of the bolter operation have a relatively weak size dependency compared to the other sampling locations. Significant size dependency is observed in the two elements most common in the clay minerals, Al and Si, at all locations except at the intake of the miner. In the samples from the immediate returns of the miner and bolter operations, these two elements show their highest concentrations on the third stage, while no significant difference is observed between the third and fifth stages at the other sampling locations. Major elements showing a significant size dependency at all the locations are Si, S, and Ca.

A noticeable difference between the immediate return samples of the miner and bolter operations is that Mg, a major element in rock dust, shows a size dependency only in the return of the roof bolter. A size dependency of Mg is also found at two crosscuts outby the face operation but disappears at four crosscuts outby. An increase in the number of

TABLE II

Effects of Size on the Trace Element Compositions

Elements(1)	Comparison(2)	Stage/Mean(3)
Sampling Location: CI		
Mn	3,5 > 7	3/ 0.319, 3/ 0.152, 7/ 0.029
Ni	3 > 5,7	3/ 0.132, 5/ 0.024, 7/ 0.007
Br	3 > 5.7	3/ 0.105, 5/ 0.035, 3/ 0.006
Sr	3 > 5,7	3/ 0.447, 3/ 0.123, 7/ 0.017
Zr	3 > 5,7	3/ 0.194, 5/ 0.033, 7/ 0.013
MANOVA Test		
Wilks' Lambda = 0.060	F (32, 24) = 2.31	Pr > F = 0.0185
Pillai's Trace = 1.307	F (32, 26) = 1.31	Pr > F = 0.1336
Sampling Location: CR		
Cl	3 > 5,7	3/ 2.433, 3/ 1.298, 7/ 0.795
V	3 > 5 > 7	3/ 0.137, 5/ 0.079, 7/ 0.002
Cr	3,5 > 7	3/ 0.081, 5/ 0.059, 3/ 0.008
Ni	3,5 > 7	3/ 0.037, 3/ 0.036, 7/ 0.008
Br	3,5 > 7	3/ 0.074, 5/ 0.038, 7/ 0.022
Rb	3,5 > 7	3/ 0.101, 5/ 0.068, 7/ 0.024
Sr	3 > 5 > 7	3/ 0.248, 5/ 0.130, 7/ 0.021
Zr	3 > 5 > 7	3/ 0.120, 5/ 0.066, 7/ 0.023
Mo	3 > 5,7	3/ 0.044, 5/ 0.007, 7/ 0.003
Pb	3,5 > 7	3/ 0.078, 5/ 0.049, 7/ 0.011
Wilks' Lambda = 0.215F (32, 78) = 2.81Pr > F = 0.0001		
Pillai's Trace = 1.045	F (32, 80) = 2.74	Pr > F = 0.0001
Sampling Location: RI		
None of the elements shows significant variation among the three different size fractions.		
Sampling Location: RR		
V	3 > 5,7	3/ 0.148, 5/ 0.068, 7/ 0.005
Mn	3,5 > 7	3/ 0.394, 5/ 0.281, 3/ 0.084
Ge	7 > 3,5	7/ 0.002, 3/ 0.000, 5/ 0.000
Br	3,5 > 5,7	3/ 0.049, 5/ 0.035, 7/ 0.021
Rb	3,5 > 5,7	3/ 0.201, 5/ 0.120, 7/ 0.027
Sr	3 > 5 > 7	3/ 0.213, 5/ 0.125, 7/ 0.036
Zr	5,3 > 7	3/ 0.121, 5/ 0.109, 7/ 0.024
Pb	3 > 5,7	3/ 0.176, 5/ 0.099, 7/ 0.038
Wilks' Lambda = 0.135	F (32, 36) = 1.94	Pr > F = 0.0279
Pillai's Trace = 1.242	F (32, 38) = 1.95	Pr > F = 0.0250
Sampling Location: 2x		
Cl	3 > 5 > 7	3/ 2.892, 5/ 1.685, 7/ 0.547
Cu	3,5 > 5,7	3/ 0.678, 5/ 0.442, 3/ 0.067
Sr	3 > 5,7	3/ 0.700, 5/ 0.196, 7/ 0.019
Wilks' Lambda = 0.037	F (32, 24) = 3.17	Pr > F = 0.0023
Pillai's Trace = 1.586	F (32, 26) = 3.11	Pr > F = 0.0020
Sampling Location: 4x		
Cl	5,3 > 3,7	5/ 2.304, 3/ 1.766, 7/ 0.650
V	5,3 > 3,7	5/ 0.075, 3/ 0.038, 7/ 0.003
Cr	5,3 > 7	5/ 0.093, 3/ 0.060, 7/ 0.013
Mn	3,5 > 5,7	3/ 0.449, 5/ 0.229, 7/ 0.022
Ni	3,5 > 5,7	3/ 0.109, 5/ 0.056, 7/ 0.011
Zn	3 > 5,7	3/ 6.852, 5/ 1.373, 7/ 0.622
Sr	3 > 5,7	3/ 0.360, 5/ 0.157, 7/ 0.016
Pb	3,5 > 7	3/ 0.286, 5/ 0.238, 7/ 0.012
Wilks' Lambda = 0.002	F (32, 12) = 8.21	Pr > F = 0.0002
Pillai's Trace = 1.780	F (32, 14) = 3.53	Pr > F = 0.0075

Notes: See the Notes for Table I.

major elements showing size dependency can be seen in the returns of the miner and bolter operations compared to that in their intakes. Concentrations of many of the major elements do not show significant differences between the third and fifth stages, but those on the seventh stage are smaller. The element P, which shows significant size effects in the samples from the immediate return of the miner is the only element that shows its highest concentration on the seventh stage.

In Table II, where trace element statistical results are shown, the MANOVA test results indicate no significant difference in the overall trace element compositions in the intake airways of the miner and bolter operations. However, the trace element compositions showed significant size dependency in the immediate return of the miner with a less significant size dependency detected in the immediate return of the bolter. Parallel to that for the major elements, the immediate return of the miner shows the most significant size dependencies in the trace element compositions as well as the largest number of elements showing size dependency. In general, the samples associated with the bolter indicate the weakest size effects among the trace elements. V, Br, Rb, Sr and Zr indicate significant size dependency in the immediate returns of the miner and bolter while the concentrations of Cl, Cr, Ni and Mo vary with size only in the immediate return of the miner operation. In the size dependencies shown for the trace elements, all had lower concentrations in the finer size ranges.

TABLE III

ANOVA Tests for Locational Variability of the Total Weight Fractions of the Major and Trace elements and Organic Component

Variables	Comparison[1]	Location/Mean[2]
On the Third Stage (10-15 um)		
Major Elements	no difference	
Trace Elements	IN > the other locations	IN/ 35.261 2X/ 13.183 4X/ 11.180 CI/ 8.830 RR/ 4.795 RI/ 4.673 CR/ 4.337
Organic Fraction	no difference	
On the Fifth Stage (3.5-6 um)		
Major Elements	IN, RI > RI, RR 2X, CI, 4X, CR	IN/510.370 RI/304.400 RR/182.710 2X/180.500 CI/172.370 4X/167.110 CR/131.120
Trace Elements	IN > the other locations	IN/ 30.905 2X/ 6.686 RI/ 6.288 4X/ 5.362 CI/ 5.107 RR/ 3.486 CR/ 2.888
Organic Fraction	CR, 4X, CI, RR, 2X, RI RI, IN	CR/ 98.660 4X/ 98.275 CI/ 98.225 RR/ 98.138 2X/ 98.128 RI/ 96.893 IN/ 94.587
On the Seventh Stage (0.9-2 um)		
Major Elements	RR, RI, CR, 2x CR, 2X, 4X, IN, CI	RR/ 62.349 RI/ 62.075 CR/ 47.205 2x/ 45.551 4X/ 37.579 IN/ 33.538 CI/ 33.270
Trace Elements	No difference	
Organic Fraction	CI, IN, 4X, 2X, CR 2X, CR, RI, RR	CI/ 99.649 IN/ 99.645 4X/ 99.610 2X/ 99.527 CR/ 99.511 RI/ 99.365 RR/ 99.360

Notes:

(1) Comparisons are made based upon the multiple F-test, REGW. Locations connected by a comma indicate no significant difference between them.

(2) The unit is 102 x percent by weight except in the organic component; percent by weight for the organic component.

It should be mentioned that all the elements below Na in the periodic table are not analyzed by the PIXE method. Most of the undetected material will be the organic components of the coal which are predominantly composed of C, H and O. Therefore, the weight fraction of the airborne coal mine dust sample other than that of the major and minor elements detected has been designated as the organic fraction in this paper. As shown in Table III, the organic fraction shows its highest concentrations in the size range of 0.9 to 2 um at all the sampling locations. This indicates that this size range is made up of more organic material than the other coarser size ranges.

One additional comment concerning the elemental composition and its relationship to the size is the general trend observed. The concentrations of most of the elements detected by the PIXE method were higher in the coarser size ranges. This led the investigators to question whether the PIXE method was providing weight percentages of the elements that were dependent upon the total weight on each substrate or whether the weights were biasing the results. To answer this question, correlations between the weight percentages of the elements and the sample weights was tested in the course of this study. Considering the result that none of the elements showed a significant positive correlation, it does not seem that the size dependency of elemental com-

TABLE IV

MANOVA Tests for Locational Variation of the Major Element Composition

Elements(1)	Comparison(2)	Location/Mean(3)
On the Third Stage (10-15 um)		
P	IN > the other locations	IN/ 36.921 CI/ 2.200 RR/ 2.110 RI/ 1.666 4X/ 1.650 2X/ 1.563 CR/ 1.000
S	IN > the other locations	IN/140.880 2X/ 30.220 RI/ 21.690 RR/ 19.140 4X/ 19.050 CI/ 16.850 CR/ 16.54
K	RI, RR, 2X, CR > RR, 2X, CR, 4X > 2X, CR, 4X, CI, IN	RI/ 17.182 RR/ 14.989 2X/ 10.292 CR/ 8.938 4X/ 7.248 CI/ 4.673 IN/ 0.894
MANOVA Test		
Wilks' Lambda = 0.122	F (54, 300) = 2.84	Prob > F = 0.0001
Pillai's Trace = 1.632	F (54, 378) = 2.62	Prob > F = 0.0001
On the Fifth Stage (3,5-6 um)		
Mg	RI, CI, RR, 2X, 4X, CR CI,RR,2X 2X, 4X, CR, IN	RI/ 3.694 CI/ 2.693 RR/ 1.517 2X/ 1.199 4X/ 0.939 CR/ 0.532 IN/ 0.000
Si	IN, RI, RR RI, RR, 2X, 4X, CI, CR	IN/130.290 RI/120.350 RR/ 72.140 2X/ 58.700 4X/ 57.220 CI/ 55.680 CR/ 47.920
P	IN > the other locations RI/ 1.340	IN/ 22.672 CI/ 2.815 4x/ 1.346 2X/ 1.124 CR/ 1.116 RR/ 8.240
S	IN > the other locations	IN/129.400 2X/ 18.710 4X/ 17.080 Ci/ 13.290 RI/ 12.180 CR/ 9.250 RR/ 1.029
K	RI, RR > RR, 2X, 4X, CI, IN, CR	RI/ 18.939 RR/ 9.953 2X/ 8.322 4X/ 7.710 CI/ 7.000 IN/ 6.239 CR/ 5.608
Ca	IN, CI CI, RI, RR, CR, 4X, 2X	IN/ 78.123 CI/ 46.313 RI/ 21.509 RR/ 20.357 CR/ 19.325 4X/ 17.557 2X/ 14.579
Fe	IN, Ri, 2X, 4X RR RI, 2X, 4X, RR, CR, CI	IN/ 78.334 RI/ 54.023 2X/ 37.764 4X/ 26.702 RR/ 24.860 CR/ 14.696 CI/ 14.616
Wilks' Lambda = 0.048	F (54, 300) = 4.52	Prob > F = 0.0001
Pillai's Trace = 1.878	F (54, 378) = 3.19	Prob > F = 0.0001

TABLE IV (Continued)

Elements(1)	Comparison(2)	Location/Mean(3)
On the Seventh Stage (0.9-2 um)		
Al	RI, RR, CR > RR, CR, 2X, 4X CR, 2X, 4X, CI, IN	RI/ 17.022 RR/ 15.187 CR/ 10.208 2X/ 9.310 4X/ 8.143 CI/ 5.896 IN/ 3.751
Si	RI, RR > RR, CR 2X, 4X, CI, IN IN/ 7.768	RI/ 22.399 RR/ 22.072 CR/ 14.394 2X/ 13.814 4X/ 11.305 CI/ 9.513
Fe	RR, 2X, RI, IN > 2X, RI, IN, CR, 4X, CI	RR/ 6.639 2X/ 5.138 RI/ 4.133 IN/ 3.436 CR/ 3.040 4X/ 2.749 CI/ 2.533
MANOVA Test		
Wilks' Lambda = 0.234	F (54, 300) = 1.83	Prob > F = 0.0009
Pillai's Trace = 1.131	F (54, 378) = 1.63	Prob > F = 0.0053

Notes:

(1) This column contains the elements showing significant locational variability at an alpha risk of 5 percent by ANOVA

(2) Comparisons are made based upon the multiple F-test, REGW. All the locations connected by commas indicate no significant difference between them.

(3) The unit for the means is 102 x percent by weight.

positions observed in this study is due to the lack of sensitivity of the PIXE method or bias related to the sample weight.

Variation With Section Location

In assessing the variation in elemental composition with the section location, a similar suite of statistical procedures was used but stepwise discriminant analysis was used in addition to identify those elements that provide a significant contribution to the locational variability. The tests were performed separately on the dust samples from the three different size fractions.

As shown in Table IV, the major element compositions in all three size ranges show significant differences among the seven different sampling locations. In the size range of 10 to 15 um, concentrations of P, S and K vary significantly over the various locations according to the MANOVA tests as well as the stepwise discriminant analysis which is summarized in Table V. These three elements show the highest concentrations in the intake air while the immediate return of the miner operation appears to contain the lowest levels even though the differences among the locations other than the intake airways are not statistically significant.

In the size range from 3.5 to 6 um, Si and K show significant locational variation and have their highest concentrations near the roof bolter operation. In addition, Ca shows a significant locational variation in this size range with the most enriched values occurring in the intake air. Because Ca occurs in abundance in rock dust, this occurrence may be due to rock dust being reentrained in the intake air stream. In the finest size range from 0.9 to 2 um, Al and Si show much higher concentrations near the miner and bolter and are significantly enriched near the bolter. This is hypothesized to be a result of the minerals present in the roof rock. As shown in Table IV, locational variation of the total weight percentages of the 9 major elements are not statistically significant in the 10 to 15 um range; however, the differences become significant in the finer size ranges. In general, the pattern that exists is that the higher weight percentage of the major elements are associated with the bolter operation in the minus 6 um range of dust size.

Table VI indicates significant locational variation of the overall compositions of the trace elements in all three size ranges. In the size range of 10 to 15 um, V, Zn and Sr are the trace elements showing significant locational variation. V and Zn are highly enriched near the face operations and in the intake airway, respectively, while Sr shows less concentration near the face. In the size range of 3.5 to 6 um, Cl, As and Rb indicate significant locational variation. Rb shows higher concentrations near the roof bolter operation, while Cl and As have lower concentrations near the face operations. In the finest size range of 0.9 to 2 um, the element As has higher concentrations in the return airway, while Br and Mo are enriched near the face operations and roof bolter, respectively. In terms of the total weight percentages of the trace elements, the intake airway shows the highest values in the size range above 3.5 um, while locational variation is not significant in the size range of 0.9 to 2 um. As shown in Table VII, in the size range below 6 um, sampling locations near the miner operation contain significantly higher organic fractions compared to the bolter operation. However, the differences are not significant in the size range of 10 to 15 um.

Effects of Geologic Materials Mined on the Elemental Composition

Effects of the materials being cut on the elemental characteristics of airborne coal mine dust can be studied by measuring the similarity in characteristics between them. The

TABLE V

Stepwise Discriminant Analysis for Locational Variability of the Major and Trace Elements

Step	Selected(1) Elements	F Statistic	Prob > F	Wilk's Lambda	Prob > Wilk's Lambda
For the Major Elements					
On the Third Stage (10-15 um)					
1	P	5.363	0.0001	0.672	0.0001
2	K	4.845	0.0004	0.464	0.0000
3	Si	3.958	0.0020	0.339	0.0000
4	S	3.551	0.0043	0.253	0.0000
5	Ca	3.186	0.0086	0.193	0.0000
On the Fifth Stage (3.5 - 6 um)					
1	K	3.679	0.0033	0.475	0.0000
2	Si	5.628	0.0001	0.311	0.0000
3	Al	15.359	0.0001	0.126	0.0000
4	Ti	3.445	0.0053	0.105	0.0000
5	Ca	2.747	0.0197	0.083	0.0000
On the Seventh Stage (0.9 - 2 um)					
1	Si	6.691	0.0001	0.622	0.0000
2	Mg	2.320	0.0432	0.512	0.0000
3	Al	2.195	0.0548	0.425	0.0000
For the Trace Elements					
On the Third Stage (10-15 um)					
1	Sr	2.834	0.0163	0.594	0.0004
2	V	3.508	0.0046	0.447	0.0000
3	Zn	2.656	0.0232	0.357	0.0000
4	As	1.933	0.0894	0.300	0.0000
5	Mn	1.893	0.0965	0.253	0.0000
6	Ni	3.615	0.0040	0.186	0.0000
On the Fifth Stage (3.5 - 6 um)					
1	Cl	3.617	0.0037	0.753	0.0037
2	As	2.922	0.0138	0.593	0.0004
3	Rb	2.802	0.0175	0.469	0.0000
On the Seventh Stage (0.9 - 2 um)					
1	As	3.811	0.0025	0.743	0.0025
2	Mo	2.811	0.0171	0.590	0.0004
3	Mn	2.384	0.0385	0.482	0.0001
4	Br	2.746	0.0196	0.382	0.0000
5	Cr	2.478	0.0326	0.308	0.0000
6	Cu	1.927	0.0906	0.259	0.0000

Note: The selected elements denote the final selection of elements excluding all the removed elements at an alpha risk of 15 percent.

similarity can be quantified through the coefficient of proportional similarity which is the cosine of the angle between the two vectors of the overall elemental compositions in the n-space of the n compositions being considered. For example, the elemental composition of the dust samples in each size fraction from the impactor in the immediate return of the miner can be compared with that of the channel samples taken at the working face. If numerous types of geologic material (bottom rock, coal, rock parting, bony coal, roof rock) are separately sampled, then the elemental characteristics of each geologic material may be tested for similarity with the airborne dust. Only a summary of the findings are discussed in this section. A detailed description of the study and analyses of the results will be available in another paper being prepared by the authors.

As a general conclusion, it can be said that the major element compositions of the dust samples from the immediate return of the miner operation are very closely associated with the coal seam, regardless of the size range of airborne dust samples and presence of noncoal bands in the coal seam. This relationship has been observed in the samples from all seven sections studied in this paper. However, the relationship based upon the trace elements is not consistent. In some sections, the trace element compositions of the dust particles in all three size ranges show high similarities with the coal bands in the seam. In other cases, their close association is observed only in the fine size range of 0.9 to 2 um, while the noncoal bands show much higher similarities in the other size ranges. The opposite relationship is also observed in other occasions; noncoal bands show much higher similarities with dust samples in the fine size range and, in the coarser size ranges, coal bands indicate higher similarities. These discrepancies may be due to the differences in the modes of occurrences of the trace elements as minerals or impurities in the organic coal or in the rock materials. However, without any information concerning these characteristics, further explanation cannot be made on the causes of the differences in the trace element compositions of the airborne coal mine dust and the materials being cut

Summary and Conclusions

The size dependency of the major and trace elements in airborne coal mine dust was shown to be significant at almost

TABLE VI

MANOVA Tests for Locational Variation of the Trace Element Composition

Elements(1)	Comparison(2)	Location/Mean(3)
On the Third Stage (10-15 um)		
Cl	IN > the other locations	IN/ 15.602 2x/ 2.892 CR/ 2.433 CI/ 2.162 4X/ 1.766 RR/ 1.656 RI/ 1.399
V	2X, RR, RI, CR, CI > RR, RI, CR, CI, 4X, IN	2X/ 0.434 RR/ 0.148 RI/ 0.141 CR/ 0.137 CI/ 0.042 4X/ 0.048 IN/ 0.000
Cu	no difference	2Z/ 0.678 CI/ 0.533 RI/ 0.297 IN/ 0.295 4X/ 0.292 RR/ 0.240 CR/ 0.140
Zn	IN > the other locations	IN/ 17.120 4X/ 6.852 CI/ 3.942 2X/ 3.801 RI/ 1.533 RR/ 1.271 CR/ 0.669
Sr	2X, CI, 4X, CR, RR CI, 4X, CR, RR, RI, IN	2X/ 0.700 CI/ 0.447 4X/ 0.360 CR/ 0.248 RR/ 0.213 RI/ 0.154 IN/ 0.014
MANOVA Test		
Wilks' Lambda = 0.089	F (96, 295) = 1.64	Prob > F = 0.0009
Pillai's Trace = 1.899	F (96, 336) = 1.62	Prob > F = 0.0010
On the Fifth Stage (3.5 - 6 um)		
Cl	IN > the other locations	IN/ 12.402 RI/ 2.458 4X/ 2.304 2X/ 1.685 CI/ 1.666 RR/ 1.528 CR/ 1.298
Mn	IN, RI, RR > RI, RR, 2X, 4X, CI, CR	IN/ 0.793 RI/ 0.565 RR/ 0.281 2X/ 0.247 4X/ 0.229 CI/ 0.152 CR/ 0.114
Cu	IN, 2X, CI, RI, 4X > 2X, CI, RI, 4X, CR, RR	IN/ 0.788 2X/ 0.442 CI/ 0.357 RI/ 0.321 4X/ 0.246 CR/ 0.143 RR/ 0.108
As	2X > the other locations	2X/ 0.040 CI/ 0.010 RR/ 0.006 4X/ 0.006 RI/ 0.005 CR/ 0.004 IN/ 0.000
Rb	RI, 2X, RR, 4X > 2X, RR, 4X, CR, CI, IN	RI/ 0.328 2X/ 0.187 RR/ 0.120 4X/ 0.109 CR/ 0.068 CI/ 0.035 IN/ 0.007
Zr	IN, 2X > 2X, RI, 4X, RR, CR, CI	IN/ 0.497 2X/ 0.209 RI/ 0.183 4X/ 0.141 RR/ 0.121 CR/ 0.066 CI/ 0.033
MANOVA Tests on the Fifth Stage		
Wilks' Lambda = 0.037	F (96, 295) = 2.42	Prob > F = 0.0001
Pillai's Trace = 2.400	F (96, 336) = 2.33	Prob > F = 0.0001

TABLE VI (Continued)

Elements[1]	Comparison[2]	Location/Mean[3]
On the Seventh Stage (0.9 - 2 um)		
MN	no difference	RR/ 0.084 RI/ 0.049 IN/ 0.047 CR/ 0.045 CI/ 0.029 2X/ 0.028 4X/ 0.022
Zn	2X, IN, CI, RR, 4X, CR > CI, RR 4X, CR, RI	2X/ 0.944 IN/ 0.922 CI/ 0.826 RR/ 0.722 4X/ 0.622 CR/ 0.602 RI/ 0.505
As	2X, 4X > 4X, IN, RR, CI, RI, CR	2X/ 0.025 4X/ 0.011 IN/ 0.009 RR/ 0.007 CI/ 0.004 RI/ 0.003 CR/ 0.002
Br	CR, IN, RR, 2X, CI, RI > IN, RR, 2X, CI, RI, 4X	CR/ 0.022 IN/ 0.021 RR/ 0.021 2X/ 0.018 CI/ 0.017 RI/ 0.005 4X/ 0.005
Mo	In, 2X, RR, CI, RI > 2X, RR, CI, RI, CR, 4X	IN/ 0.033 2X/ 0.024 RR/ 0.015 CI/ 0.013 RI/ 0.003 CR/ 0.003 4X/ 0.000
MANOVA Test		
Wilks'Lambda = 0.096	F(96,295) = 1.58Prob > F = 0.0021	
Pillai's Trace = 1.798	F(96,336) = 1.50Prob > F = 0.0049	

Notes:

(1) This column contains the elements showing significant locational variability at an alpha risk of 5 percent by ANOVA.

(2) Comparisons are made based upon the multiple F-test, REGW. All the locations connected by comma indicate no significant difference between them.

(3) The mean is in unit of 102 x % by weight.

all locations in underground coal mine sections utilizing continuous miners. In general, the size effects were more significant near the miner operation and the immediate return of the face operation indicated higher size dependency than the immediate intake.

The elemental compositions of airborne coal mine dust varied significantly among the various sampling locations. However, the elements showing significant locational variation were different in the different size ranges analyzed. Most of the elements with significant locational variability were found to be enriched near the bolter operation. The organic fraction of airborne coal mine dust was higher in the fine size range of 0.9 to 2 um and near the miner operation.

Concentrations of almost all elements detected by the PIXE method were relatively higher in the coarser size ranges. Statistical tests indicated that this result was not due to bias in the analytical procedure. It is thought that this result is a function of the size of the salts and minerals that are the source of the trace elements.

The major element composition of airborne coal mine dust generated from the face was shown to be very similar to that of the coal seam. However, characterization of the mineral components and study of the occurrence mode of the trace elements are necessary to explain the discrepancies in the relationship of the trace element composition between the airborne coal mine dust and materials being cut a different sections.

As a final point of discussion, it should be mentioned that this study of elemental compositions is a part of a larger and more encompassing study that will consider the mineralogical and morphological characteristics as well. However, this study has proven that airborne coal mine dust is certainly not a homogeneous material. The composition is clearly shown to vary with size, the location in the mine workings, and with the characteristics of the source materials. This has very clear implications in further studies, particularly with regard to the types of coal used in medical studies related to CWP development.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

References

1. **Hamilton, R.J.:** *Industrial Health and Saftey.* A synthesis report on research supported by the Commission of the European Community during the period 1977-82, Luxembourg (1985).

TABLE VII

Variation In the Total Weight Fractions of the Major and Trace Elements and the Organic Components of Coal Mine Dust

Sampling Locations	Major Elements			Trace Elements			Organic Components		
	Weight Percentages[(2)]								
Stage[(1)]	3	5	7	3	5	7	3	5	7
IN[(3)]	485.31/	510.37/	33.54	35.26/	30.91/	1.98	94.79/	94.59/	99.65
CI	213.14/	172.37/	33.27	8.83/	5.11/	1.93	97.78/	98.23/	99.65
CR	227.16/	131.03/	47.21	4.34/	2.89/	1.65	97.69/	98.66/	99.51
RI	286.51/	304.40/	62.08	4.67/	6.29/	1.40	97.09/	96.89/	99.37
RR	299.38/	182.71/	62.35	4.80/	3.49/	1.60	98.21/	98.14/	99.36
2X	387.19/	180.50/	45.55	13.18/	6.69/	1.78	96.00/	98.13/	99.53
4X	209.93/	167.11/	37.58	11.18/	5.36/	1.46	97.79/	98.28/	99.61

Notes:

(1) The columns headed by 3, 5 and 7 indicate the weight percentages on the third, fifth and seventh stages in the cascade impactors.

(2) The unit for the major and trace elements is 102 x percent by weight, percent by weight for the organic components.

(3) See Table I for identification of sampling location codes.

2. **O'Gorman, J.V.:** Studies on Mineral Matter and Trace Elements in North American Coals. Unpublished Ph.D. Thesis, The Pennsylvania State University, University Park, PA (1971).

3. **Glick, D.C.:** Variability in the Inorganic Content of United States' Coals, A Multivariate Statistical Study. Unpublished M.S. Thesis, The Pennsylvania State Univerity, University Park, PA (1984).

4. **Carlberg, J.R., J.V. Crable, L.P. Limhaco et al:** Total Dust, Coal, FreeSilica, and Trace Metal Concentrations in Bituminous Coal Miners' Lungs. *Am. Ind. Hyg. Assoc. J. 32*:432-440 (1971).

5. **Sweet, D.V., W.E. Crouse, J.V. Crable et al:** The Relationship of Total Dust, Free Silica, and Trace Metal Concentrations to the Occupational Respiratory Disease of Bituminous Coal Miners. *Am. Ind. Hyg. Assoc. J. 5*:479-485 (1974).

6. **Sorenson, J.J., T.E. Kober and H.G. Petering:** The Connection of Cd, Cu, Fe, Ni, Pb and Zn in Bituminous Coals from Mines with Differing Incidences of Coalworkers' Pneumoconiosis. *Am. Ind. Hyg. Assoc. J. 35*:93-98 (1974).

7. **Wesson, T.C. and F.E. Armstrong:** Elemental Composition of Coal Mine Dust. U.S. Bureau of Mines RI 7992 (1975).

8. **Mutmansky, J.M. and C. Lee:** An Analysis of Coal and Geological Variables Related to Coal Workers' Peumoconiosis. *Proceedings of the Coal Mine Dust Conference.* West Virginia University, Morgantown, WV (1984).

9. **Lee, C. and J.M. Mutmansky:** A Strategy for Coal Mine Respirable Dust Sampling Using Multi-Stage Impactors for Characterization Purposes. *Proceedings of the Symposium on Engineering Health and Safety in Coal Mining.* A.W. Khair, Ed. Society of Mining Engineers of AIME, Littleton, CO (1986).

10. **Crable, J.V., R.G. Keenan, R.E. Kinser et al:** Metal and Mineral Concentrations in Lungs of Bituminous Coal Miners. *Am. Ind. Hyg. Assoc. J. 29*:106-110 (1968).

11. **Keenan, R.G., J.V. Crable, A.W. Smallwood and J.R. Carlberg:** Chemical Composition of the Coal Miners' Lung. *Am. Ind. Hyg. Assoc. J. 32*:392-397 (1971).

12. **Sharkey, A.G. Jr., T. Kessler and R.A. Friedel:** Trace Elements in Coal Dusts by Spark-Source Mass Spectrometry. *Trace Elements in Fuel,* Advances in Chemistry Series No. 141, Ch. 4. S.P. Babu Ed. American Chemistry Society, Chicago, IL (1975).

13. **Freedman, R.W.:** Procedures for Analysis of Respirable Dust as Related to Coal Workers' Pneumoconiosis. *Analytical Methods for Coal and Coal Products*, Vol. II, Ch. 28. K. Clarence, Jr., Ed. Academic Press Inc., NY (1978).

14. **Corn, M., F. Stein, Y. Hammad et al:** Physical and Chemical Properties of Respirable Coal Dust from Two United States Mines. *Am. Ind. Hyg. Assoc. J. 33*:295-285 (1973).

15. **Ahlbert, M.S., A.C.D. Leslie and J.W. Winchester:** Environmental and Occupational Health Analysis Using Proton-Induced X-Ray Emission. Electron Microscopy and X-ray *Applications to Environmental and Occupational Health Analysis,* Ch. 4. P.S. Russel and A.E. Hutchings, Eds. Ann Arbor Science, Ann Arbor, MI (1978).

16. **Hudson, G.M., H.C. Kaufman, J.W. Nelson and M.A. Bonacci:** Advances in the Use of PIXE and PESA for Air Pollution Sampling. *Nuclear Instruments and Methods 168*:259-263. North-Holland Publishing Co., Amsterdam (1980).

17. **Johansson, S.A.E. and T.B. Johansson:** Analytical Application of Particle Induced X-ray Emission. *Nuclear Instrument and Methods 137*:473-516. North Holland Publishing Co., Amsterdam (1976).

18. **Chen, J.R., H. Kneis, B. Martin et al:** Trace Elemental Analysis of Bituminous Coals Using the Heidelberg Proton Microprobe. *Nuclear Instruments and Methods 181*:151-157. North-Holland Publishing Co., Amsterdam (1981).

Variation in Mineral and Elemental Composition of Respirable Coal Mine Dusts by Worker Location and Coal Seam

R.A. ANDRE, B.S.[A], T. SIMONYI, B.S.[B] and R.L. GRAYSON, Ph.D.[B]
[A]West Virginia Geological Survey; [B]West Virginia University

The purpose of this paper is to disclose analytical, statistical, and observational results relating to mineralogy and trace elements in respirable dust samples collected from two different mines in West Virginia. Samples were taken from longwall panels, and the panels operated in different coal seams, one located in the northern part of the state and the other in the southern region. Mining conditions and equipment arrangements on the panels will be described along with dust control techniques used. Results from sample analyses are summarized with emphasis on relationships between mineralogy, trace elements, and mineral particle size to worker locations. Correlations are made between micro x-ray diffraction and energy dispersive x-ray analyses for sample mineralogy.

Introduction

Through the work of many researchers worldwide, the health of coal miners in modern societies is now protected from harmful exposure to respirable coal mine dust. A vast amount of research culminated in the exposure-response model of Jacobsen, *et al*,[1] which has been used to establish the 2 mg/m^3 exposure limit in the United States. According to the model, exposure to respirable dust for 35 years at this level or less would prevent the occurrence of a clinically significant case of coal workers' pneumoconiosis (CWP) in a miner. The exposure limit, of course, must be adjusted whenever greather than five percent free silica exists in the respirable dust.

The Jacobsen model was built around a mean mass concentration exposure, which generally showed the highest correlation with both incidence and progression of CWP. As Morgan, *et al* noted, however, the quantity of respirable dust inhaled is not the only significant factor.[2] They noted that although mass of respirable dust correlates highest with the incidence of CWP, it is not a causal factor. Admittedly, the insidious processes causing the disease occur at the lund cell-dust particle level.

A look at past and present research is helpful in determining the properties of respirable coal mine dust warranting characterization. Studying the cytotoxicity of respirable coal dusts, Reisner and Robock correlated cell damage positively with mineral content.[3] Earlier, Leiteritz, Bauer, and Bruckman concluded that the incidence of CWP is related to both quartz and fine dust concentration.[4] The mineral composition of respirable coal mine dust requires closer scrutiny, however, since Walton, Hadden, and Jacobsen suggested that mineral matter may be a protective factor[5], whereas Davis, Ottery, and LeRoux found that the severity of CWP increased in miners with the occurrence of quartz and clay mineral enrichment.[6] A review of research throughout Europe indicates significant activity in mineralogical characterization of respirable coal dusts.[7] An interesting finding in France revealed that not a single case of CWP has occurred in a mine located in the Provence coalfield where a high level of calcite was detected in the dust.

A study of chest x-rays taken of coal miners participating in the National Coal Study illustrated that the incidence of category 1 CWP and progression of the disease to more complicated forms is higher in certain parts of the United States.[8] An analysis by the authors of 87 West Virginia cases of "dust disease of the lung," as reported in the 1984 Health and Safety Analysis Center (HSAC) data base, revealed that 75 cases were initiated from mines operating in the southern part of the state, seven originated from mid-state locations, and five were filed in the northern part of the state. Research is continuing on correlating reported lung diseases and coal seams in which the victims work.

Because of known toxicity of quartz, its characterization is important, but Morgan, as well as Davis, Ottery, and LeRoux, concluded that quartz is not the only cause of progression from CWP to progressive massive fibrosis.[6,9] Mutmansky emphasized that attention should also be placed on the potential relationship between trace elements in respirable dust and CWP.[10] Stein and Corn suggested that more research is needed into the physical and chemical properties of coal mine dusts and the dependence of these properties on mine of origin and particle size.[11] With regard to these properties, it is important that characterization of respirable dusts taken from coal mines be coordinated with research designed to characterize respirable dusts in the lungs of miners. It is also important that analytical results be correlated with mining conditions and methods, worker locations, and coal seams.

In summary, more research is needed in coordinating respirable mass concentration with other physical and chemical properties of respirable dusts. Through such research an explanation of the processes causing incidence of CWP may be achieved. It is evident that mineral composition, trace element existence, and mineral particle size distributions are all aspects warranting closer scrutiny. It is important to note, however, as did Sharkey, Kessler, and Friedel, that there exists a great degree of deviation in the composition of respirable dust from parent material mined.[12] This applies both to mineral and trace element constituents. Therefore, the mechanics of dust generation and transport and the utilization of dust control methods must be described concurrently to explore the reasons for such variability in composition.

Description of Longwall Panels

The longwall panel operating in the Pittsburgh seam, located in Northern West Virginia, had a 167.6 m (550 ft) long face and was equipped with a double-ended ranging drum shearer. The shearer took a 762 mm (30 in) cut and loaded coal onto a 732 mm (28.8 in) wide armored face conveyor. A crusher was mounted on the stage loader to reduce the size of rock, which frequently fell from exposed roof. An average mining height of 1.98 m (78 in) was maintained, with an average of 0.20 m (8 in) of floor mined. Normal practice was to cut from the tailgate to the headgate with the leading drum raised and the tail drum lowered, cutting bottom. After reaching the headgate, the shearer was reversed and both drums lowered for a clean-up pass. The last 12.2 m (40 ft) of the face on the tailgate end was cut on the clean-up pass. The shearer traveled at a speed ranging from 0.054 m/s (10.7 fpm) to 0.093 m/s (18.3 fpm) while cutting, depending on physical conditions. Varying roof conditions were observed, with as much as 0.91 m (3 ft) of drawslate falling from the roof over a distance of forty shields. Generally, however, local areas of bad roof were observed, usually limited to a ten- to twenty-shield span. Production during sampling ranged from 1397 t (1540 st) to 2286 t (2520 st) per shift with an average cutting time of 157 minutes.

For dust control purposes, the shearer in the first panel was equipped with two banks of four water sprays each and two large, "flood" sprays on the headgate end and one bank of three sprays and one "flood" spray on the tailgate end. Additionally, sixteen sprays were located behind the cutting bits on each drum. The spray system was operated at 0.586 MPa (85 psi), delivering 307 liters of water per minute (81 gpm) to knock down dust. The two large, "flood" sprays and the gob-side bank of four sprays on an extension arm at the headgate end of the shearer were directed against the air flow causing roll back of dust over the shearer operators.

Fresh air was provided to the face via the track heading and a parallel intake entry. The air was split at the headgate with 2.36 m^3/s (5000 cfm) routed down the belt entry and the remaining 8.97 m^3/s (19,000 cfm) to 12.74 m^3/s (27,000 cfm) directed toward the face. Between 5.75 m^3/s (12,180 cfm) and 8.03 m^3/s (17,010 cfm) actually reached the tailgate location. No ventilating check curtain was used between the first sheild and the solid rib to prevent air from leaking into the gob, but the minimum air velocity of 1.524 m/s (300 fpm) required on the face by the ventilation plan was maintained. A ventilating check curtain was used between the stage loader and the pillar being mined to prevent dust-laden air from flowing over the shearer operator during cut-out into the headgate entry. The direction of air flow on the face was opposite that of coal flow on the conveyor (non-homotropol).

The other panel, located in the Beckley seam in Southern West Virginia, had a 127.1 m (417 ft) long face and was equipped with a high-speed plow. The plow sliced off a 101.6 mm (4 in) cut of coal each pass. The average mining height was 1.17 m (46 in) with no roof or floor being mined. Some roof rock would fall onto the conveyor at times, but workers generally were able to control the size of such rocks. Unlike the first panel, workers were stationed on the panel and remained there for the entire shift. Production during the sampling period ranged from 816 t (900 st) to 2380 t (2624 st) per shift, as the plow averaged 1.81 m/s (356 fpm) in traveling up and down the face.

Solenoid-activated water sprays were mounted along the armored face conveyor, one per pan section. The water system was operated at 200 psi, delivering 6.8 lpm per water spray. Fresh air was provided at both the headgate and tailgate entries, but only headgate air was directed down the face. A minimum volume of 4.58 m^3/s (9,700 cfm) of air was observed on the panel. No ventilating check curtains were used on the panel unless methane became a problem. Airflow was non-homotropol on this face relative to coal travel.

Methodology

Dust Sampling Procedures

Respirable dust samples which met the criteria required of coal operators for compliance sampling were obtained for characterization[13] Gravimetric samples were collected from fixed positions on the longwall faces using MSA personal sampling units equipped with Dorr-Oliver 10-mm cyclones and DuPont P2500 constant flow pumps calibrated to operate at 2 lpm. Sampling units were hung from shields and on the shearer in panel 1 at a height which approximated the level of the nose and mouth of employees. Personal sampling of shieldmen on panel 1 was also done. In order to obtain a good approximation of the average respirable mass concentrations for the different locations over time, ninety nearly full shift samples were collected from panel 1 and seventy samples from panel 2.

Locations sampled on panel 1 included: 1) intake air, 2) headgate, 3) 1/2 face, 4) 3/4 face, 5) tailgate, 6) lead shearer, 7) mid-shearer, 8) tail shearer, and 9) shieldman. Locations sampled on panel 2 were: 1) head intake, 2) headgate, 3) 1/4 face, 4) 1/2 face, 5) 3/4 face, 6) tailgate, and 7) tail intake.

Pre-weighed MSA PVC filters, 37-mm in diameter with a 0.5 um mean pore size, were used for sampling. These filters were checked routinely by the Mine Safety and Health Administration (MSHA) for accuracy of weighings, but additional checks were made to ensure that deviations remained less than 0.1 mg. A Sartorius, Type 2462S00Z0, semi-automatic, electronic analytical balance with digital readout was used for weighing samples to the nearest 0.01 mg, both before and after sampling.

During sampling on a shift, supplemental notes were taken regarding cutting time, downtime, the amount and location of bad roof areas, tram speed of the cutting machine, the type of cutting, and the cross-sectional area and air velocity at sampling locations. Ventilation arrangements, dust control procedures used, work habits of employees, the amount of mineral partings and floor mined, and shift productivity were logged.

Following determination of mass concentrations, twenty-seven samples from the first panel and twenty-one samples from the second panel were designated for mineral and elemental composition analysis and mineral particle sizing using available scanning electron microscopes (SEM's). The samples were selected from shifts which had varying condi-

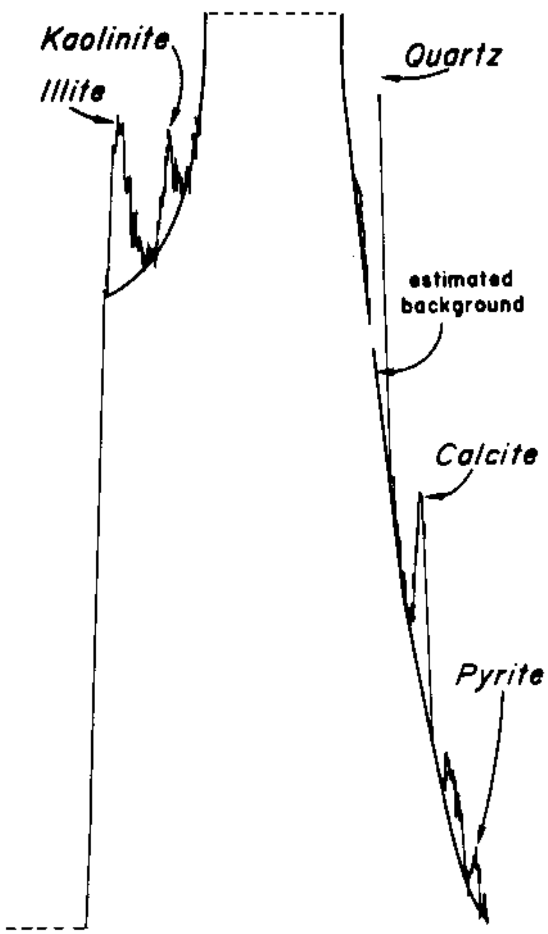


FIGURE 1. X-ray diffraction trace generated by a microphotodensitometer.

tions of roof in order to describe the variability in the various respirable dust characteristics being analyzed.

Scanning Electron Microscope Analysis

Respirable dust was ultrasonically bathed from a field sample in a beaker of alcohol. A portion of the dust-alcohol suspension was immediately transferred to a polished carbon stud and allowed to evaporate such that dust particles appeared to be uniformly dispersed on the background. The sample mount was then coated with a conductive layer of gold to prevent surface charging.

Two Cambridge Stereoscan SEM's (Model 150 and Model 180) were available for identification of elements and minerals and particle size analysis. Kevex 7000 analytical spectrometers were interfaced with the SEM's in order to identify elements on the basis of their energy levels (energy dispersive x-ray analysis).

The mineralogy of a particle was determined by comparing the EDX spectrum obtained for major and minor elements (Si, Al, K, S, Ca, Fe) with the known standard elemental spectra of minerals. The electron beam accelerating voltage used for mineral identification was typically 20 KV. Time of exposure to electron bombardment varied, but generally 20 to 74 seconds were needed to accurately determine the proportionality of elements and positively identify the mineralogy of an individual particle.

A scanning screen was used to randomly locate a field on the sample mount. Each particle within the field was "spotted" and bombarded for identification. Following identification, particle size (Feret's diameter) was determined by superimposing a graticule and scale onto the focused image on the screen. A total of 100 inorganic particles were analyzed for each mounted sample.

Micro X-ray Diffraction Analysis

Very small quantities of dust are collected in respirable sampling, generally ranging from 0.1 to 3.2 mg on longwall panels for a full shift. Standard X-ray diffraction techniques, which can be used to determine the mineral composition of materials semi-quantitatively based upon the crystalline structure of its components, require samples containing at least 100 mg of dust. X-ray diffraction analysis can be done on respirable dust samples, however, by mounting the dust, along with a minimum amount of Apiezon-L substrate, onto a thin glass spline mounted in wax on a copper stud. The sample to be x-rayed is placed into a large Phillips Debye-Scherrer powder camera, which is then mounted on an X-ray generator. The aligned, rotating sample is bombarded with copper radiation for 4 to 18 hours to obtain a good film pattern. The exposure time depends on the amount of sample.

A properly exposed film contains a number of sharply defined lines forming a concentric pattern in the forward direction. According to Bragg's Law, the positions of these lines are dependent on the interplanar d-spacings of the crystalline materials in the sample. From a list of d-spacings for common minerals in coal dust, the mineralogy of the sample can be determined. The intensity of a diffraction line on the film is directly proportional to the amount of material that produced it. A microphotodensitometer is used to measure intensities from the film pattern, and the resulting diffraction trace contains a peak for each line on the film (Figure 1). The height of a peak is directly proportional to the darkness of the corresponding line.

TABLE I

Percent Composition of Respirable Mineral Dust by Panel Based on Particle Count Using SEM/EDS

	Mineral				
Panel	Calcite	Illite	Quartz	Kaolinite	Pyrite
1 Pittsburgh Seam (N = 2682)	20.7	55.8	8.7	2.0	6.0
2 Beckley Seam (N = 400)	47.3	29.3	8.5	8.0	0.5

TABLE II

Percent Composition of Respirable Mineral Dust by Location Within Panel 1 Based on Particle Count Using SEM/EDS

Location	Calcite	Illite	Quartz	Kaolinite	Pyrite
	Mineral				
Intake	54.3	13.0	14.3	0.3	0.7
Headgate	50.7	25.0	7.0	2.0	2.3
1/2 Face	10.7	70.7	7.3	0.7	4.3
3/4 Face	8.2	71.5	10.2	1.8	6.2
Tailgate	6.5	77.2	7.8	1.8	3.8
Shearer	10.5	58.0	6.8	1.5	15.8
Shieldman	25.0	52.0	6.0	6.7	4.7

The mineralogy of a respirable dust sample can be estimated semi-quantitatively from a trace following the procedure of Renton.(14) In this procedure, the height of each peak is measured and the estimated background, which occurs primarily because of the grease and the organic matrix of coal dust, is subtracted out. The raw intensities are then multiplied by weighting factors determined by Renton. The weighting factors compensate for differences in crystallinity of minerals. The weighting factor used for illite, for example, is large since illite is poorly crystalline relative to other minerals in West Virginia coals and does not diffract X-rays efficiently. Mineral percentages are then determined using the sum of weighted intensities as the denominator. The overall accuracy of determinations is approximately +/- 15 percent, which includes uncertainty associated with background estimation and the weighting procedure. The weighting factor reflects not only the crystallinity of a mineral, which can vary substantially as it does for illite, but also the diffraction method used.

Discussion of Results

Mineralogy

Based upon availability of in-house technology, the mineralogy of respirable dust samples was determined using an energy dispersive X-ray analysis system interfaced with a scanning electron microscope. This procedure facilitated simultaneous mineral particle size analysis. The mineral composition of each sample was determined by identifying the mineralogy of each of 100 particles. Realizing the variability inherent in this procedure, corroboration was sought using the micro X-ray diffraction technique, which is also semi-quantitative but involves a larger amount of material. Twenty-seven respirable dust samples were analyzed using SEM/EDS for the first panel and four (out of twenty-one) have been completed for the second panel. To date, seven samples have been characterized by both SEM/EDS and XRD.

Table I shows the average mineralogy of respirable mineral dust by panel based on SEM/EDS analysis of 2682 particles for panel 1 and 400 particles, thus far, for panel 2. The mineral composition is quite different for the two panels. Quartz content is nearly identical at 8.5 percent, but pyrite and kaolinite contents differ, with more kaolinite found in the Beckley seam and more pyrite detected in the Pittsburgh seam. Illite was the dominant mineral found in the Pittsburgh seam, followed by calcite. In the Beckley seam, the roles are reversed.

Table II depicts the mineral composition of respirable mineral dust by location in panel 1. Values for each location are derived from analysis of approximately 300 particles. Definite trends are seen for the variation of calcite and illite by location. A fitted, multiple linear regression model for the variation of illite content by location yielded the equation:

$$I = -8.45 + 37.61X - 3.99X^2$$

where:
I is percent illite at face location X and X is the proportionally-coded face location (1,. . .,5).

The model reveals that illite content increases along the longwall face but at a decreasing rate. The model explains 78 percent of the variability in illite content and is statistically significant ($F = 17.95$).

A fitted, multiple linear regression model for the variation of calcite content by location yielded the equation:

$$C = 82.84 - 36.43X + 4.20X^2$$

where:
C is percent calcite at face location X.

This model reveals that calcite content decreases along the face but at a decreasing rate. The model explains 80 percent of the variability in calcite content and is also statistically significant ($F = 19.49$).

TABLE III

Percent Composition of Respirable Mineral Dust by Location Within Panel 2 Based on Particle Count Using SEM/EDS

Location	Calcite	Illite	Quartz	Kaolinite	Pyrite
	Mineral				
Head Intake	63.0	20.0	8.0	5.0	0
1/4 Face	40.0	33.0	10.0	10.0	1.0
1/2 Face	25.0	46.0	10.0	10.0	1.0
Tail Intake	61.0	18.0	6.0	7.0	0

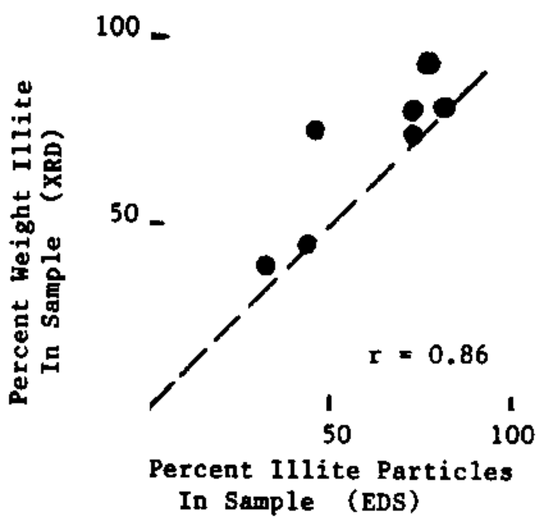


FIGURE 2. XRD versus EDS results for illite.

No general relationship was found for quartz, kaolinite, or pyrite content variation by location on panel 1. Table II indicates that quartz and kaolinite content of respirable mineral dust was relatively constant on the face, but a significant increase in the amount of pyrite (15.8%) was detected at the shearer locations. This latter phenomenon can be attributed to the rollback of the dust cloud generated from the cutting action over the shearer operators. The inability to find a relationship for quartz, kaolinite, and pyrite is not surprising because of the high variability in SEM/EDS determinations for minerals that are present in small percentages. Hundreds of particles would have to be analyzed for each sample to determine accurate percentages for such quantities. The important point here is that quartz, kaolinite, and pyrite do exist in small amounts, whereas illite and calcite exist in much larger amounts.

Table III provides mineralogical results to date for the second panel. However, only 100 particles for each location have been analyzed to date, with seventeen samples pending analysis. The second panel differed from the first one in the provision of fresh air up the tailgate entry, which impacted the mineralogy at that location. Because of this situation and generally smaller amounts of illite, calcite is the dominant mineral. The same general trands for calcite and illite content variation by location exist for this panel, but not enough data is presently available to develop regression models. Thus far, it can be said that illite content increases linearly with face location, except at the tailgate. Calcite content appears to decrease at a decreasing rate, except at the tailgate, but the rate of decrease is slower for panel 2 than it was for panel 1.

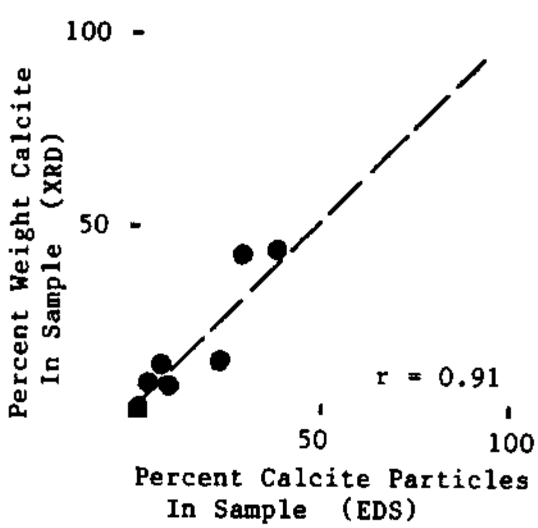


FIGURE 3. XRD versus EDS results for calcite.

Comparison of Table III with Table II revesls that 1) kaolinite content is much higher in panel 2; 2) pyrite content is much lower in panel 2; 3) quartz content is not much different; 4) calcite content is higher in panel 2 at each location; and 5) illite content is considerably lower in most locations in panel 2.

Correlation of SEM/EDS and XRD mineralogical results is made by mineral type in Figures 2 through 5. Figure 2

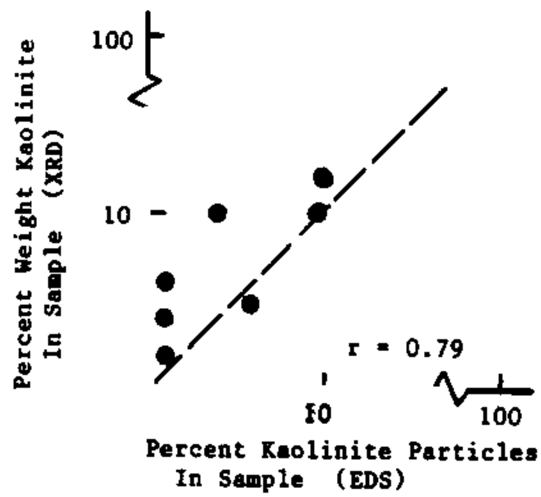


FIGURE 4. XRD versus EDS results for kaolinite.

reveals that a high correlation (r = 0.86) exists between illite content determinations by the different methods, with either XRD slightly overestimating illite content or SEM/EDS slightly underestimating it. Figure 3 shows a higher correlation (r = 0.91) between results for calcite content, with no trends apparent in method bias. Figure 4 shows either a possible overestimation of kaolinite content by XRD or an underestimation by SEM/EDS, but a good correlation (r = 0.79) was obtained. Figure 5 indicates either possible overestimation of pyrite content by SEM/EDS or underestimation by XRD, but, again, good correlation (r = 0.79) exists. Results for quartz content are not shown because of poor correlation (r = 0.12), with no trends in bias apparent.

Correlation results are very good considering 1) weight percentages are compared with number percentages, and 2) sources for error in the two analytical methods. Since particles are in the respirable fraction of mine dust and mean particle sizes were similar in magnitude, number percentages are tantamount to weight percentages, thereby yielding good correlations. Estimation of the background and the use of unadjusted weighting factors in XRD analysis appear ade-

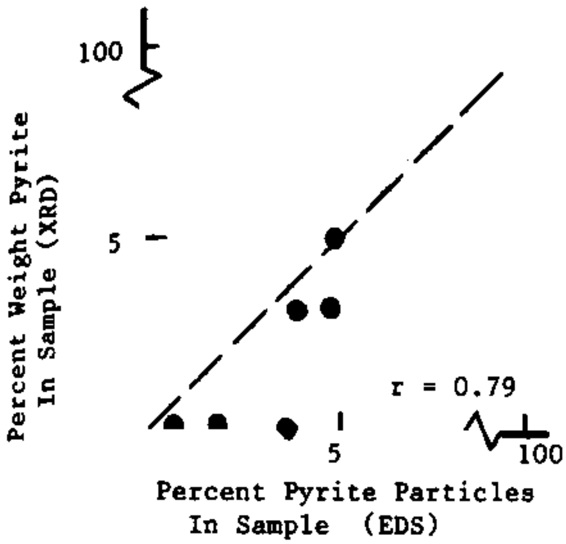


FIGURE 5. XRD versus EDS results for pyrite.

quate for gross determination of mineralogy, except in the case of quartz. Classification of clay minerals as either illite or kaolinite in the SEM/EDS analysis hinges on the ratio of aluminum to silicon and the presence of a potassium peak in a particle, and results indicate that good judgment has been exercised. Determinations of pyrite content by XRD depends on the crystalline structure of pyrite, which has been seen to vary considerably. Defects in the crystal structure of some pyrites may explain the non-existence of this mineral in many of the XRD determinations while it was detected in the SEM/EDS analysis. Quartz content determinations present a real problem but may be related to the amount of contamination in a particle. Only 28 percent of the quartz particles analyzed in panel 1 were possibly uncontaminated by other elements. In contrast, over 68 percent of the quartz particles in panel 2 were potentially uncontaminated. However, the answer to the problem may lie in the use of a weighting factor that is too low since most of the data indicate that the XRD method underestimates quartz content relative to SEM/EDS.

Trace Elements

During SEM/EDS analysis of dust samples for mineralogy, elements which showed a peak energy level above the gold background but were not primary in determining the mineralogy of a particle were logged as trace elements for that particle. In this way, the number of occurrences could be tabulated. Table IV shows the results of this procedure. The elements listed in Table IV are those which were identified more than one time. The percent of occurrence for each element is determined based on the total number of particles analyzed per panel. The denominator for panel 1 is therefore 2682, while the denominator for panel 2 is presently only 400. Elements such as aluminum, potassium, iron, silicon, sulfur, and calcium, although they quite frequently showed up in trace amounts, are not included becasue they consistently occur as major or minor constituents of other minerals.

TABLE IV

Percent Trace Element Occurrence by Panel Based on Particle-by-Particle SEM/EDS Analysis

	Element					
Panel	Cl	Cr	Mg	Mn	Na	Ti
1	5.3	4.5	16.1	2.8	2.4	7.8
2	1.0	5.0	5.3	3.5	0.5	4.0

Table IV indicates that chlorine and magnesium occur more frequently in panel 1 than they do in panel 2. It also indicates that sodium and titanium occur more frequently but in a smaller ratio. Levels of chromium, which Mutmansky hypothesized may be associated with causes of CWP,[11] and levels of manganese are virtually the same.

TABLE V

Percent Trace Element Occurrence by Location Within Panel 1 Based on Particle-by-Particle SEM/EDS Analysis

	Element					
Location	Cl	Cr	Mg	Mn	Na	Ti
Intake	15.7	5.3	18.0	2.3	6.3	3.3
Headgate	3.7	2.7	11.3	5.7	3.3	8.7
1/2 Face	0.3	4.7	15.0	2.0	2.0	8.7
3/4 Face	4.3	5.8	19.0	1.0	1.0	9.3
Tailgate	1.8	3.0	21.5	3.3	0.8	6.5
Shearer	6.2	4.5	15.7	2.7	2.2	9.2
Shieldman	5.0	6.7	13.3	3.7	1.3	8.7

Table V breaks down the percent occurrence of trace elements by location for panel 1. Chlorine occurrences appear to be particularly high in intake air and somewhat higher at the shearer positions. The data for magnesium indicates a trend of increasing occurrence from headgate to tailgate along the face, much like the trend for illite in the mineralogical analysis. No other relationships are evident, except for the possible reduction in the occurrence of sodium from headgate to tailgate along the face. No relationships can be concluded from the minimum amount of data for panel 2, which is shown in Table VI.

Mineral Particle Size

As mentioned previously, Feret's diameter was recorded for each mineral particle analyzed under SEM to determine

TABLE VI

Percent Trace Element Occurrence by Location Within Panel 2 Based on Particle-by-Particle SEM/EDS Analysis

	Element					
Location	Cl	Cr	Mg	Mn	Ni	Ti
Head Intake	1.0	4.0	7.0	2.0	1.0	3.0
1/4 Face	1.0	4.0	5.0	3.0	0	4.0
1/2 Face	0	6.0	6.0	4.0	0	7.0
Tail Intake	2.0	6.0	3.0	5.0	1.0	2.0

size distributions for minerals and to detect differences in mineral particle size by location. Table VII reveals the results of mineral particle sizing by location on panel 1. A minimum of 300 particles were sized for each location. An analysis-of-variance (ANOVA) performed on diameter means by location (three means per location) indicated that the mean mineral particle size at the tailgate is significantly smaller than those for all other locations. Results, using Fisher's least significant difference test following a significant F-test, are presented in Table VII by grouping. It is important to note that no difference in mineral particle size was detected by date, especially since physical conditions on the panel changed. It is also significant to note that the mean particle size obtained for the shieldman reflects the fact that he spends two-thirds of his time in intake air rather than on the face.

TABLE VII

Variation of Mineral Particle Size (Feret's Diameter) by Location on Panel 1

Location	Mean Feret's Diameter (um)	Least Significant Difference Test Group
Tailgate	1.17	A
1/2 Face	1.55	B
Shearer	1.56	B
3/4 Face	1.66	B
Headgat	1.67	B
Shieldman	1.75	B
Intake	1.82	B

Table VIII lists the mean particle size of minerals by location on panel 1, as well as the overall mean particle size for each mineral. Performing an analysis-of-variance on this data revealed that the mean diameters of quartz (1.38 um) and pyrite (1.29 um) are significantly smaller than those of illite (1.53 um) and calcite (1.65 um). From this table, it is also seen that the trend for smaller particle size at the tailgate is demonstrated by all minerals.

At this time not enough data exists for an analysis of particle size by location on panel 2, but, thus far, the average mineral particle size (for 400 particles) is 1.36 um, which is smaller than the average for panel 1 (1.58 um).

TABLE VIII

Variation of Mineral Particle Size (Feret's Diameter) by Mineral Type of Panel 1

	Mineral			
Location	Quartz	Illite	Calcite	Pyrite
Intake	1.40	2.17	1.74	--
Headgate	1.28	1.53	1.70	1.72*
1/2 Face	1.39	1.54	1.74	1.34
3/4 Face	1.61	1.64	1.61	1.30
Tailgate	0.97	1.22	1.28	1.01
Shearer	1.56	1.55	1.69	1.23
Shieldman	1.18	1.64	1.77	1.50
Average	1.38	1.53	1.65	1.29

*Only one sample of three had greater than 3 particles.

Conclusions

Determination of variations in mineralogical and elemental composition of respirable coal mine dusts and in mineral particle size by worker locations on production panels and across different coal seams may eventually lead to discoveries regarding the causes of CWP. Causes are still unclear, and contradictions exist relative to the role of quartz and other minerals. Although major progress has been achieved in prevention of CWP, no definitive answers concerning causes have been revealed. Potentially, results from mineralogical, elemental and particle size analyses of lung sections taken from disease victims, when coupled with knowledge regarding work history, may lead to important correlations with data from analysis of in-mine samples.

This paper has presented two methods for determining gross mineralogy of respirable coal mine dust samples. Good correlation was obtained between particle-by-particle SEM/EDS and small-quantity micro-XRD results. Differences in mineralogy by coal seam and by worker location on a production panel can be detected using analysis-of-variance techniques, and relationships between the percentage of an existing mineral and worker location can be developed. Many of the differences and relationships can be explained by phenomena observed in mines. Some variations, for example, can be explained by physical conditions, panel configurations, equipment arrangements, or work practices.

Along with mineralogical results, information relative to the existence of trace elements in respirable dust and mineral particle size data can be obtained from SEM/EDS analyses. Differences in the occurrence of different trace elements in particles and in mineral particle sizes can be determined. For example, more magnesium and chlorine were found to exist in the Pittsburgh seam than in the Beckley seam, and mineral particles at the tailgate location on a longwall panel were found to be significantly smaller than particles at other locations. Also, quartz and pyrite particles were smaller than illite and calcite particles in the longwall panel operating in the Pittsburgh seam.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142

References

1. **Jacobsen, M. et al:** The Relationship Between Pneumoconiosis and Dust Exposure in British Coal Mines. *Inhaled Particles III,* pp. 903-917. W.H. Walton, Ed. Unwin Bros., Old Woking, Surrey (1971).

2. **Morgan, W.K.C. et al:** The Prevalence of Coal Workers' Pneumoconiosis in U.S. Coal Miners. *Arch. Environ. Health 27*:221-226 (1973).

3. **Reisner, M.T.R. and K. Robock:** Results of Epidemiological, Mineralogical, and Cytotoxicological Studies on the Pathogenicity of Coal-Mine Dusts. *Inhaled Particles IV,* pp. 703-715. W.H. Walton, Ed. Unwin Bros., Old Woking, Surrey (1977).

4. **Leiteritz, H., D. Bauer and E. Bruckman:** Mineralogical Characteristics of Airborne Dust in Coal Mines of Western Germany and Their Relations to Pulmonary Changes in Coal Hewers. Inhaled Particles III, pp. 729-743. W.H. Walton, Ed. Unwin Bros., Old Woking Surrey (1971).

5. **Walton, W.H., G.G. Hadden and M. Jacobsen:** The Effect of Quartz and Other Non-coal Dusts in Coalworkers' Pneumoconiosis, Part I, Epidemiological Studies. *Inhaled Particles IV,* pp. 669-690. W.H. Walton, Ed. Unwin Bros., Old Woking, Surrey (1975).

6. **Davis, J.M.G., J. Ottery and A. LeRoux:** The Effect of Quartz and Other Non-coal Dusts in Coalworkers' Pneumoconiosis, Part II, Lung Autopsy Study. *Inhaled Particles IV,* pp. 691-702. W.H. Walton, Ed. Unwin Bros., Old Woking, Surrey (1975).

7. **Industrial Health and Safety:** *A Synthesis Report on Research Supported by the Commission During the Period 1977-82.* R.J. Hamilton, Ed. Commission of the European Communities, Luxembourg (1985).

8. **Attfield, M. R. Reger and R. Glenn:** The Incidence and Progression of Pneumoconiosis Over Nine Years in U.S. Coal Miners: II. Relationship with Dust Exposure and Other Potential Causative Factors. *Am. J. Ind. Med. 6*:417-425 (1984).

9. **Morgan, W.K.C.:** Coal Workers' Pneumoconiosis. *Am. Ind. Hyg. Assoc. J. 32*:29-34 (1971).

10. **Mutmansky, J.M. and C. Lee:** An Analysis of Coal and Geologic Variables Related to Coal Workers' Pneumoconiosis. *Proc. Coal Mine Dust Conference, Morgantown, 1984,* pp. 236-249. S.S. Peng, Ed. West Virginia University (1984).

11. **Stein, F. and M. Corn:** Shape Factors of Narrow Size Range Samples of Respirable Coal Mine Dust. *Powder Technology 13*:133-141 (1976).

12. **Sharkey, A.G., T. Kessler and R.A. Friedel:** Trace Elements in Coal Dust by Spark-source Mass Spectrometry. *Trace Elements in Fuel,* pp. 48-56. S.B. Babu, Ed. American Chemical Society, Washington (1975).

13. 30 CFR Part 70 Subpart B.

14. **Renton, J.J.:** Use of Weighted X-ray Diffraction Data for Semi-Quantitative Estimation of Minerals in Low-Temperature Ashes of Bituminous Coals and in Shale. Technical Report MERC/CR-79/5. U.S. Department of Energy (1979).

HEALTH EFFECTS –
CELLULAR RESPONSE

The Effects of Coal Mine Dust Particles on the Metabolism of Arachidonic Acid by Alveolar Macrophages

LAURENCE M. DEMERS, Ph.D., MATTHEW ROSE, Ph.D. and GERALD L. BARTLETT, M.D., Ph.D.

The Department of Pathology, The Milton S. Hershey Medical Center, The Pennsylvania State University, Hershey, Pennsylvania 17033

The pulmonary alveolar macrophage is a major defensive cell which counteracts the invasive properties of bacteria and particles when these substances invade the pulmonary environment. Pulmonary exposure to coal dust particles is believed to activate these macrophages to release a host of chemical mediators which can neutralize or contribute to the harmful effects of these dust particles. Our efforts have been concerned with assessing a specific family of mediator substances produced by the alveolar macrophage from arachidonic acid when these cells are in contact with activating substances such as coal dust. Metabolites of arachidonic acid produce a vast array of effects which can impact significantly on pulmonary function both with normal pulmonary events and with pathologic processes of the lung. Our studies demonstrate that isolated alveolar macrophages obtained from rats or guinea pigs cultured *in vitro* release appreciable amounts of the cyclooxygenase products prostaglandin E_2 and thromboxane A_2 and release significant amounts of the lipoxygenase products, 5-HETE and LTB4. In the presence of 1×10^{-4} - 1×10^{-7} g/ml of a coal dust suspension, alveolar macrophages from the rats and guinea pigs alters their pattern of arachidonic acid metabolite release. In the rat, exposure of alveolar macrophages *in vitro* to the higher concentrations of coal dust causes a significant reduction in PGE_2, TXB_2 and LTB_4 in a 4 hour time course study. In contrast, macrophages from the guinea pig in response to coal dust had little change in TXB_2 release, only a slight inhibition in PGE_2 production and an initial stimulation in LTB_4 release over the 4 hour time course. Cells from guinea pigs released considerably more TXB_2 than the rat under these conditions while rat cells formed considerably more LTB_4 than guinea pig alveolar macrophages. These findings support the following conclusions.

1. **Alveolar macrophages from rats and guinea pigs form significant amount of the arachidonic acid metabolites PGE_2, TXB_2, LTB4.**
2. **Exposure of the alveolar macrophage to coal dust induces an alteration in the pattern of arachidonic acid metabolism which is different between rats and guinea pigs.**
3. **At high concentration of coal dust (1×10^{-4} g/ml), there is a significant reduction in mediator release by rat alveolar macrophages. In contrast, guinea pig cells appear to augment their production of leukotriene LTB_4 in response to coal dust exposure.**
4. **Electron microscopy of the coal dust exposed macrophages reveals intense phagocytosis and internalization of coal dust particles by these cells in culture.**

In conclusion, the reactivity of the alveolar macrophage to coal mine dust exposure involves alterations in macrophage arachidonic acid mediator release which varies between different species.

Introduction

Coal workers' pneumoconiosis (CWP) is associated with a build up of black deposits in the lung from chronic exposure to coal dust.[1] CWP presents with few clinical symptoms itself but if left unattended leads to a progressive, complicated respiratory disease process with extensive pulmonary fibrosis, severe respiratory compromise and eventually death. Both CWP and its associated pulmonary fibrosis are believed to be a result of chronic exposure to a particular type of coal dust. Exposure levels to dust is also considered to be an important contributor to the onset of CWP.

The alveolar macrophage is a major defensive white blood cell which resides within the pulmonary space to counteract the invasive properties of microorganisms and foreign particles when they present to the lungs.[2] Their principal function is to maintain a sterile environment in the lower respiratory tract. Bacteria,[3] fungi and viruses[4] as well as non-infectious foreign particles[5] are normally neutralized by the alveolar macrophage through phagocytosis preventing entry into the systemic circulation. With activation, the alveolar macrophage exhibits an increase in metabolic activity including increased oxygen consumption, rapid glucose utilization, increased superoxide production[6] and the release of several important chemical mediators which affect the functional role of the alveolar macrophage as well as other cells and tissues in the pulmonary environment.[7,8]

Several metabolites of arachidonic acid are formed by the alveolar macrophage when activated and released as mediators of the inflammatory response.

Arachidonic acid is a 20 carbon fatty acid stored in most cells as phospholipid and released when the cells become activated. In the alveolar macrophage, at least two distinct metabolic pathways for arachidonic acid exist[9] (Figure 1). A cyclooxygenase enzyme system catalyzes the formation of prostaglandins and thromboxane from released arachidonic acid. Leukotrienes and hydroxy fatty acids are formed by a second major pathway catalyzed by a lipoxygenase enzyme. These metabolites produced a variety of effects in the lungs and can impact significantly on both normal and abnormal pulmonary function.[10,11] Chronic release of these metabolites in the lungs are associated with damage to the lung and if left unchallenged can evoke many of the pathologic changes associated with miners lung disease.

The interaction of the pulmonary alveolar macrophage with non-infectious particles such as asbestos has been shown to evoke a stimulation in arachidonic acid derived mediator release.[8] Although little information is available regarding coal dust effects on alveolar macrophage arachidonic acid metabolism, there is evidence to show intense phagocytosis of coal dust particles by these cells.[12]

Our present study was designed to investigate the interaction of coal dust particles with the alveolar macrophage *in vitro*, specifically assessing the metabolism of arachidonic acid to products of the cyclooxygenase and lipoxygenase pathway following exposure of these cells to coal dust particles in suspension.

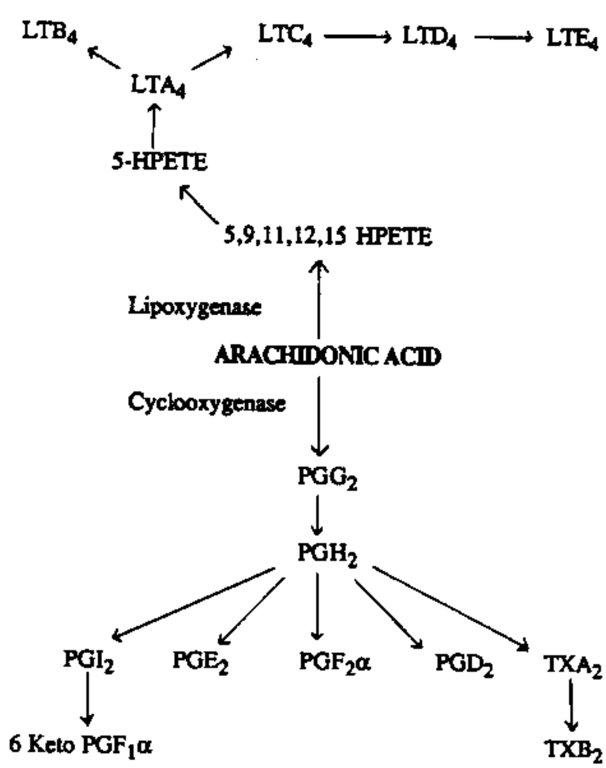


FIGURE 1. Metabolic pathways of arachidonic acid.

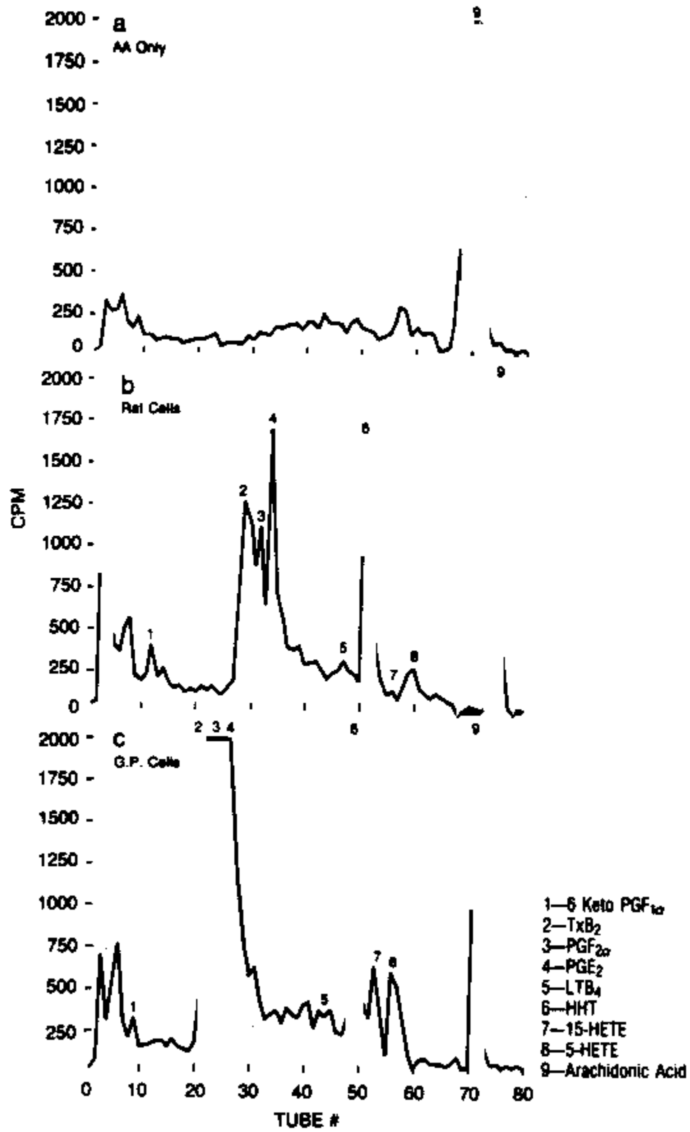


FIGURE 2. Products of arachidonic acid metabolism by rat and guinea pig alveolar macrophages after 4 hour incubation with 14C-arachidonic acid. Cells were prepared as described in Materials and methods. a) Arachidonic acid only, b) Rat alveolar macrophages, c) Guinea pig alveolar macrophages.

Materials and Methods

Cell Culture of Alveolar Macrophages

Rat and guinea pig lung macrophages were obtained by pulmonary lavage with Ca^{2+} and Mg^{2+}-free phosphate buffered saline containing 0.1 percent (w/v) ethylenediaminetetraacetic acid. The lungs were lavaged 3x each with an 8 ml volume of lavage fluid. The resulting cell suspension was centrifuged at 600 xg for 10 minutes and the cell pellet washed with Medium 199. The cells were resuspended in 2 mls Medium 199 and enumerated by counting in a hemocytometer. Viability was assessed by trypan blue exclusion. The cells were diluted to 0.5×10^6/ml and 2 ml of the suspension were placed in wells of multi-well plates. The cells were incubated for 1 hour at 37°C in a humidified CO_2 controlled atmosphere (5 percent CO_2 in air). The medium was then removed and the adherent cells were washed 3x with M-199. The medium was replaced and the cells were incubated for varying times in the presence of coal dust preparations, or known effectors of arachidonic acid metabolism. In certain experiments ^{14}C-arachidonic acid (New England Nuclear, 400,000 cpm/well) was added.

Analysis of Metabolites of Arachidonic Acid

Analysis of ^{14}C-Labelled Metabolites by High performance liquid chromatography

At the end of each incubation, medium was collected and acidified by the addition of .01 M citric acid (25 ul/ml). Radiolabelled metabolites were extracted by shaking for 10 minutes with an equal volume of cyclohexane:ethylacetate (1:1 v/v) in silanised glass extraction tubes. Phase separation was achieved by centrifugation at 600 xg for 10 minutes. The organic layer was transferred to a second silanised tube and the solvent was evaporated under nitrogen. The residue was redissolved in 50 ul of HPLC Solvent A (acetonitrile: water 26:74 v/v, pH 3.0 with phosphoric acid). Arachidonic acid metabolites were separated on a Waters C18 radial compression cartridge using 2 solvent systems. Solvent system 1 consisted of HPLC Solvent A pumped isocratically for 26 minutes at 3 mls/min. This was followed by solvent system 2 which consisted of a linear gradient over 60 minutes for 100 percent Solvent A to 22 percent Solvent A and 78 percent Solvent B (acetonitrile:water 95:5 v/v, pH 3.0 with phosphoric acid) flow rate was maintained at 3 mls/min. Eluting solvent was collected into 1 ml fractions and 7 mls scintillation fluid (ACS, Amersham) was added. Radioactivity was determined by counting in a Searle Delta 300 liquid scintillation system. Retention times of arachidonic acid metabolites were compared with those of authentic standards.

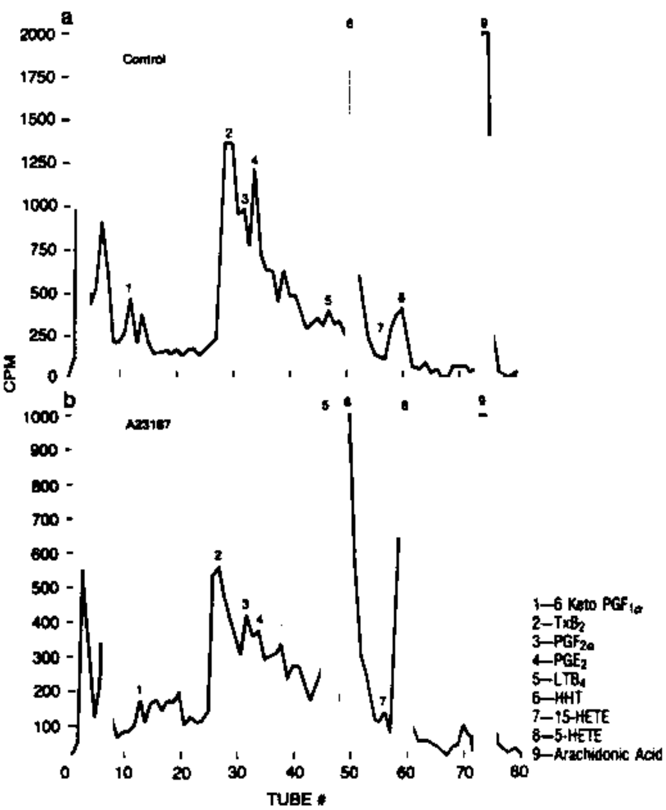


FIGURE 3. Stimulation of lipoxygenase pathways by calcium ionophore. a) Baseline conversion of arachidonic acid by rat macrophages. b) Stimulation of lipoxygenase products LTB4 and HETE by calcium ionophore (10 ug/ml). Cells were prepared as previosly described and incubated for 4 hours with arachidonic acid in the presence or absence of calcium ionophore.

Quantitative Determination of Arachidonic Acid Metabolites

Prostaglandin E_2, prostaglandin F_2 and thromboxane B_2 were determined by radioimmunoassay as previously described from this laboratory.[13] Culture medium from the alveolar macrophage cultures were analyzed by RIA following a cyclohexane:ethyl acetate extraction step.

Leukotriene B_4 was determined by radioimmunoassay using reagents purchased from Seragen Inc. (Waltham, Mass.)

Coal Dust Samples

Samples of coal dust prepared to respirable quality by the Department of Mineral Engineering, Pennsylvania State University, were obtained and suspended in Medium 199 by the addition of 1 percent tween followed by sonication.

Chemicals

All chemicals used in these studies including the calcium ionophore A23187 and nordihydroguaiaretic acid (NDGA) were obtained from the sigma Chemical Company.

Results

Metabolism of ^{14}C-Arachidonic Acid by Alveolar Macrophages

Alveolar macrophages isolated from the lungs of both guinea pigs and rats metabolized in culture under basal conditions ^{14}C-arachidonic acid to a variety of compounds of both the lipoxygenase and cyclooxygenase pathways. The major cyclooxygenase products released into the medium were identified as thromboxane B_2 (TXB_2), PGF_2 PGE_2, and hydroxyheptadecatrienoic acid (HHT). Lipoxygenase products identified included LTB_4, 15-hydroxyeicosatetraenoic acid (15-HETE) and 5-hydroxyeicosatetraenoic acid (5-HETE). Figure 2 reflects the pattern of products produced from AA when alveolar macrophages from rats and guinea pigs were incubated with ^{14}C-arachidonic acid for four hours.

As shown in Figure 3, exposure of these cells to a known lipoxygenase stimulant such as the calcium ionophore (10 ug/ml) augmented the release of HETE products and LTB_4 into the medium. Although not shown, the addition of the lipoxygenase inhibitor NDGA (10^{-5}M) was effective in reducing the formation of HETE products to 20 percent of the control response. Addition of various preparations of coal dust in suspension to the culture medium was shown to inhibit the conversion of ^{14}C-arachidonic acid to cyclooxygenase products by rat alveolar macrophages (Figure 4).

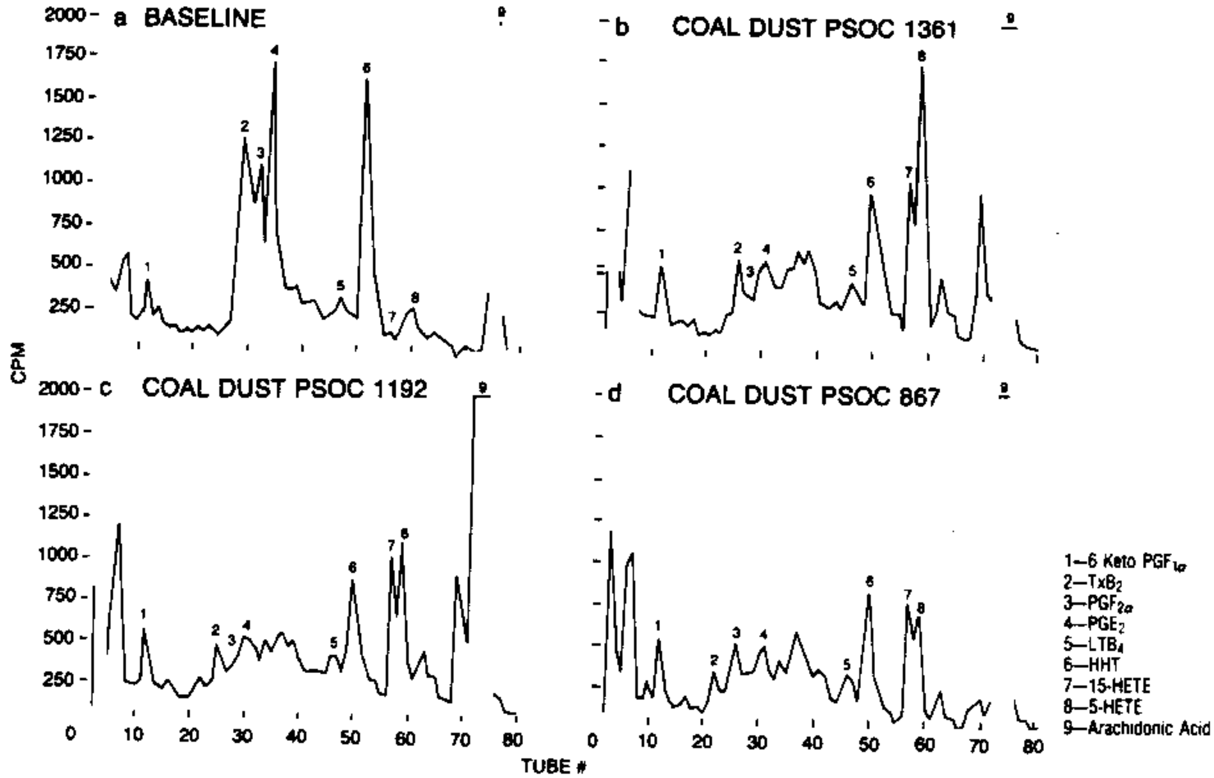


FIGURE 4. Effect of various coal dust preparation on metabolism of [14]C-arachidonic acid. a) No addition, b) Coal dust PSOC 1361, c) Coal dust PSOC 1192, d) Coal dust PSOC 867.

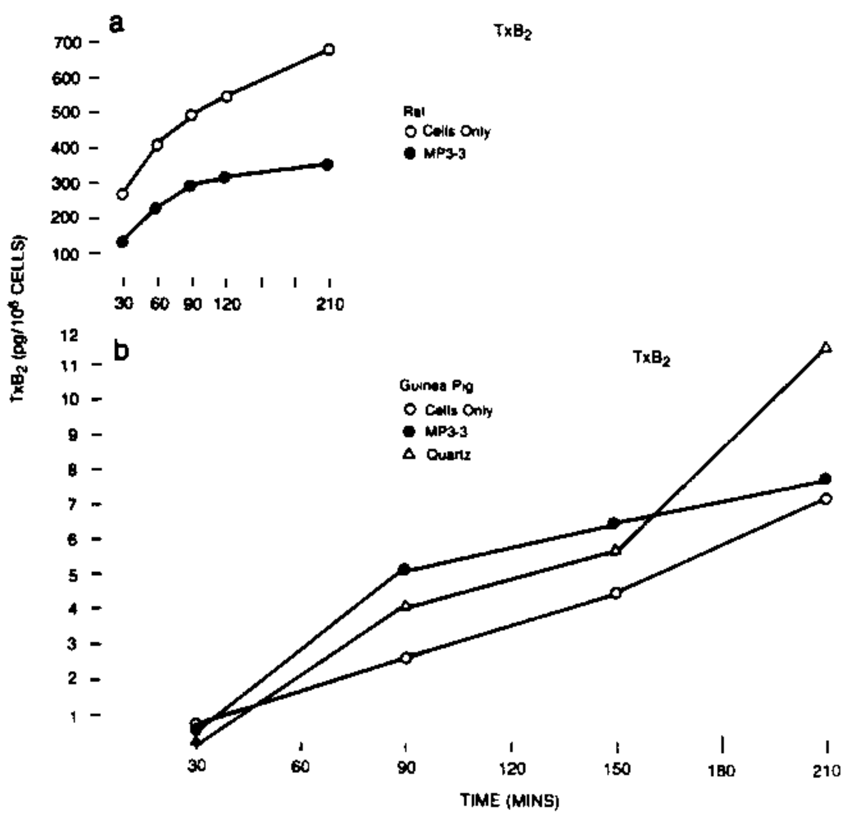


FIGURE 5. Time course of release of thromboxane as measured by TXB2 radioimmunoassay by rat (a) and guinea pig (b) alveolar macrophages in the presence and absence of coal dust MP3-3 (100 ug/ml).

Quantitation of Arachidonic Acid Metabolites

In time course experiments, it was observed that the presence of coal dust (MP3-3, 100 ug/ml) appeared to inhibit the release of thromboxane from incubated rat alveolar macrophages. Interestingly, the alveolar macrophages from the guinea pig were only slightly affected by the coal dust preparations (Figure 5). It was also noted that guinea pig alveolar macrophages released in quantity substantially more thromboxane (approximately 10-fold) than did the rat alveolar macrophages.

The release of PGE_2 into the medium when assessed quantitatively was not markedly affected by the presence of MP3-3 (100 ug/ml) during early periods of exposure but did appear to be compromised by 3 1/2 hours (Figure 6). It was also observed that guinea pig cells released more PGE_2 than did the rat cells.

Changes in lipoxygenase product formation were affected differently by the coal dust exposure. As shown in Figure 7, although the release of LTB_4 from the rat alveolar macrophage appeared to be suppressed by the presence of coal dust (MP3, 100 ug/ml), the release of this lipoxygenase product by guinea pig alveolar macrophages appeared to be stimulated at earlier time points reaching a plateau as shown in Figure 7

The effects of different concentrations of coal dust on the arachidonic acid metabolites is shown in Figure 8. Products of the cyclooxygenase pathway were suppressed by high concentrations of coal dust MP3-3 whereas LTB_4 release was suppressed more at the lower concentrations.

In Figure 9 are depicted the effects of different coal dust matter on PGE_2 and TXB_2 production by these cells. As noted previously, coal dust such as the MP3-3 produced a modest suppression of both these products. The effects of limestone, however, was more pronounced in suppressing TXB_2 release when compared to PGE_2 release by these cells.

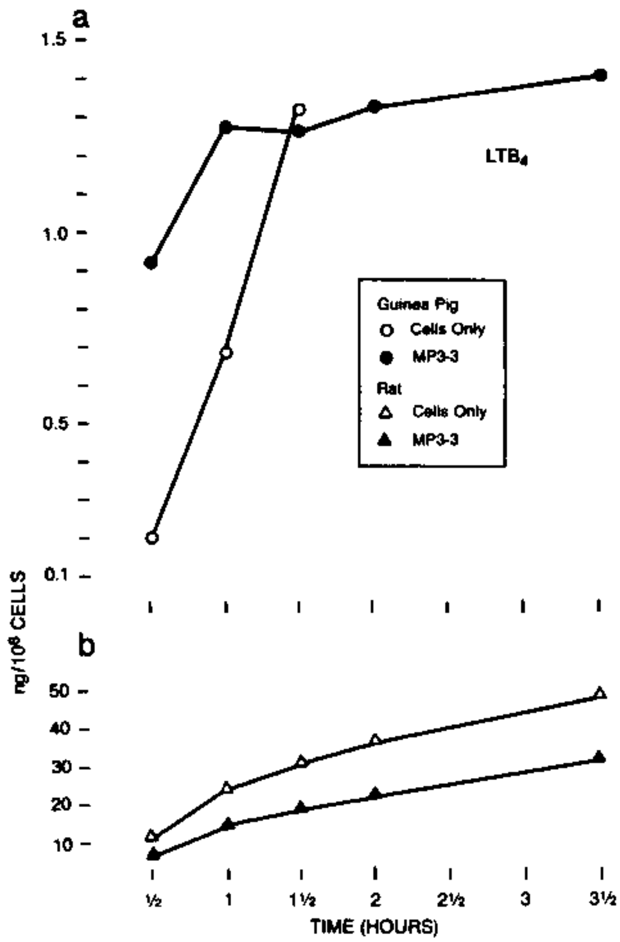


FIGURE 7. Time course of release of LTB4 by rat and guinea pig alveolar macrophages in the presence and absence of coal dust MP3-3 (100 ug/ml).

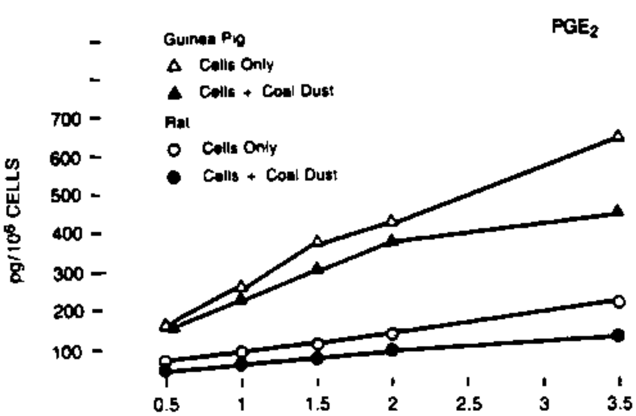


FIGURE 6. Time course of release of PGE2 by rat and guinea pig alveolar macrophages in the presence and absence of coal dust MP3-3 (100 ug/ml).

Electron Microscopy

Electron micrographs were prepared of the cells exposed to coal dust. Figure 10 is a representative figure revealing the internalization of the coal dust particles by the alveolar macrophage in culture.

Discussion

The aims of the experiments described were to determine whether alveolar macrophages could react *in vitro* with coal dust particles and whether this interaction has any effect on arachidonic acid metabolism.

We observed that alveolar macrophages from both rats and guinea pigs are able to metabolize arachidonic acid to a variety of lipoxygenase and cyclooxygenase products and that the pathways can be altered by known modulators of arachidonic acid metabolism. It was also evident that alveolar macrophages from rats and guinea pigs have differing capacities to produce arachidonic acid metabolites.

It was postulated that the interaction of coal mine dust particles with alveolar macrophage may lead to activation of the cells and release of immunologic mediators such as arachidonic acid metabolites, in a fashion similar to that of asbestos particles. These mediators could in turn, through activation of the immune system, lead to pathogenic events.

In rat alveolar macrophage cultures we were unable to demonstrate a significant stimulation of arachidonic acid metabolism after exposure to coal dust. Any alterations observed tended to be of an inhibitory nature. The alveolar macrophages of guinea pigs did not appear to be as sensitive to the effects of coal dust preparations at the levels tested.

Although fibrous particles such as asbestos may stimulate arachidonic acid metablism as do other non-infectious particles such as carbonyl iron particles,[8] not all phagocytosed particles may be as effective. It has been observed that phagocytosis of latex particles has no effect on prostaglandin synthesis in pulmonary macrophages.[7] The interaction of small particles with macrophages depends on many factors. Phagocytosis may be enhanced by opsonizing factors and in the absence of antibody-antigen reactions, physical properties such as surface change may play a role.

The absence of a stimulatory effect of coal dust particles on rat alveolar macrophages could be due to coal dust particles, which are not fibrous, behaving more like latex particles than asbestos particles. If this is true then the observed pathology of CWP could be partially accounted for by a failure of the pulmonary immune response thus leading to ineffective clearance of dust particles and a build up of molecules. Unknown physical or chemical properties of various coal dusts could lead to toxic effects on cells which have ingested the partices,[12] causing cell death and release of inflammatory cellular components.

However, our results also suggest that there are basic differences in arachidonic acid metabolism between species, and that there could be variations in the response of different species to coal dust particles. There is evidence to suggest that in coal miners there may be inter-individual susceptibility to altered lung function[14] and that different ranks of coal are associated with a different prevalence of pneumoconiosis.[15]

The pathogenic events which could lead to CWP and PMF and altered pulmonary function may depend on the ability of the individual to respond to the damaging effects of particles which in turn may depend on duration of exposure level and type of particle involved. Given the different particulate mix of coal dust in any one mine, it may well be that a combination of factors may synergize the pathologic response. Studies are continuing to explore further the differing effects of different coal dust preparations on the macrophage processing of arachidonic acid.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the

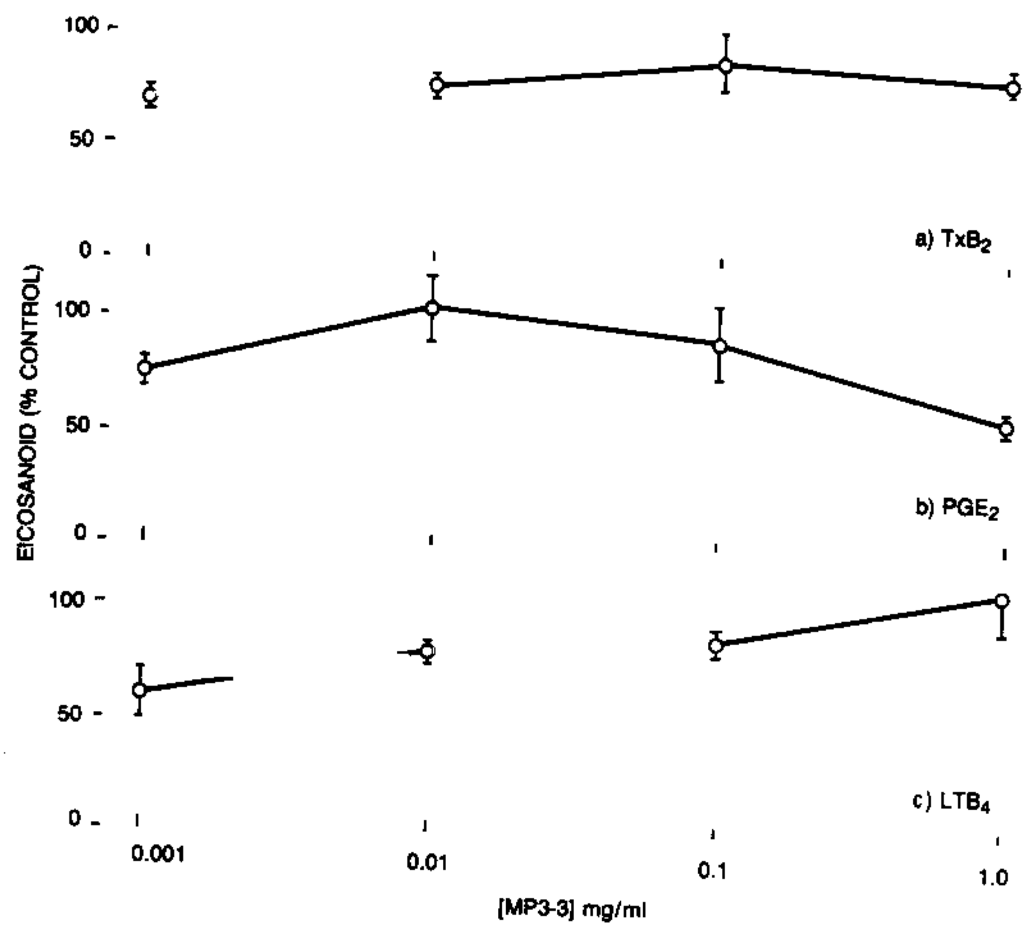


FIGURE 8. Release of arachidonic acid metabolites by rat alveolar macrophages in the presence of different concentration of coal dust MP3-3 after 1 hour incubation.

Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

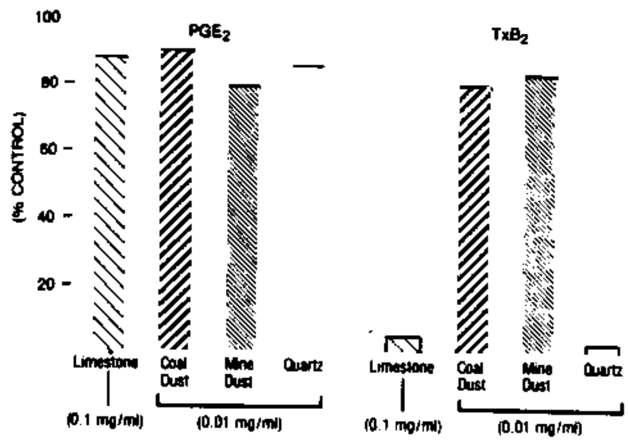


FIGURE 9. Effect of different coal dust particles on PGE2 and TXB2 production by rat alveolar macrophage.

FIGURE 10. Transmission electron micrograph of alveolar macrophage following exposure to coal dust under in vitro conditions.

References

1. **Morgan, W.K.C.:** *Occupational Lung Diseases*, pp. 149-215. W.B. Saunders Co. (1975).

2. **Hunninghake, G.W., J.E. Gadek, O. Kawanami et al:** Inflammatory and Immune Processes in the Human Lung in Health and Disease: Evaluation by Bronchoalveolar Lavage. *Am. J. Pathol. 97(1):* 149-205 (1979).

3. **Harris, J.O., E.W. Swenson and J.E. Johnson, III:** Human Alveolar Macrophages: Comparison of Phagocytic Ability, Glucose Utilization and Ultrastructure in Smokers and Nonsmokers. *J. Clin. Invest. 49*:2086-2096 (1970).

4. **Drew, W.L., L. Mintz, R. Hoo and T.N. Finley:** Growth of Herpes Simplex and Cytomegalovirus in Cultured Human Alveolar Macrophages. *Am. Rev. Resp. Dis. 119*:287-291 (1979).

5. **Yeager, H., Jr., S.M. Zimmet and S.L. Schwartz:** Pinocytosis of Human Alveolar Macrophages. Comparison of Smokers and Non-smokers. *J. Clin. Invest. 54*:247-251 (1974).

6. **Hoidal, J.R.:** Alveolar Macrophages from Young, Asymptomatic Cigarette Smokers and Non-smokers Use Equal Amounts of O_2 and Glucose but Smokers make more Superoxide Anion. *Am. Rev. Resp. Dis. 119*:222A (1979).

7. **Hsueu, W.:** Prostaglandin Biosynthesis in Pulmonary Macrophages. *Am. J. Pathol. 97*:137-148 (1979).

8. **Kouzan, S., A.R. Brody, P. Nettesheim and T. Eling:** Production of Arachidonic Acid Metabolites by Macrophages Exposed *in vitro* to Asbestos Carbonyl Iron Particles or Calcium Ionophore. *Am. Rev. Resp. Dis. 131*:624-632 (1985).

9. **Needleman, P., J. Turk, B.A. Jakschik et al:** Arachidonic Acid Metabolism. *Ann. Rev. Biochem. 55*:69-102 (1986).

10. **Fantone, J.C., S.L. Kunkel and P.A. Ward:** Chemotactic Mediators in Neutrophil-dependent Lung Injury. *Ann. Rev. Physiol. 44*:283-293 (1982).

11. **Hyman, A.L., E.W. Spannhake and P.J. Kadowitz:** Prostaglandins and the Lung. *Am. Rev. Respir. Dis. 117*:111-136 (1978).

12. **Tilkes, F. and E.G. Beck:** Macrophage Functions After Exposure to Nonfibrous Mineral Dusts. *Environ. Health Persp. 51*:167-171 (1983).

13. **Demers, L.M.:** Prostaglandins, Thromboxane and Leukotrienes. *Laboratory Medicine.* G. Race, Ed. Harper & Row, New York (1983).

14. **Hurley, J.F. and C.A. Soutar:** Can Exposure to Coal Mine Dust Cause a Severe Impairment of Lung Function? *Brit. J. Ind. Med. 43*:150-157 (1986).

15. **Morgan, W.K.C.:** Prevalence of Coal Workers' Pneumoconiosis. *Am. Rev. Respir. Dis. 98*:306-310 (1968).

Effects of Coal Dusts and Alveolar Macrophages on Growth of Lung Fibroblasts

GERALD L. BARTLETT, M.D., Ph.D. and ANN B. PEDERSEN, B.S.
Department of Pathology, The Milton S. Hershey Medical Center, The Pennsylvania State University, Hershey, Pennsylvania

As a part of our study of how coal mine dusts injure the lung we have studied the effects of dusts and dust-exposed pulmonary alveolar macrophages (PAMs) on the growth of lung fibroblasts (LF). Fibroblasts were cultured near confluence in low-serum medium, either alone or in the presence of dusts, dusts plus PAMs, dust leachates or supernatants of dust-exposed PAM cultures. We report here provisional conclusions, based on initial observations. Rat LF were relatively unresponsive to direct effects of dusts, showing weak stimulation in only a few cultures, and there was no evidence that dust-exposed rat PAMs had released any growth-regulatory products. In contrast, guinea pig cells were more responsive to the dusts. The pattern of responses was quite complex. Three of the dusts stimulated LF directly (with no mediation by PAMs). Two dusts were essentially inert when added directly to fibroblast cultures, either with or without PAMs, but their leachates were active: 867 leachate was inhibitory and RF leachate was stimulatory. Dust 1361, either directly in the cultures or as an aqueous leachate, was stimulatory, and it activated cocultured PAMs to stimulate LF growth; however, supernatant products of 1361-stimulated PAMs were inhibitory. Direct exposure to 1192 stimulated LF, but its leachate was inert; cocultured PAMs exposed to 1192 had weak stimulatory effects, but supernatants of 1192-exposed PAMs were mildly inhibitory. MP3-3 had effects similar to 1192, except that the cocultured, dust-exposed PAMs had no effect on growth. We conclude 1) that guinea pig lung cells are more responsive to dusts than are rat lung cells, 2) that dusts can influence growth of LF by four kinds of interaction (by direct dust-cell interaction, by release of soluble dust components into the culture medium, by activating PAMs to exert direct cell-cell interactions, and by activating PAMs to release growth regulatory products into the culture medium), 3) that each kind of interaction may be neutral, inhibitory or stimulatory, depending on the dust tested, 4) that four of the dusts tested were neutral, inhibitory or stimulatory, depending on the assay (the fifth dust was either neutral or stimulatory), and 5) that the effects of soluble mediators (leachates or products of activated PAMs) frequently did not correspond with the direct dust-cell or PAM-fibroblast effects. These results suggest that the nature of the dust-lung interaction at the level of cells and molecules is exceedingly complex. These observations need to be confirmed and extended to determine what characteristics of the dusts determine the nature of the cellular responses, and to determine which patterns of responses are detrimental andwhich are beneficial in the overall health of the dust-exposed lung.

Introduction

Chronic occupational exposure to the dusts in coal mines commonly results in coal worker's pneumoconiosis (CWP), the progressive accumulation of coal mine dusts in the substance of the lung. The effects on pulmonary function may range from minimal to debilitating. One common feature of the degenerative changes that occur in CWP is the production of increased amounts of fibrous connective tissue ("scar"). This process of fibrosis converts the normally pliable, elastic lung tissue into a more or less rigid, nonelastic organ. Even when fibrosis is minimal, it exerts traction on surrounding delicate alveolar walls, contributing to the emphysema that is a part of the milder forms of CWP. If the dust-lung interaction could be characterized sufficiently to define the sequence of events that leads to fibrosis, it might be possible to prevent the development of fibrosis in CWP by modulating the lung's response to dust. Likewise, prevention of CWP would be facilitated if the characteristics of dusts that trigger the fibrotic process could be identified, leading to the recognition of which dusts are most likely to cause serious disease. Our long range objective is to learn how to prevent CWP. To that end we are studying the interaction of coal dusts and lung cells in cell culture in order to determine how that interaction results in fibrosis and to determine whether dusts with different physical and chemical characteristics interact with lung cells in qualitatively or quantitatively different ways.

A key component of the fibrotic process is the proliferation of the fiber-producing cells of the lung, called lung fibroblasts (LF). In the normal, healthy lung the LF are a part of the supporting framework of the lung and are generally quiescent. They undergo division only rarely, so they synthesize DNA at a low rate. When the lung is responding to injury, the LF are mobilized to produce the new fibers necessary to patch up the area of injury. Part of that mobilization response is an increase in the rate of cell division in order to increase the numbers of LF available to carry out the repair. The response of most tissues to injury is orchestrated, in large part, by a class of mobile, protective cells called macrophages; in the lung they are called pulmonary alveolar macrophages (PAMs). Studies of pneumoconiosis and pulmonary fibrosis due to other agents have suggested that when macrophages ingest the inhaled particulates they are "activated," resulting in increased synthesis and secretion of several different compounds that regulate various aspects of the inflammatory, repair and immune processes.[1-9] In particular, it has been shown that PAMs exposed to asbestos release more fibroblast growth factor than do control PAMs.[10] Similar studies have been performed with other agents,[11-14] but not with well-characterized coal dusts. Likewise, many such studies have used macrophages from parts of the body other than the lung (i.e., from the peritoneal cavity)[9,15-17] and have used fibroblasts either from other sites, such as skin[9,15-18] or from established, heterologous cell lines in culture.[11] The overall purpose of this study is to test the hypothesis that exposure of PAMs to coal dusts causes the PAMs to secrete factors that stimulate growth of LF; related hypotheses and corollaries are tested in the course of the study. To our knowledge, this is the only investigation that uses coal dusts, PAMs and LF.

Materials & Methods

Animals

Female Hartley random-bred guinea pigs were purchased from Hazelton Research, Denver, Pennsylvania. Female Fisher 344 inbred rats were purchased from Charles River Laboratories, Kingston, New York.

Macrophages

PAMs were obtained by bronchial lavage of adult female rats or guinea pigs under nembutal anesthesia. Five ml of phosphate buffered saline (pH 7.4) with 0.1 percent ethylenediamine tetraacetic acid was instilled through the trachea, flushed five times and collected in a sterile plastic centrifuge tube on ice. Each animal was lavaged three times. Cells from different rats were pooled, but cells from different guinea pigs were not pooled. The cell suspensions were centrifuged at 400 g for 15 min, and resuspended at 2×10^5 cells/ml in Dulbecco's Minimal Essential Medium (DMEM) containing fetal calf serum (FCS), 1 percent for cocultures or 0.5 percent for supernatant production.

Supernatants and Leachates

Products of stimulated guinea pig PAMs were prepared as described by Lemaire.[10] Briefly, PAMs were added to the 24 mm diameter wells of 12-well cluster plates at the rate of 0.5 ml (10^6 cells)/well, and incubated at 37°C for one hour to allow the cells to adhere. One hour later, 0.5 ml of dust suspension was added to each well containing 10^6 newly plated PAMs, so that the final nutrient volume was 1.0 ml and the final FCS concentration was 0.5 percent. The cells were incubated at 37°C, 5 percent CO_2 for 24 hours. At the end of the incubation period, the nutrient medium was aspirated from each well, and the supernatants of replicate wells (same additive, same concentration, cells from different donor animals) were pooled. Supernatant pools were centrifuged at 1600 g for 15 min, distributed in 1 ml aliquots in plastic tubes and frozen at −70°. Leachates were prepared in parallel with the supernatants, incubating the dust in 1 ml of DMEM (0.5 percent FCS) without PAMs for 24 hours.

Lung Fibroblasts (LF)

Young adult guinea pigs (approximately 2 months old) were killed by an overdose of nembutal, and the lungs were removed aseptically. Small fragments of lung tissue (< 1 mm^3) were placed in dry 35 mm plastic tissue culture dishes; after several minutes to permit firm attachment to the dish, the explants were covered with 2 ml DMEM (20 percent FCS). Fibroblasts were permitted to grow out of the explants, and when they covered a majority of the surface of the primary culture dish, they were harvested and passed to larger culture vessels for expansion of the population. Cells were harvested by 10 min incubation in 0.05 percent trypsin, washed in DMEM with 20 percent FCS and counted in a hemacytometer. In some experiments, rat lung fibroblasts were prepared from 60-80 gm weanling rats and used in the same fashion.

Coal Dust Samples

Five different coal dusts have been tested thus far. For each of the first four dusts, the coal sample was collected in the mine, transported to the Mineral Engineering laboratory at Pennsylvania State University, crushed, screened and milled to produce dust with a size distribution predominantly in the respirable range (< 5 um diameter). Those specimens include: MP3-3 (Upper Freeport, Bituminous); PSOC-867 (Primrose, Anthracite); PSOC-1192 (Lower Kittanning, Bituminous); and PSOC-1361P (Upper Freeport, Bituminous). The first was kindly provided by Professor R. Hogg, Pennsylvania State University, and the latter three were provided by the Generic Technology Center for Respirable Dust. The fifth dust is the respirable fraction of a coal mine dust sample collected in the Arkwright Mine by Joe Parenty (Pittsburgh, Bituminous), and distributed by the Generic Technology Center.

Dusts aliquots were preweighed and autoclaved dry. Under aseptic conditions they were suspended at 1 gm/100 ml in DMEM containing 0.4 percent Tween 80, centrifuged (1600 g, 15 min), washed in medium without FCS or Tween, then resuspended at 10^{-3} gm/ml in DMEM and stored frozen in 1 ml aliquots.

Growth of LF

Monolayers of LF were harvested just as they reached confluence. The cells were washed in DMEM and resuspended at 2×10^5 cells/ml in DMEM with 20 percent FCS. The cell suspension was added to the wells of 96-well cluster plates, usually 20,000 cells per well. Radioactive tracer, tritiated thymidine (^{3}H-TdR, 1 uCi/well) was added to the culture medium to assess proliferative activity by incorporation of 3H-TdR into DNA of growing cells. For harvest, each well was treated with 0.05 percent trypsin at 37°C for 10 minutes. Then the cells were aspirated with a multiple-well automated sample harvester, deposited on glass fiber filters, washed, dried, suspended in Betafluor (Beckman) and counted in a liquid scintillation counter. Other conditions (concentrations, times, etc.) are described with each experiment. Results were recorded as counts per minute (CPM)/well, and values for triplicate wells are reported in the tables as mean CPM/well +/- the standard error of the mean (SEM) in thousands (i.e., $\times 10^{-3}$). Differences between experimental and control values were tested for statistical significance using the Student's t-Test.

TABLE I

Growth of Rat LF* Exposed to Dusts in Culture With or Without Cocultured PAMs (CPM/well x 10^3)

Concentration of Dust (Log, gm/ml)	LF Only Mean +/- SEM**	LF + PAMs Mean +/- SEM***
MP3-3		
0	2.2 +/- 0.1	2.6 +/- 0.3
-10	1.9 +/- 0.2	2.3 +/- 0.1
-9	2.0 +/- 0.5	2.2 +/- 0.2
-8	1.9 +/- 0.2	2.6 +/- 0.3
-7	1.9 +/- 0.3	2.9 +/- 0.3
-6	1.9 +/- 0.2	1.9 +/- 0.1
-5	1.7 +/- 0.3	2.2 +/- 0.5
-4	2.0 +/- 0.3	2.3 +/- 0.1
PSOC-867		
0	20.2 +/- 3.4	19.3 +/- 3.6
-10	25.1 +/- 3.6	22.6 +/- 1.7
-9	21.5 +/- 2.2	21.1 +/- 3.1
-8	21.4 +/- 0.8	23.3 +/- 0.8
-7	36.8 +/- 3.6+	31.4 +/- 0.2
-6	34.5 +/- 2.4+	34.7 +/- 2.4
-5	33.1 +/- 4.0	34.7 +/- 2.4
-4	22.3 +/- 0.8	22.1 +/- 1.6
PSOC-1192		
0	9.8 +/- 0.8	9.3 +/- 1.9
-10	9.5 +/- 0.6	7.9 +/- 0.9
-9	7.2 +/- 0.8	8.1 +/- 0.9
-8	9.1 +/- 1.7	7.1 +/- 1.1
-7	18.5 +/- 2.2+	12.5 +/- 1.0
-6	13.8 +/- 2.5	12.4 +/- 0.8
-5	13.0 +/- 1.8	12.1 +/- 0.8
-4	7.1 +/- 0.4-	7.0 +/- 0.2
PSOC-1361		
0	9.4 +/- 0.8	8.8 +/- 1.9
-10	11.6 +/- 0.7	11.7 +/- 1.7
-9	10.4 +/- 0.3	9.6 +/- 1.0
-8	10.3 +/- 0.7	10.7 +/- 1.5
-7	14.7 +/- 0.8++	11.9 +/- 1.2
-6	14.1 +/- 0.7++	12.9 +/- 2.3
-5	12.8 +/- 1.4	12.9 +/- 1.1
-4	7.2 +/- 0.2	7.9 +/- 0.4
CMD-RF		
0	10.2 +/- 1.4	10.8 +/- 1.7
-10	8.5 +/- 1.4	9.7 +/- 1.0
-9	7.7 +/- 0.9	9.0 +/- 1.6
-8	9.3 +/- 1.4	9.5 +/- 1.6
-7	11.9 +/- 3.1	10.7 +/- 0.8
-6	11.6 +/- 1.7	11.3 +/- 1.2
-5	13.6 +/- 1.5	11.4 +/- 0.6
-4	9.0 +/- 1.4	8.9 +/- 0.5

Notes:

* 20,000 LF seeded/well in DMEM with 0.5 percent FCS; 5000 PAMs and/or dusts added after overnight incubation. 1 uCi/well 3H-TdR added 2 hour, cells harvested 48 hours after addition of dusts. PAMs only, 198 +/- 13 CPM/well. Triplicate wells for each condition.

** + = stimulation, - = inhibition of growth compared to control wells (0 gm/ml dust), (t-Test): one symbol, $p < 0.05$; two symbols, $p < 0.02$.

*** Growth of LF in the presence of PAMs was not different from growth of LF alone.

Results

Effects of Coal Dusts on Growth of Rat LF

This series of tests was performed to test the hypothesis that aqueous suspensions of coal dusts would have a direct effect on growth of rat LF, without the intervention of PAMs. Based on preliminary experiments it was expected that the dusts would be relatively inert in this assay, except for some inhibition of proliferation at the highest concentration (100 ug/ml). Rat LF were incubated in DMEM with 0.5 percent for 48 hours, either alone or in the presence of dust suspensions (10^{-10} to 10^{-4} gm/ml). The cells were labelled continuously during the experiment with ^{3}H-TdR. The results of this assay for the five dust samples are shown in the left column of Table I. In the experiment testing MP3-3, growth of fibroblasts in all wells was unusually low, suggesting that, for unknown reasons, the cells in that experiment were not suitable for detecting growth effects of the dust. Among the tests of the other four dusts, only (1192) had a significantly inhibitory effect on the cells, and that was only at the highest dose tested (100 ug/ml). Three of the dusts (867, 1192 and 1361) showed significant stimulation of LF growth, but only at one or two doses. The respirable fraction of dust from the Arkwright Mine had no significant effect on cell growth. We conclude that three dusts have a weak direct stimulatory effect on growth of rat LF.

Effects of Dust-Exposed PAMs on Growth of Cocultured Rat LF

The next experiments were done to test the hypothesis that dust-exposed rat PAMs would affect growth of cocultured rat LF, compared to growth of the LF in the presence of the same concentration of dust without PAMs. As part of the each experiment described above, replicate wells were incubated with LF and dusts as described, plus 5000 PAMs per well that were added at the time of dust exposure. The results are in the right column of Table I; each value is to be compared to the adjacent value in the left column to determine if the presence of the PAMs had any significant effect on LF growth. Again the test with MP3-3 was uninterpretable. For the remaining four dusts, growth of LF in the presence of dust and PAMs was not significantly different from growth of LF in the presence of the dust alone. Thus, we conclude that under these conditions, the dusts tested here did not stimulate any growth-regulatory activity of the PAMs.

Effects of Coal Dusts on Growth of Guinea Pig LF

Because rat LF & PAMs were relatively unresponsive to coal dusts, we next used guinea pig LF to test the hypothesis that coal dusts would have a direct effect on growth of guinea pig LF. These tests were performed under identical conditions to those described above, except that guinea pig LF were used. The results are in the left column of Table II. Three dusts (867, 1192 and RF) were inhibitory at the highest concentration tested (100 ug/ml). Two of those three dusts (867 and RF) had no effect on fibroblast growth at any of the lower concentrations. The other three dusts each stimulated fibroblast growth to a significant degree over a range of concentrations. The most consistent effect was by 1361, stimulating proliferation of LF from 100 pg/ml to 10 ug/ml; 1192 and MP3-3 were stimulatory from a low concentration of 10 ng/ml to a high concentration of 1 or 10 ug/ml respectively. We conclude 1) that dusts differ in their toxicity for guinea pig fibroblasts, 2) that dusts differ in their ability to stimulate guinea pig fibroblasts, 3) that the same dust may be either toxic or stimulatory at different concentrations, and 4) that guinea pigs and rats differ in their susceptibility to either toxic or stimulatory effects of coal dusts for LF.

Effects of Dust-Exposed PAMs on Growth of Cocultured Guinea Pig LF

The next experiments were done to test the hypothesis that dust-exposed guinea pig PAMs would affect growth of cocultured guinea pig LF, compared to growth of the LF in the presence of the same concentrations of dust without PAMs. As part of the each experiment described in the previous paragraph, replicate wells were incubated with LF and dusts as described, plus 5000 PAMs per well that were added at the time of dust exposure. The results are in the right column of Table II. Each value is to be compared to the adjacent value in the left column to determine if the presence of the PAMs had any significant effect on fibroblast growth. In two experiments, PAMs alone had a weak or moderate

TABLE II

Growth of Guinea Pig LF* Exposed to Dusts in Culture With or Without Cocultured PAMs (CPM/well x 10^{-3})

Concentration of Dust (Log, gm/ml)	LF Only Mean +/- SEM**	LF + PAMs Mean +/- SEM***
MP3-3		
0	20.3 +/- 2.0	26.6 +/- 0.8+
-10	25.1 +/- 2.0	26.0 +/- 2.5
-9	30.6 +/- 4.0	31.5 +/- 5.4
-8	33.0 +/- 2.8+	29.0 +/- 1.1
-7	37.7 +/- 4.4+	25.8 +/- 2.4
-6	27.2 +/- 1.0+	26.0 +/- 1.2
-5	30.8 +/- 0.4+++	36.2 +/- 2.5
-4	16.6 +/- 1.2	20.0 +/- 0.9
PSOC-867		
0	65.3 +/- 11.3	74.3 +/- 3.9
-10	78.3 +/- 6.8	75.5 +/- 3.7
-9	65.2 +/- 14.3	68.5 +/- 12.3
-8	63.2 +/- 4.4	64.9 +/- 13.6
-7	72.7 +/- 9.9	76.4 +/- 4.6
-6	65.2 +/- 6.5	79.2 +/- 5.9
-5	51.2 +/- 4.0	51.6 +/- 4.5
-4	32.1 +/- 0.8-	31.6 +/- 3.0
PSOC-1192		
0	45.7 +/- 2.1	58.7 +/- 7.5
-10	48.8 +/- 0.3	66.5 +/- 1.4++++
-9	52.5 +/- 5.9	50.2 +/- 6.7
-8	63.6 +/- 6.0+	54.4 +/- 7.1
-7	56.1 +/- 2.0+	71.8 +/- 3.2++
-6	70.3 +/- 6.0++	64.9 +/- 1.7
-5	59.8 +/- 5.7	62.7 +/- 6.3
-4	26.6 +/- 1.9---	32.5 +/- 1.1
PSOC-1361		
0	27.3 +/- 1.0	42.0 +/- 2.1+++
-10	35.0 +/- 0.1+++	51.1 +/- 3.7++
-9	32.2 +/- 0.5++	55.2 +/- 2.3++++
-8	51.5 +/- 6.1++	68.1 +/- 0.2
-7	61.7 +/- 6.1++	65.8 +/- 2.4
-6	62.6 +/- 4.0++	66.0 +/- 5.7
-5	45.9 +/- 0.6++++	75.0 +/- 0.1++++
-4	22.5 +/- 2.8	28.6 +/- 2.1
CMD-RF		
0	60.1 +/- 5.3	45.5 +/- 7.4
-10	60.0 +/- 4.5	51.6 +/- 1.7
-9	60.5 +/- 4.1	44.1 +/- 6.1
-8	55.7 +/- 2.6	49.0 +/- 5.3
-7	66.2 +/- 2.1	57.6 +/- 7.3
-6	57.6 +/- 0.7	78.3 +/- 12.8
-5	58.7 +/- 4.3	52.2 +/- 0.8
-4	35.4 +/- 2.0--	33.5 +/- 2.1

Notes:

* 20,000 LF seeded/well in DMEM with 0.5 percent FCS; 5000 PAMs and/or dusts added after overnight incubation. 1 uCi/well ^{3}H-TdR added 2 hour, cells harvested 48 hours after addition of dusts. Triplicate wells for each condition.

** + = stimulation, - = inhibition of growth compared to control wells (0 gm/ml dust) (t-Test): one symbol, $p < 0.05$; two symbols, $p < 0.02$; three symbols, $p <$ 01; four symbols, $p < 0.001$.

*** + = stimulation, - = inhibition of growth compared to the adjacent leachate control: one symbol, $p < 0.05$; two symbols, $p < 0.02$; three symbols, $p < 0.01$; four symbols, $p < 0.001$.

stimulatory effect on growth of LF in the absence of dusts. Three dusts (MP3-3, 867 and RF) did not cause the PAMs to exert any growth regulatory effect at any dust concentration. PAMs exposed to two different concentrations of 1192 stimulated fibroblast growth, and PAMs exposed to 1361 were stimulatory at three concentrations. We conclude that, in contrast to rat PAMs, guinea pig PAMs may be activated by two of the five dusts to stimulate growth of cocultured guinea pig LF.

Effects of Dust Leachates on Growth of Guinea Pig LF

Since LF are nonphagocytic, and since suspensions of dust particles can stimulate or inhibit LF growth without the mediation of phagocytic cells (Table II, left column), it is important to determine whether the effects of the dusts are mediated by direct contact with the cells or by some constituent of the dust that becomes dissolved in the aqueous medium. Therefore, this series of experiments tested the hypothesis that aqueous leachates of the dusts would either inhibit or stimulate growth of guinea pig LF. After overnight incubation of 20,000 guinea pig fibroblasts/well, the medium was removed and replaced with 100 ul/well DMEM containing 0.5 percent FCS. Then each well received 100 ul of dust leachate and 1 uCi 3H-TDR, and cells were harvested 24 hours later. The results are in the left column of Table III. Leachates of 1192 had no effect and those from MP3-3 had a weak effect at only one concentration. Two dusts, 1361 and RF, produced leachates that stimulated LF growth in the middle to higher concentration range. In contrast, the leachates from 867 had significant inhibitory effects on fibroblast growth across the whole spectrum of concentrations tested. We conclude 1) that some dusts (MP3-3 and 1192) do not contain aqueous extractable components that alter growth of guinea pig LF, 2) that aqueous extracts of other dusts (1361 and RF) stimulate LF growth, and 3) that aqueous extracts of surprisingly small amounts of dust 867 are inhibitory for growth of guinea pig LF.

Effects of Supernatants from Dust-Exposed PAM Cultures on Growth of Guinea Pig LF

Table II showed that dust-exposed PAMs had growth stimulatory properties on cocultured LF. The following experiments were to test the hypothesis that growth-regulatory effects of dust-exposed PAMs are mediated by soluble products secreted by the PAMs into the culture medium. They were performed as part of each of the leachate experiments described in the previous paragraph, using replicate wells of cultured LF. Supernatant media were collected after 24 hour incubation in the presence of PAMs and various concentrations of the five dusts, and they were added to cultures of guinea pig LF and labelled for 24 hours. The results are shown in the right column of Table III. Such supernatants would be expected to contain both the products released by activated PAMs and any components of the dusts extracted by the aqueous medium. Therefore, each experimental value is to be compared with the adjacent leachate control to determine to what extent the products of dust-exposed PAMs altered growth, as distinct from effects of the leachate. Media from PAMs exposed to RF were essentially inert, having no significant effect at most concentrations when compared to the effects of the same concentration of leachate. Supernatants from 867-exposed PAMs were significantly stimulatory across the entire range of concentrations. In contrast, the other three dusts caused the PAMs to release into the medium soluble materials that inhibited fibroblast growth. We conclude 1) that one of the dusts (RF) did not activate PAMs to secrete growth-regulatory products, 2) that three dusts (MP3-3, 1192 and 1361) caused PAMs to release growth inhibitory products, 3) that one dust, 867, activated PAMs to secrete growth stimulatory products, and 4) that the growth regulatory effects of soluble products of dust-exposed PAMs do not correspond to the growth regulatory effects of cocultured, dust-exposed PAMs.

Discussion

The experiments reported here have not yet been repeated for confirmation, so the conclusions drawn are, of necessity, provisional. The data are based on results of triplicate cultures; in some instances duplicate values were used if results from one well of a set were not obtainable for technical reasons, or if one well of a set deviated substantially from the mean of the other two ("outlyers"). Differences between experimental and control wells were tested for statistical significance by the Student's t-Test. We hope to perform a more comprehensive statistical evaluation of these (or subsequent) data using the analysis of variance test with the Newman-Keuls and Dunnette tests. Because results of multiple-comparison assays were tested with a pair-wise statistic, statements about the significance of inhibitory or stimulatory effects reflected an assessment of the pattern of effects over a range of several dust doses; isolated values that were significant by the t-test were not regarded as biologically significant.

The major working hypothesis for this phase of our study was that coal dusts stimulate PAMs to secrete materials that stimulate the growth of fibroblasts. The results of Table III confirm that, at least for the one anthracite sample we tested, the hypothesis is true. Supernatants of PAMs exposed to dust 867 caused up to a two-fold increase in the rate of proliferation of LF. However that conclusion is not generally applicable since in the same series of experiments, supernatants of PAMs exposed to three of the bituminous samples caused up to 40 percent inhibition of LF proliferation, and supernatants induced by the respirable fraction of mine dust were inactive as far as LF proliferation is concerned. It is tempting to view the stimulatory effects of 867-induced supernatants as detrimental and the inhibitory or inactive supernatants as biologically neutral, and that would conform to the conventional wisdom that the pension was added to each well containing 10^6 newly platedareas. However, under some circumstances, inhibition of the proliferation needed to maintain normal homeostasis would be detrimental. Therefore, much more on assay and that different dusts induce secretion

A priori one might predict that any PAM-mediated effects on LF would be at least qualitatively similar whether assessed with cell-free PAM culture supernatants or with PAMs growing in direct contact with the LF. However, our results showed that results of the two assays were not qualitatively similar. In two instances, dust-stimulation of PAM-LF cocultures had no effect on LF growth while the super-

TABLE III

Growth of Guinea Pig LF* Exposed in Culture to Dust Leachates or to Supernatants of Dust-exposed PAMs (CPM/well X 10^{-3})

Dust in Preculture (Log, gm/ml)	LF + Leachates Mean + SEM**	LF + Supernatants Mean + SEM***
MP3-3		
0	11.6 +/- 0.7	9.3 +/- 0.3-
-10	12.1 +/- 0.5	10.2 +/- 0.6
-9	11.9 +/- 0.7	8.3 +/- 0.5--
-8	12.5 +/- 0.4	8.6 +/- 0.1---
-7	13.8 +/- 1.6	10.7 +/- 0.7
-6	14.7 +/- 0.6+	7.6 +/- 0.3---
-5	15.1 +/- 1.1	8.4 +/- 0.7--
-4	13.0 +/- 1.8	9.9 +/- 0.7
PSOC-867		
0	45.0 +/- 1.7	43.7 +/- 1.9
-10	30.8 +/- 1.9--	38.9 +/- 1.5+
-9	27.1 +/- 2.0--	37.1 +/- 1.5++
-8	25.5 +/- 3.4---	37.8 +/- 2.2+
-7	26.0 +/- 0.4---	33.0 +/- 0.1++++
-6	28.4 +/- 3.0--	37.9 +/- 6.6
-5	28.4 +/- 4.6-	44.6 +/- 0.6+
-4	20.0 +/- 3.3--	44.6 +/- 3.1+++
PSOC-1192		
0	14.1 +/- 1.2	11.1 +/- 0.5
-10	12.1 +/- 2.0	10.1 +/- 1.0
-9	12.2 +/- 0.4	8.5 +/- 0.4--
-8	11.5 +/- 0.9	8.6 +/- 0.4-
-7	13.3 +/- 1.1	9.4 +/- 0.8-
-6	19.2 +/- 1.5	15.1 +/- 2.1
-5	16.6 +/- 0.9	11.3 +/- 0.4--
-4	11.7 +/- 0.8	10.2 +/- 0.9
PSOC-1361		
0	52.9 +/- 1.3	38.2 +/- 0.7---
-10	46.2 +/- 1.5-	36.6 +/- 1.0--
-9	43.5 +/- 4.0	33.2 +/- 3.3
-8	45.5 +/- 3.2	34.5 +/- 0.8-
-7	73.3 +/- 4.9++	72.3 +/- 1.5
-6	73.1 +/- 4.6++	55.5 +/- 1.4--
-5	75.2 +/- 1.6+++	51.2 +/- 1.9---
-4	34.5 +/- 1.7--	26.6 +/- 0.4-
CMD-RF		
0	81.0 +/- 0.9	81.7 +/- 7.7
-10	85.3 +/- 10.1	86.5 +/- 11.3
-9	85.3 +/- 2.2	87.9 +/- 11.1
-8	93.0 +/- 7.3	83.9 +/- 12.4
-7	106.9 +/- 3.0+++	87.8 +/- 4.4-
-6	99.9 +/- 4.7++	81.6 +/- 13.4
-5	103.9 +/- 6.6+	88.3 +/- 6.9
-4	96.1 +/- 1.5+++	89.5 +/- 8.9

Notes:

* 20,000 fibroblasts seeded/well in DMEM with 0.5 percent FCS; leachates or supernatants added after overnight incubation. Labelled with 1 ug/well 3H-TdR 24 hours after addition of dusts. Triplicate wells for each condition.

** + = stimulation, - = inhibition of growth compared to control wells (0 gm/ml dust) (t-Test): one symbol, $p < 0.05$; two symbols, $p < 0.02$; three symbols, $p < 0.01$; four symbols, $p < 0.001$.

*** + = stimulation, - = inhibition of growth compared to the adjacent leachate control (t-Test): one symbol, $p < 0.05$; two symbols, $p < 0.02$; three symbols, $p < 0.01$; four symbols, $p < 0.001$.

natants of PAMs stimulated by those dusts were inhibitory and stimulatory respectively. Further, two dusts that had stimulatory effects in PAM-LF cocultures induced production by PAMs of inhibitory supernatants. At this early stage of the study it is not evident how the cocultured PAMs affect LF growth other than by their secreted products. Presumably the dust-stimulated PAMs in LF-coculture secrete into the shared medium the same kinds and same amounts of products that they secrete into medium when they are cultured without LF. So, the proliferative rate that was observed must be the net result of the of rat LF

In addition to the PAM-mediated effects on LF growth mentioned above, these experiments revealed that dust or dust leachates can modulate growth of LF without the mediation of PAMs. Three dusts were mildly to moderately stimulatory when in direct contact with LF (in the absence of PAMs), and for one dust that stimulation could be repeated using a centrifuged leachate of the dust. In contrast, leachates of the other two dusts were inactive, suggesting that the stimulatory effects of those dusts was due to direct dust-LF contact, not to water-soluble dust components conveyed by the culture medium. Finally, two dusts that had no effect when in direct contact with the LF released soluble components into the leachate that had potent inhibitory effects in one case and moderate stimulatory effects in the other case. Again, it is not yet possible to conclude that one kind of dust-cell interaction of "bad" and that others are "good," but it is clear that coal dusts can have potent, and sometimes opposite, effects on LF proliferation, independent of PAMs.

It should be mentioned that the nature of the dust effects (stimulatory/inhibitory) and their pattern may reflect not only the character of the dust and the way it was assayed in these experiments, but may depend to some extent on other experimental conditions that were not varied in this study. For instance, the methods of collecting and culturing PAMs might alter their reactivity in small or large ways. Likewise, this system is only one of a variety of experimental conditions that can be used to assess the proliferative behavior of LF. As done here (20,000 cells/well and low serum concentration [0.5 percent]), the cells are relatively quiescent. In other systems, LF could be studied during a maximal growth phase (low cell density and high serum concentration), and at various times in their growth pattern. Experiments testing some of those variables are planned.

From a practical standpoint it is important to emphasize the major species difference in responses to coal dusts that we have observed. Both rats and guinea pigs have been used extensively to study lung diseases and to study the functions of macrophages. However, most cell culture studies of macrophage function in the rat have used macrophages from the peritoneal cavity. We have observed that that rat PAMs are not functionally equivalent to peritoneal macrophages or to PAMs of other species. Rat and guinea pig macrophages from the lung, from the peritoneum and from inflammatory exudates were stimulated with tetradecanoyl phorbol acetate. Each class of macrophages, except rat PAMs, promptly released a significant amount of superoxide anion radical.(19) The results presented here further indicate that rat PAMs and LF are not equivalent to guinea pig PAMs in terms of response to coal dusts. On that admittedly limited evidence we have decided to use the guinea pig for most of our studies in the near future. It will not be possible to determine which species' response pattern is most representative of human responses until similar experiments can be performed using human cells.

The major conclusion to be drawn from this work is that, even at this preliminary stage of investigation, there are clear differences in the ways in which different coal dusts affect PAMs and LF of the guinea pig. The response patterns are complex, and for reasons stated above it is not possible to identify any particular pattern as "good" or "bad." However, the existence of these intersample differences means that it will soon be possible to design experiments to identify which chemical or physical characteristics of the dusts are responsible for the various kinds of responses, and how those responses are mediated at the cellular and molecular level.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

References

1. **Koretzky, G.A., J.A. Elias, S.L. Kay et al**: Spontaneous Production of Interleukin-1 by Human Alveolar Macrophages. *Clin. Immunol. Immunopathol. 29*:443-450 (1983).

2. **Hunninghake, G.W.**: Release of Interleukin-1 by Alveolar Macrophages of Patients with Active Pulmonary Sarcoidosis. *Am. Rev. Respir. Dis. 129*:569-572 (1984).

3. **Martin, T.R., L.C. Altman, R.K. Albert and W.R. Henderson**: Leukotriene B4 Production by the Human Alveolar Macrophage: A Potential Mechanism for Amplifying Inflammation in the Lung. *Am. Rev. Respir. Dis. 129*:106-111 (1984).

4. **Sherman, M.P. and R.I. Lehrer**: Superoxide Generation by Neonatal and Adult Rabbit Alveolar Macrophages. *J. Leukocyte Biol. 36*:39-50 (1984).

5. **Tate R.M., H.G. Morris, W.R. Schroeder and J.E. Repine**: Oxygen Metabolites Stimulate Thromboxane Production and Vasoconstriction in Isolated Saline-perfused Rabbit Lungs. *J. Clin. Invest. 74*:608-613 (1984).

6. **Vilim, V., J. Wilhelm, P. Brzak and J. Hurych**: The Chemiluminescence of Rabbit Alveolar Macrophages Induced by Quartz Dust Particles. *Immunol. Lett. 8*:69-73 (1984).

7. **Kouzan, S., A.R. Brody, P. Nettesheim and T. Eling**: Production of Arachidonic Acid Metabolites by Macrophages Exposed in vitro to Asbestos, Carbonyl Iron Particles or Calcium Ionophore. *Am. Rev. Respir. Dis. 131*:624-632 (1984).

8. **Nugent, K.M., J. Glazier, M.M. Monick and G.W. Hunninghake**: Stimulated Human Alveolar Macrophages Secrete Interferon. *Am. Rev. Respir. Dis. 131*:714-718 (1985).

9. **Kampschmidt, R.F., M.L. Worthington III and M.I. Mesecher**: Release of Interleukin-1 (IL-1) and IL-1-like Factors from Rabbit Macrophages with Silica. *J. Leukocyte Biol. 39*:123-132 (1986).

10. **Lemaire, I., H. Beaudoin, S. Masse and C. Grondin**: *Am. J. Path. 122*:205-211 (1986).

11. **Burrell, R. and M. Anderson**: The Induction of Fibrogenesis by Silica-treated Alveolar Macrophages. *Environ. Res. 6*:389-394 (1973).

12. **Nourse, L.D., P.N. Nourse, H. Botes and H.M. Schwartz**: The Effects of Macrophages Isolated from the Lungs of Guinea Pigs Dusted with Silica on Collagen Biosynthesis by Guinea Pig Fibroblasts in Cell Culture. *Environ. Res. 9*:115-127 (1975).

13. **Lugano, E.M., J.H. Dauber, J.A. Elias et al**: The Regulation of Lung Fibroblast Proliferation by Alveolar Macrophages in Experimental Silicosis. *Am. Rev. Resp. Dis. 129*:767-771 (1984).

14. **Kovacs, E.J. and J. Kelley**: Secretion of Macrophage-derived Growth Factor During Acute Lung Injury Induced by Bleomycin. *J. Leukocyte Biol. 37*:1-14 (1985).

15. **Harington, J.S., M. Ritchie, P.C. King and K. Miller**: The *in-vitro* Effects of Silica-treated Hamster Macrophages on Collagen Production by Hamster Fibroblasts. *J. Path. 109*:21-37 (1971).

16. **Aalto, M. and A.G. Heppleston**: Fibrogenesis by Mineral Fibres: An *in-vitro* Study of the Roles of the Macrophage and Fibre Length. *Brit. J. Exp. Path. 65*:91-99 (1984).

17. **Hart, P.H., L.W. Powell, W.G.E. Cooksley and J.W. Halliday**: Mononuclear Cell Factors that Inhibit Fibroblast Collagen Synthesis. I. *In vitro* Conditions Determining Their Production and Expression.

Scand. J. Immunol. 18:41-49 (1983).

18. **Aalto, M., H. Turakainen and E. Kulonen**: Effect of SiO2-liberated Macrophage Factor on Protein Synthesis in Connective Tissue *in vitro. Scand. J. Clin. Lab. Invest. 39*:205-213 (1979).

19. **Bartlett, G.L. and A.B. Pedersen**: Unpublished observations (1985).

Measurement of Superoxide Release from Single Pulmonary Alveolar Macrophages Exposed to Dusts

E.V. CILENTO, K.A. DIGREGORIO and R.C. LANTZ

Departments of Chemical Engineering and Anatomy, West Virginia University, Morgantown, West Virginia

An electro-optical method was used to quantify superoxide (SO) release from *single* rat pulmonary alveolar macrophages (PAM) exposed *in vitro* to respirable quartz and kaolin dusts and *in vivo* to quartz. Release was determined by measuring the reduction of nitroblue tetrazolium (NBT) to a diformazan precipitate at 550 nm from video-recorded images of individual cells. *In vitro* exposure to 0.025 or 0.05 mg/ml kaolin for 40 minutes resulted in no significant differences in either the total diformazan produced (max) or the maximum rate of diformazan production (R). *In vitro* exposure to 0.025 mg/ml quartz decreased max 38 percent while no significant change was found using 0.05 mg/ml. However, R was decreased 31 percent and 24 percent for the low and high dose, respectively. In contrast, PAM obtained from animals exposed *in vivo* to quartz dust for two or four weeks in inhalation chambers exhibited increased production of diformazan. However, only PAM analyzed three days post-exposure showed significant increases, while PAM from animals sacrificed ten or 31 days post-exposure were not significantly different from control. The combined *in vitro* and *in vivo* quartz results might suggest that there is an initital acute response to exposure that decreases the ability of PAM to produce SO, followed by recruitment of production of PAM with increased SO producing capability. It appears that removal of animals from the source of exposure permits PAM to return to control levels of SO production by 31 days. Whether this would be true for chronic exposure remains to be elucidated.

Introduction

Pulmonary alveolar macrophages (PAM) protect the lungs by phagocytizing foreign debris and bacteria.[1] This process involves ingestion as well as destruction of foreign matter. Phagocytosis usually is accompanied by a respiratory burst which increases cellular oxygen consumption leading to the release of highly reactive oxygen metabolites.[2] These agents have been implicated in the killing of bacteria by phagocytes, but they have also been shown to be toxic and have been linked to cancer, emphysema, arthritis, diabetes, and other diseases.[3] Toxic effects may be a result of 1) an abnormally low production of metabolites, resulting in damage to lung tissue by the respired bacteria and/or dusts; or 2) an abnormally high production resulting in direct damage to lung tissue by metabolites themselves.

The initial oxygen metabolite released is thought to be superoxide anion (SO) produced from the reduction of oxygen by NADPH oxidase.[2] Superoxide can readily dismutate to form hydrogen peroxide and subsequently, other antimicrobial agents.[2,3] Exposure of PAM to respirable dusts may lead to hyper- or hypo-secretion of superoxide resulting in either too much or too little of these antimicrobial agents. This may then lead to pneumoconiosis, silicosis, or other respiratory disease.

In this study an electro-optical technique was used to quantitatively measure the release of superoxide from *single* cells which had been obtained from animals exposed *in vivo* in inhalation chambers or *in vitro* to respirable quartz, or *in vitro* to kaolin dusts. NBT reduction to a diformazan precipitate by SO was measured from *single* PAM during adherence. The initial (maximum) rate of productions and total mass of diformazan produced were measured and compared among the different dusts.

Materials and Methods

PAM were obtained from male Long-Evans hooded rats (Charles River) weighing between 250 and 300 grams using the tracheal lavage method developed by Myrvik *et al.*[4] Briefly, the diaphragm was severed, the animal exsanguinated, and a 15 guage needle inserted through an incision in the trachea. Lavage fluid (145 mM NaCl, 5 mM KCl, 1.9 mM NaH_2PO_4, 9.35 mM Na_2HPO_4, and 5 mM glucose) at pH 7.4 and 4°C was injected into the lung through the needle and slowly withdrawn to obtain cells. A total of 80 ml of lavage fluid was collected by repeating this process approximately 12 times. PAM collected were centrifuged at 500 g for five minutes at 4C and resuspended in Hepes-buffered medium (140 mM NaCl, 5 mM KCl, 1.5 mM $CaCl_2$, 10 mM Na-Hepes [N-2-hydroxyethyl piperazine-N'-2-ethane sulfonic acid] and 5 mM glucose) at pH 7.4 and 4°C. Following a second wash, PAM were resuspended in approximately 6 ml of Hepes-buffered medium and placed in an ice-water bath.

Nitroblue tetrazolium (NBT) was added to the Hepes-buffered medium to obtain soluble NBT solutions at a concentration of 2.0 mg/ml. NBT, in the presence of a strong reducing agent such as superoxide, is reduced to an insoluble diformazan product which absorbs light at 550 nm. Three ml of NBT solution at 37°C was placed in a tissue culture dish (Falcon 3001) and an aliquot of 400 uL of the cell suspension ($2 - 5 \times 10^5$ cells), was added. A layer of paraffin oil (37°C) was placed on top of the aqueous layer to reduce evaporation.

TABLE I

The Mean (+/- SE) Total Diformazan Produced (max) and Initial Rate of Diformazan Production (R) for PAM Exposed *in vitro* to Either Respirable Quartz or Kaolin Dust

	Total Diformazan Production (fmoles)		Diformazan Production Rate (10-3 fmoles/sec)	
	Quartz	Kaolin	Quartz	Kaolin
CON*	15.3 +/- 1.6	11.7 +/- 1.0	24.5 +/- 2.3	10.5 +/- 0.8
LOW	9.5 +/- 1.5**	10.2 +/- 1.5	16.8 +/- 1.7**	10.5 +/- 1.4
HIGH	13.0 +/- 1.6	8.1 +/- 0.9	18.6 +/- 2.1**	10.6 +/- 1.4

* CON = control; LOW = 0.26 mg/ml; HIGH = 0.05 mg/ml.

** $p < 0.05$.

n = 18 cells in each case.

The culture dish was placed on a temperature-controlled (37°C) heating element located on the stage of an Olympus (model IMT) inverted light microscope and trans-illuminated at 550 nm. A microscopic field of at least six PAM was televised using a low light-level Cohu (model 4410) silicon-vidicon television camera and videorecorded for 40 minutes using a 3/4-inch Sony (model V05600) videocassette recorder. PAM were stimulated to release superoxide by adherence to the bottom of the culture dish.

Temporal changes in light intensity over single PAM were determined by play back of videorecorded images through an IPM (modeli 204A) video photometric analyzer. The analyzer generates two windows which act as phototransistors sensitive to changes in average light intensity in the window area. Each window was placed over a single PAM and the output video voltage from each window was digitized (12 bit) using a Keithley DAS (model 520) every ten seconds for 40 minutes, and stored on an IBM PCXT. This procedure was repeated to obtain measurements from at least six PAM in each videorecorded image.

Background light intensity was determined in regions of the image containing no cells. Following correction for any background variation, changes in optical density (OD) for each cell were calculated using the Beer-Lambert Law. The OD value was multiplied by the window area and the molar extinction coefficient (30,000 M^{-1} cm^{-1}) to determine the mass of diformazan produced.

Temporal changes in mass of diformazan produced, M, exhibited a time delay followed by an exponential-like increase to an asymptotic maximum value (max). Therefore, the data were fit to the following first-order equation:

$$M = max[1 - \exp(-(t - t_d)/T)]$$

where:

t = time

t_d = delay time measured between stimulation and detection of diformazan production

T = time constant

The total diformazan produced, max, was determined from an average of the last six values of M (1 min) and td was estimated by observing the point at which diformazan production increased significantly above baseline. T was determined by fitting the data to the log linearized form of this equation. The maximum (initial) rate of diformazan production, R, was calculated from the derivative of the equation at time t_d; that is, as max/T.

The effects of *in vitro* exposure to respirable quartz and kaolin on superoxide release were tested using concentrations of 0.025 or 0.05 mg/ml added to NBT solutions just prior to addition of PAM. PAM were added to dishes containing either the high or low dust concentrations as well as a control dish containing no dust.

The effects of *in vivo* exposure of PAM to respirable quartz (20 mg/m^3, 16 hr/day, 5 days/wk of MIN-U-SIL 10, 95% < 5 um) was tested by housing six animals each for two or four weeks in the West Virginia University (WVU) inhalation facilities. Six control (no quartz) animals were also kept in the inhalation chambers for two or four weeks. Following exposure, animals were removed from the inhalation chambers and housed in WVU animal-care facilities for 3, 10, or 31 days post-exposure, at which time animals were removed for analysis of superoxide production. At each analysis period PAM were obtained from two exposed and two control animals. This appraoach permitted analysis of the effects of exposure and post-exposure time.

Experiments were analyzed using ANOVA at the 95 percent confidence level. When significant differences were found, the Newman-Keuls test was used to determine the significant differences among means.

Results

In vitro exposure of PAM to the low dose of quartz (0.025 mg/ml) decreased max 38 percent compared to control while exposure of PAM to the high dose (0.05 mg/ml) did not significantly change max. The maximum rate of diformazan production, R, decreased 31 percent for the low dose and 24 percent for the high dose when compared to control (Table

TABLE II

The Mean (+/- SE) Total Diformazan Produced (max) and Initial Rate of Diformazan Production (R) for PAM Exposed *in vivo* to Respirable Quartz Dust

	Total Diformazan Production (fmoles)	Diformazan Production Rate (10-3 fmoles/sec)
CON (72)*	7.6 +/- 0.5	16.1 +/- 1.3
3 Days (23)	12.4 +/- 2.5**	19.3 +/- 2.6
10 Days (24)	11.0 +/- 0.9	19.6 +/- 2.5
31 Days (24)	7.7 +/- 0.9	23.1 +/- 2.9

* CON = control; 3, 10, 31 days post-exposure; n given in parentheses as number of cells.

** $p < 0.05$.

1). *In vitro* exposure to either the low or high dose of kaolin did not significantly change either max or R.

In vivo exposure of all animals (including animals exposed for both two and four weeks and analyzed at 3, 10, and 31 days) to quartz dust *increased* max 36 percent and R 29 percent compared to control animals. No significant differences were obtained between animals exposed for two or four weeks, therefore, data for *in vivo* experiments in Table II represent a combined average. Max was increased 69 percent for quartz-exposed animals analyzed three days post-exposure compared to control animals analyzed three days post-exposure, but the 10- and 31-day groups were not significantly increased above their respective controls. The 3-day group was also significantly increased (61%) compared to 31 days post-exposure.

Discussion

Superoxide release may play an important role in silicosis and other respiratory diseases. *In vitro* assays on large numbers of cells in culture using hemolysis of red blood cells or release of enzymes from PAM following dust exposure have been used to analyze cytotoxicity. In such systems, kaolin has been found to have an activity comparable to quartz on a mass basis.[5] However, *in vivo* quartz is highly fibrogenic resulting in silicosis while kaolin is relatively inert biologically.[5] Therefore, these cellular assays do not correlate with the *in vivo* effects of quartz and kaolin. It has been hypothesized that the difference between assay results and *in vivo* data may be due to dust interaction with pulmonary surfactant in the lung.[5] In this study, *in vitro* exposure of PAM to quartz resulted in decreased production of diformazan while *in vitro* exposure to kaolin did not significantly effect PAM compared to control. These results correlate with *in vivo* effects of quartz being toxic and kaolin being inert and helps support the usefulness of this superoxide assay in evaluating the effects of respirable dusts on cell function.

The low dose of quartz resulted in less diformazan production compared to the high dose in the *in vitro* experiments. The reason for this difference is at present unknown and further studies are needed to elucidate this discrepancy.

Interestingly, *in vivo* exposure to quartz resulted in increased production of diformazan rather than the decreased production observed *in vitro*. This difference may be due to a change in cellular function from the *in vivo* to the *in vitro* environment. However, the in vitro results also may be due to an initial (acute) response to quartz, since PAM were analyzed for 40 minutes immediately after contacting dusts. In contrast, the *in vivo* responses were considered more long-term since animals were exposed for two or four weeks followed by a post-exposure period before analyses were made. Thus, it may be possible that quartz causes an initial injury to PAM resulting in decreased production of superoxide followed by recruitment or activiation of PAM having increased production capabilities.

Further support is the significant increase in production of diformazan observed in PAM analyzed three days follwoing *in vivo* exposure compared to the control levels generated by PAM analyzed ten and 31 days post-exposure. Thus, after removal from dust exposure, PAM continue increased superoxide production initially but gradulally fall back to control values by ten to 31 days post-exposure.

Finally, the quartz-exposed PAM analyzed three days post-exposure exhibited a wider range than the control and 10- and 31-day post-exposure groups. Heterogeneity has been reported by this lab and others and may explain this variation.[6-8] However, the range exhibited here seems to indicate more than the usual biological variation. Specifically, perhaps due to quartz exposure two populations of PAM were present: 1) cells injured by initial or long-term dust contact, resulting in decreased superoxide production; and 2) recruited or activated PAM which exhibited increased superoxide production. In conclusion, studies to examine this further as well as the effects of *in vitro* and *in vivo* exposure to PAM to respirable coal dusts are currently in progress.

Acknowledgments

The authors wish to acknowledge the support of this research by the Department of Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142 and CDC-NIOSH grant number 1K01-0h00019-01.

References

1. **Miles, P.R., V. Castranova and P. Lee**: Reactive Forms of Oxygen and Chemiluminescence in Phagocytizing Rabbit Alveolar Macrophages. *Am. J. Physiol. 235(3):*C103-C108 (1978).

2. **Babior, B.M.:** The Respiratory Burst of Phagocytes. *J. Clin. Invest. 73*:599-601 (1984).

3. **Klebanoff, S.J.:** Oxygen Metabolism and the Toxic Properties of Phagocytes. *Ann. Int. Med. 93*:480-489 (1980).

4. **Myrvik, Q.N., E.S. Leake and B. Fariss:** Studies on Pulmonary Alveolar Macrophages from the Normal Rabbit: A Technique to Produce them in a High State of Purity. *J. Immunol. 86*:128-132 (1961).

5. **Wallace, Jr., W.E., V. Vallyathan, M.J. Keane and V. Robinson:** *In vitro* Biologic Toxicity of Native and Surface-modified Silica and Kaolin. *J. Toxicol. Environ. Health 16*:415-424 (1985).

6. **DiGregorio, K.A., E.V. Cilento and R.C. Lantz:** Superoxide Release from Single Pulmonary Alveolar Macrophages. *Fed. Proc. 45(3)*:309 (1986).

7. **Holian, A., J.H. Dauber, M.S. Diamond and R.P. Daniele:** Separation of Bronchoalveolar Cells from the Guinea Pig on Continuous Gradient of Percoll: Functional Properties of Fractionated Lung Macrophages. *J. Reticuloend. Soc. 33*:157-164 (1983).

8. **Zwilling, B.S., L.B. Campolito and N.A. Reiches:** Alveolar Macrophage Subpopulations Identified by Differential Centrifugation on a Discontinuous Albumin Density Gradient. *Am. Rev. Respir. Dis. 125*:448-452 (1982).

The Effect of Lecithin Surfactant and Phospholipase Enzyme Treatment on Some Cytotoxic Properties of Respirable Quartz and Kaolin Dusts

W.E. WALLACE,[A,B] M.J. KEANE,[A] C.A. HILL,[B] V. VALLYATHAN,[A] F. SAUS,[A] V. CASTRANOVA[A] and D. BATES[A]

[A]Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health; [B]West Virginia University

Two *in vitro* systems are being developed to model initial stages in the interaction of respired dusts with the acinar region of the lung. Incubation of quartz and kaolin with dipalmitoyl glycerophosphorylcholine, a major component of pulmonary surfactant, suppresses the prompt cytotoxicity of both dusts as measured by *in vitro* enzyme release from pulmonary macrophages or assay by erythrocyte hemolysis. Additional data is presented to quantitate the detoxification of quartz and kaolin by dipalmitoyl lecithin. Subsequent incubation of lecithin treated dusts with phospholipase enzymes results in partial to complete restoration of the assayed cytotoxic potentials, dependent on the lipase activity applied, the incubation time, and the mineral. Restored cytotoxic potential is due to removal of the prophylactic lecithin surface coating and/or due to residual lysolecithin which is produced by the partial enzymatic digestion of lecithin. Data is presented on the contribution of each mechanism to the restored toxicity. Again, this is dependent on the mineral used, the lipase activity applied, and digestion time. Additionally, a system is under development to challenge pulmonary macrophages in culture with native and surfactant treated dusts. A preliminary test of the dipalmitoyl lecithin — quartz — rabbit pulmonary macrophage system is presented to illustrate the method.

Introduction

Respirable quartz dust exposure is known to cause fibrotic lung disease; respirable clay dust exposure is less likely to do so as indicated by epidemiologic data on occupational exposures and by animal model studies.[1-7] The hypothesis that damage to pulmonary macrophages in the acinar region of the lung by respired dusts is an early event in the disease process requires consideration because kaolin clay and quartz dusts are comparably cytotoxic to pulmonary macrophages *in vitro*.[8,9]

Simulating dust interaction in the lung, quartz and kaolin dusts have been assayed for their cytotoxicity both in their native state and after incubation with an emulsion of dipalmitoyl glycerophosphorylcholine (DPL), called dipalmitoyl lecithin.[8,9] Lecithins are a major component of pulmonary surfactants which stabilize the surface properties of the hypophase coating of pulmonary alveoli.[10] This surfactant adsorbs to kaolin and to quartz from emulsion in physiologic saline. Adsorption isotherms for these dusts have been measured.[11,12] The cytotoxicity of both dusts is suppressed by such DPL adsorption at 37°C[8,9,12] as assayed *in vitro* by macrophage release of cytosolic and lysosomal enzymes or erythrocyte hemolysis. Lecithins are also major components of cellular membranes. Interactions of quartz with the bilayer lipid membrane have been proposed as a mechanism of cell lysis; and effects of dust surface crystallinity and coatings on this lysis have been studied.[13-15] Our simulation of pulmonary surfactant interaction with respired dusts replaced a false positive toxicity assay for kaolin with a false negative assay for quartz.

Removal of serum protein from phagocytized silica has been observed.[16] As a research hypothesis, we presume that the prophylactic surfactant coating adsorbed on a respired particle following contact with pulmonary surfactant is subject to enzymatic digestion following phagocytosis by pulmonary macrophages. We have been exploring this hypothesis by *in vitro* studies using dipalmitoyl lecithin in physiologic saline for alveolar hypophase surfactant and phospholipase enzymes A2 and C for two lysosomal enzymatic digestion processes. We used pulmonary macrophage cytosolic or lysosomal enzyme release or erythrocyte hemolysis assays to monitor the cytotoxicity of the quartz and kaolin dusts treated in different experimental protocols.[8,9,12]

In this report we provide quantitative data showing suppression of hemolytic potential of quartz and kaolin dusts as a function of DPL dose. We provide more data on the effects of phospholipase enzymes A2 and C on treated dusts. We discuss the bases for enzymatic restoration of cytotoxicity of treated dusts by providing initial data on the time course of enzymatic digestion and retoxification.

Although this simulation provides for detailed analyses of some proposed steps in the interaction of a mineral particle with pulmonary surfactant and macrophages, the adequacy of the selected parameters to model the complex *in vivo* situation must be questioned. We are developing a complementary method which may model that reality more closely, but which thereby poses more problems of interpretation. In this system, pulmonary macrophages are challenged *in vitro* with surfactant-treated or native dusts. The attempt is then made to maintain their viability in culture for a sufficient period of time to detect macrophage attrition due to the surfactant treated dusts at levels above those for negative controls, i.e., macrophages which have not been challenged with dust. We discuss the method using preliminary data for rabbit pulmonary macrophages challenged with DPL treated and untreated quartz.

Materials and Methods

Alpha quartz used is at least 98.5 percent pure as determined by x-ray energy spectrometric analysis. It has a specific surface area of 3.97 m^2/g as determined by nitrogen adsorption. Kaolin used is at least 96 percent pure, contains no crystalline silica, and has a specific surface area of 13.25 m^2/g.

emulsion and the mixtures incubated for one hour at 37°C in a shaking water bath. Dusts were then centrifuged for ten minutes at 990 g and resuspended in calcium and magnesium free Dulbecco's phosphate-buffered saline (PBS).

Commercially supplied Phospholipase A2 was obtained from: porcine pancreas (Sigma) or from *Crotalus adamanteus* venom (Cooper Biomedical), as indicated. Phospholipase C from *Clostridium perfringens* was obtained from Sigma. Enzymes were dissolved in phosphate-buffered saline (PBS) containing 2.0 m*M* calcium chloride, to provide specific activities for designed digestion steps. Amounts of native or DPL-treated dusts were resuspended in PBS with 2.0 m*M* $CaCl_2$, desired amounts of the enzyme solution added, and the samples incubated for specified times at 37°C in a shaking water bath. Following incubation, the dusts were resuspended in PBS containing 2.0 m*M* EDTA to stop the

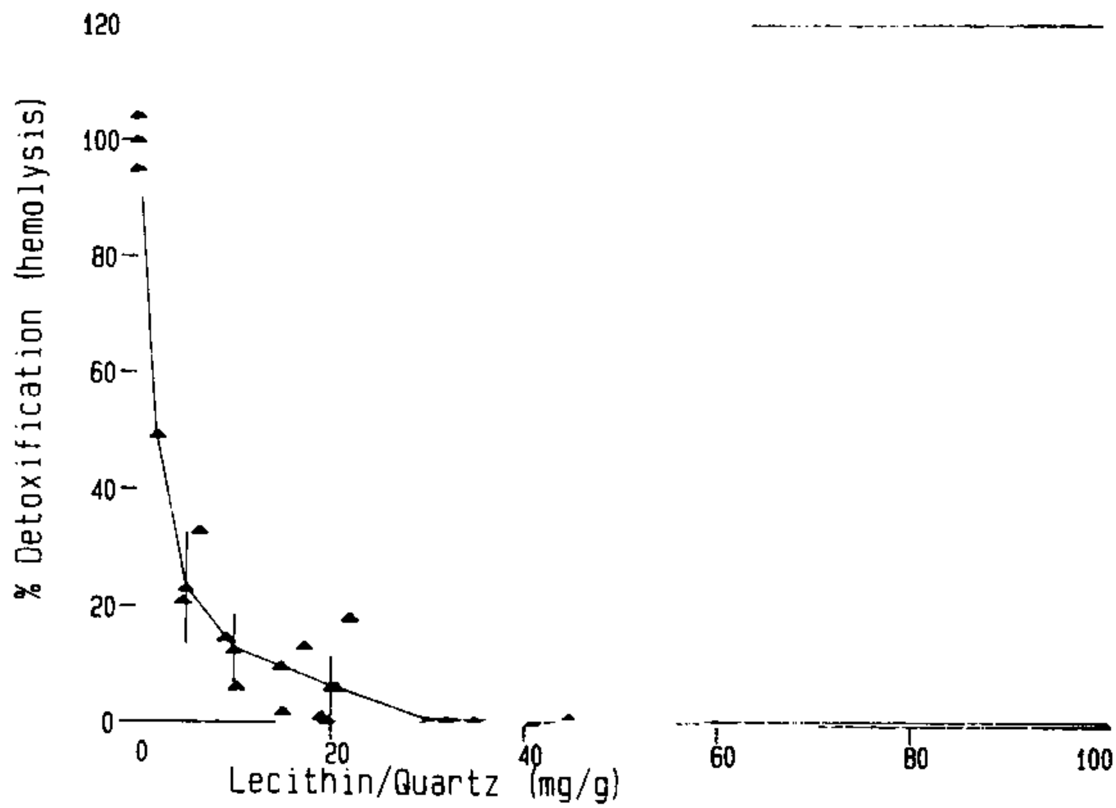


FIGURE 1. Hemolytic potential of quartz versus dipalmitoyl lecithin treatment. Erythrocyte hemolysis values are given as percentages of the value for untreated quartz. Open triangles connected by line segments show the diminution as a function of DPL added to the system. Line segments are connected between average values; and the bars show the ranges measured. The solid triangle scatter graph shows values from additional measurements where abscissa values are the amounts of lecithin actually adsorbed as measured by elution from the particles.

Erythrocytes were obtained for hemolysis assay from a sheep maintained on a fixed diet. Pulmonary macrophages were obtained by lavage of rats or rabbits, as indicated, using Hank's Balanced Salt Solution (HBSS). Cells were washed twice and resuspended in HBSS.

Commercially obtained L-alpha-dipalmitoyl glycerophosphorylcholine (DPL) (Calbiochem) was ultrasonically dispersed in 0.165 *M* sodium chloride to produce emulsions of the desired DPL concentration. Dry quartz or kaolin dust at the ratio of mass of dust to mass and concentration of DPL desired were dispersed into DPL

enzymatic digestion, and then resuspended in PBS alone. For conceptual purposes, we have expressed phospholipase activity in terms of "activity equivalents" which equal 0.0817 units of phospholipase. Using the equilibrium amounts of DPL adsorbed on kaolin from the adsorption isotherm study,[9] one activity equivalent would ideally remove that amount of DPL within one hour at 37°C.

Hemolytic potential of variously treated dusts was assayed by the erythrocyte hemolysis assay of Harington *et al.*[17] Suspensions of erythrocytes (2% by volume) and 1.0 mg dust per ml were incubated in PBS at 37°C for one hour.

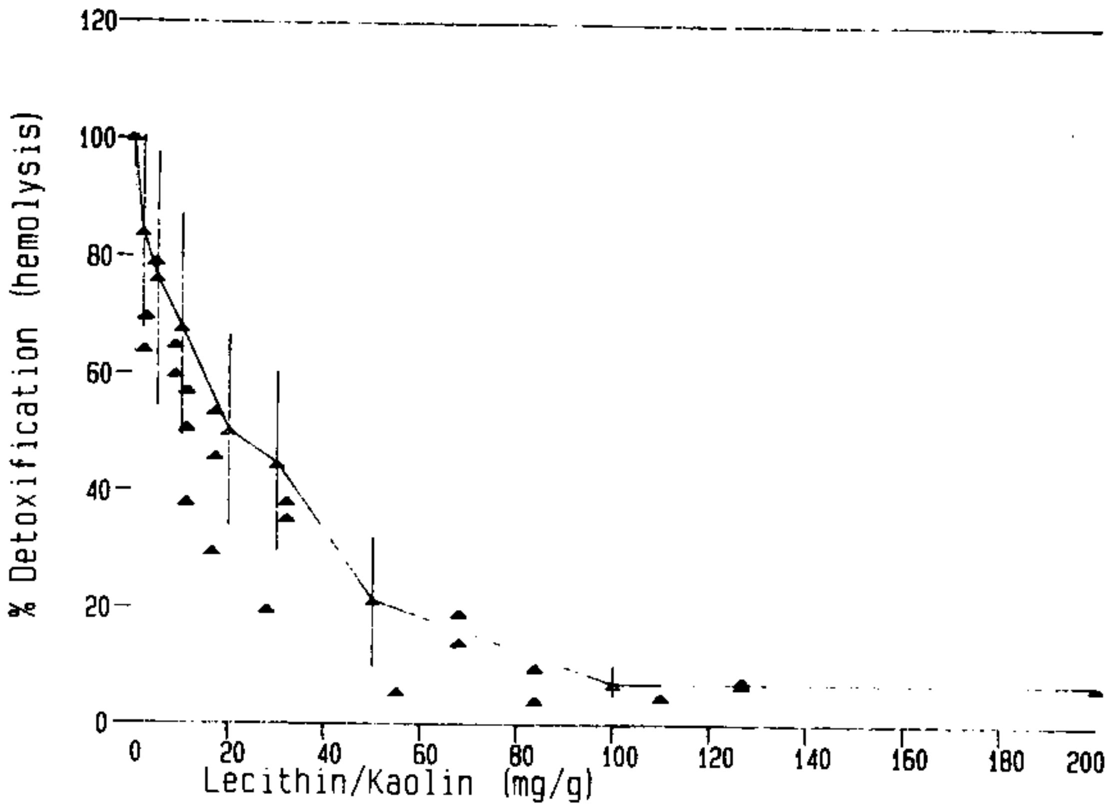


FIGURE 2. Hemolytic potential of kaolin versus dipalmitoyl lecithin treatment. Open triangles connected by line segments have as their abscissa values the amounts of lecithin added. The solid triangle scatter graph shows the potentials versus DPL eluted from the particles.

After centrifugation at 500 g, the optical density of the supernatant was spectrophotometrically determined at 540 nm wavelength to measure the hemoglobin concentration.

The release of lactate dehydrogenase from pulmonary macrophages was determined by the method of Reeves and Fimignari;[18] beta-N-acetyl glucosaminidase by the method of Lockart and Kennedy;[19] and beta-glucuronidase by the method of Sellinger *et al.*[20]

DPL or lysolecithin (L-alpha-lecithin, beta palmitoyl) adsorbed to dusts was measured by freeze drying the dust, eluting phospholipids from the dust with methanol/chloroform (2/1 by volume), separating by thin layer chromatography, and phosphate quantitating by the method of Bartlett.[21]

Suppression of the hemolytic cytotoxicity of quartz and of kaolin by DPL was measured after incubation of each dust in DPL emulsion at concentrations calculated to provide coatings from 2 to 200 mg lecithin per gram dust, assuming total adsorption of the lecithin in emulsion. Some experiments were run with parallel samples which were then analyzed for amount of DPL adsorbed as measured by the phosphate assay.

Combined effect of DPL and lysolecithin (which is itself a lytic agent) adsorbed to quartz and to kaolin on their hemolytic potentials was similarly measured, except that the dusts were incubated with DPL emulsion containing an equal molar concentration of dissolved lysolecithin.

Time course experiments for the effect of PLA2, from porcine pancreas, on DPL-treated dust hemolytic potential was determined for dusts incubated at 7.5 mg dust per ml of DPL emulsion. The emulsion concentration was 10 mg DPL per ml saline. This is sufficient to provide saturation as determined by the adsorption isotherm measurements. Enzyme activity at levels from 10 to 300 activity equivalents was applied for periods of 2 to 216 hours. Following the incubation with enzymes and washing procedures, the hemolytic strengths of the dusts were measured and the amounts of residually adsorbed DPL and lysolecithin measured.

For tests in a simulated long-term system, pulmonary macrophages were obtained from rabbits and maintained in tissue culture for different periods of time. Cells were washed twice with HBSS and resuspended in Medium 199 containing 10% fetal calf serum and penicillin/streptomycin 100 ug/ml. Approximately 4 x 10^6 cells were placed in individual culture wells, permitted to stabilize for 24 hours at 37 C, 5% CO_2, and 90% relative humidity, and then challenged with native or DPL-treated quartz at levels of 400 ug dust per 4 x 10^6 cells. Cells which were not challenged with dust were also maintained to determine the background rate of macrophage damage. Cytotoxicity was assayed by LDH and beta-N-acetyl glucosaminidase release.

Results

Hemolytic potentials of DPL-treated quartz are shown with respect to untreated quartz in Figure 1. The highest abscissa value is around 50 mg lecithin per gram quartz, in concert with adsorption isotherm values.[12] The hemolytic strength of quartz is reduced by adsorbed lecithin, reaching

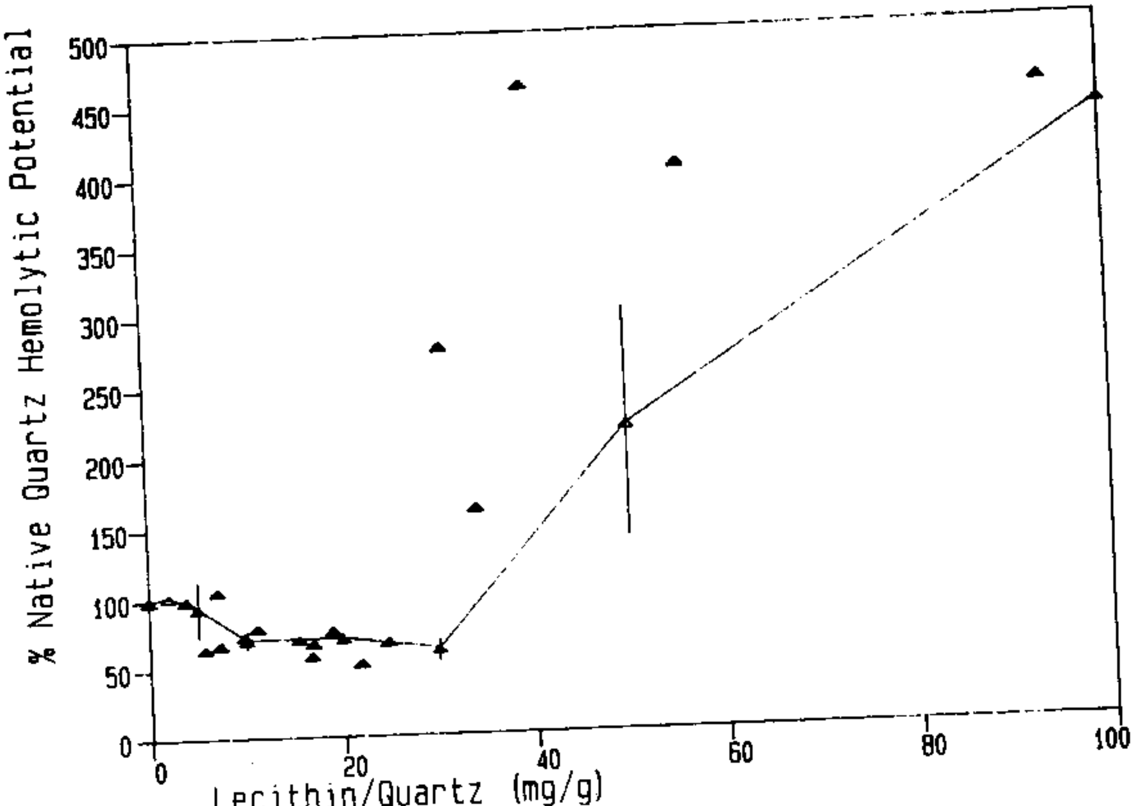


FIGURE 3. Hemolytic potential of quartz versus treatment by lysolecithin and dipalmitoyl lecithin added in equal molar amounts. Ordinate values are expressed as percentages of the value for untreated quartz. Open triangles with line segments have DPL added as their abscissa values. Solid triangle abscissa values are amounts of DPL eluted.

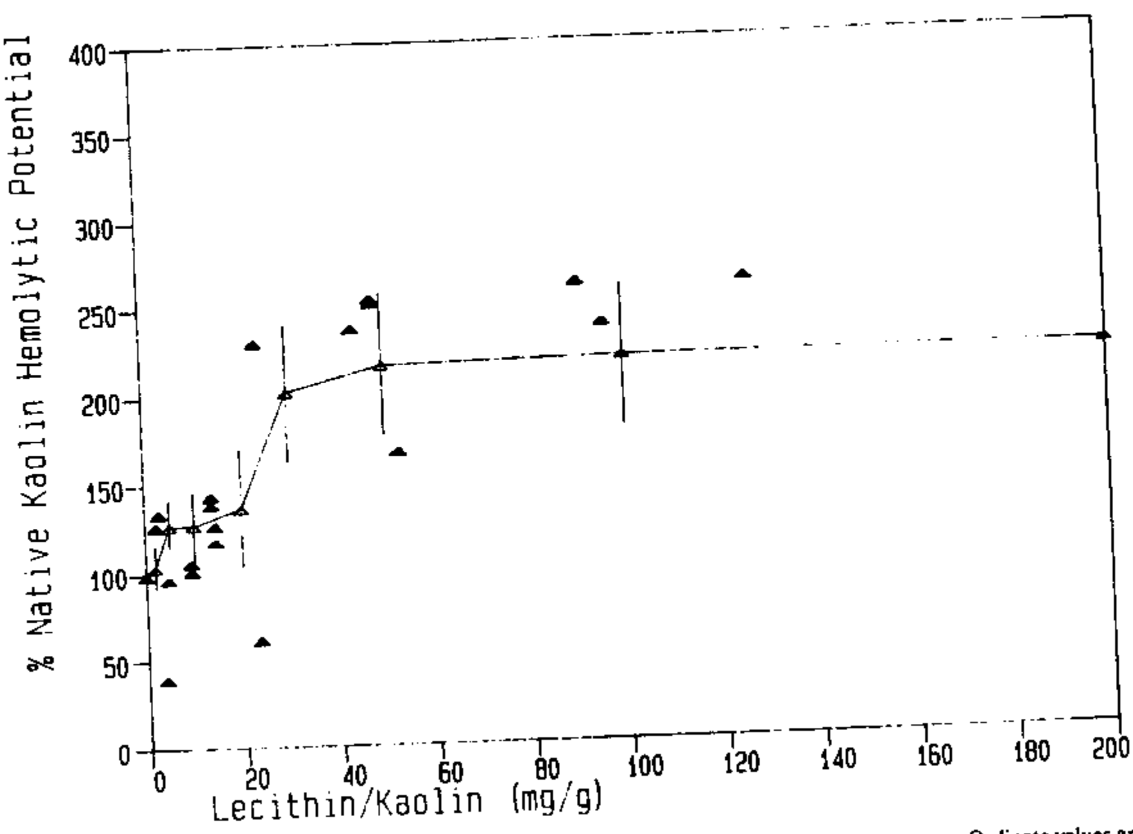


FIGURE 4. Hemolytic potential of kaolin treated with lysolecithin and dipalmitoyl Lecithin in equal molar amounts. Ordinate values are expressed as percentages of the value for untreated kaolin.

background levels between 20 and 30 mg/g adsorbed lecithin. Figure 2 similarly quantitates the hemolytic potential of kaolin. Maximum specific lecithin adsorption is about 130 mg/g; and values approach background between 80 and 100 mg/g. When comparing values between the quartz and kaolin dusts used, one should note the ratios of their specific surface areas, the kaolin having about three times the value of the quartz for surface area per gram.

Hemolytic potentials of quartz and kaolin treated with DPL and lysolecithin in combination were also measured. We have previously reported that the retoxification of dusts treated first with DPL and then with phospholipase enzymes can be due to a combination of functionally available particle surface activity and to adsorbed lysolecithin produced by the enzymatic digestion of lecithin.[8,12] Figure 3 shows the hemolytic potential for quartz treated with equimolar concentration of lecithin and lysolecithin together in physiologic saline. Figure 4 presents comparable data on the hemolytic potentials of lecithin and lysolecithin-treated kaolin. In both Figures 3 and 4, the maximum values of hemolytic potential reached are limited by the measurement conditions; that is, all the erythrocytes have been lysed. The hemolytic potentials above the untreated dust levels are presumed to be due to lysolecithin adsorbed to the dust or adsorbed to lecithin on the dust. In general the amount of lysolecithin eluted was less than the lecithin eluted, the lysolecithin being substantially more soluble in saline than the lecithin. Figure 5 presents the 37°C adsorption isotherm for lysolecithin on quartz and kaolin in physiologic saline; the corresponding lecithin isotherms have been presented elsewhere for these dusts.(12)

The hemolytic potential of DPL-treated quartz after phospholipase A2 digestion *in vitro* is shown in Figure 6. Hemolysis is shown as a function of enzyme activity and digestion time. With the exception of one point at the highest enzyme activity, the potential rises with digestion time to approach untreated quartz levels between 44 and 72 hours. Parallel samples were eluted with organic solvent, the eluted material separated by thin layer chromatography, and measured by phosphate analysis. Figure 7 shows the amount of DPL remaining on the quartz following digestion. This is shown as a function of applied enzyme activity and time of enzymatic digestion. There is a rapid decrease in the amount of adsorbed DPL by the end of two hours, the shortest digestion time used. At 72 hours the levels detected are within the background for this method of separation and quantitation. Figure 8 shows similar measurements of the lysolecithin which was separated from DPL by the thin layer chromatography of eluted material. Much lower amounts of lysolecithin are seen, which decrease to background levels around 44 hours. The hemolysis and DPL retention data are overlaid on the maps of hemolytic potential of DPL and lysolecithin treated quartz in Figure 9. Values typically fall in the region indicating contributions to the cytotoxicity from both mechanisms, with the dust surface contribution increasing with digestion time.

The hemolytic potential of DPL-treated kaolin after digestion with phospholipase A2 is shown in Figure 10. Unlike the quartz results, the kaolin potential generally is sig-

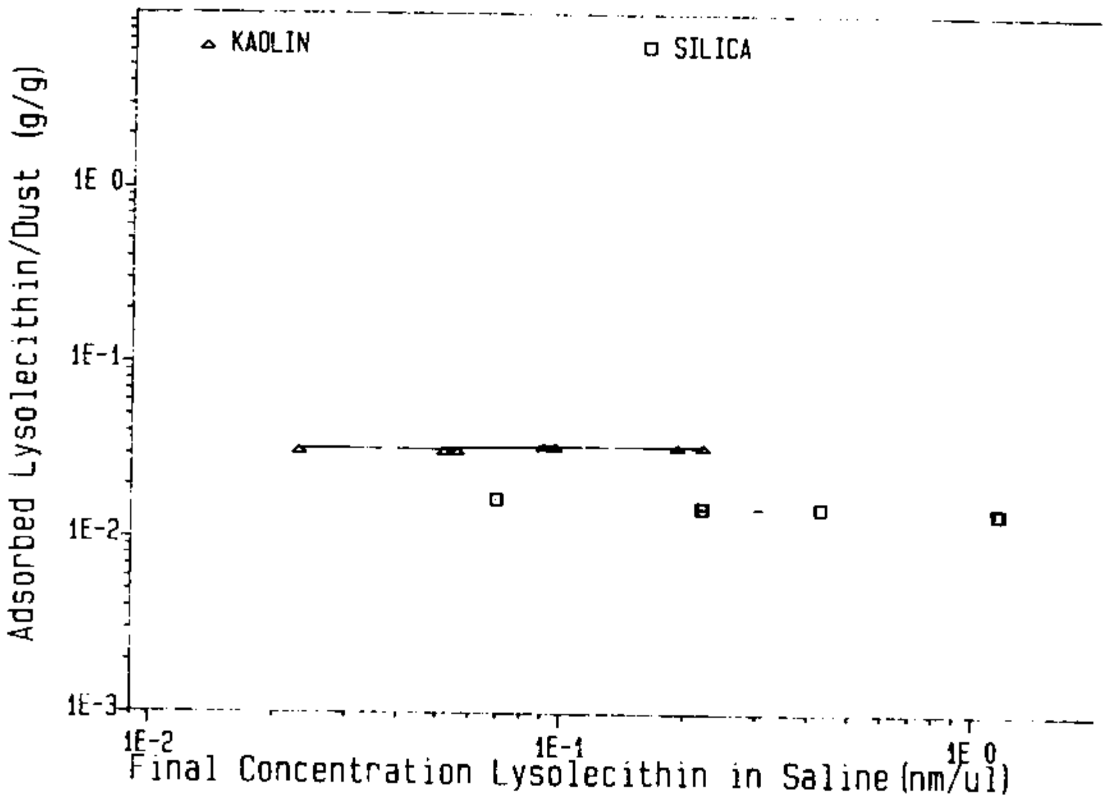


FIGURE 5. Adsorption isotherm for lysolecithin adsorption on kaolin and on quartz from saline at 37C. Ordinate values are mass specific adsorption as measured from initial and final concentration of lysolecithin in solution.

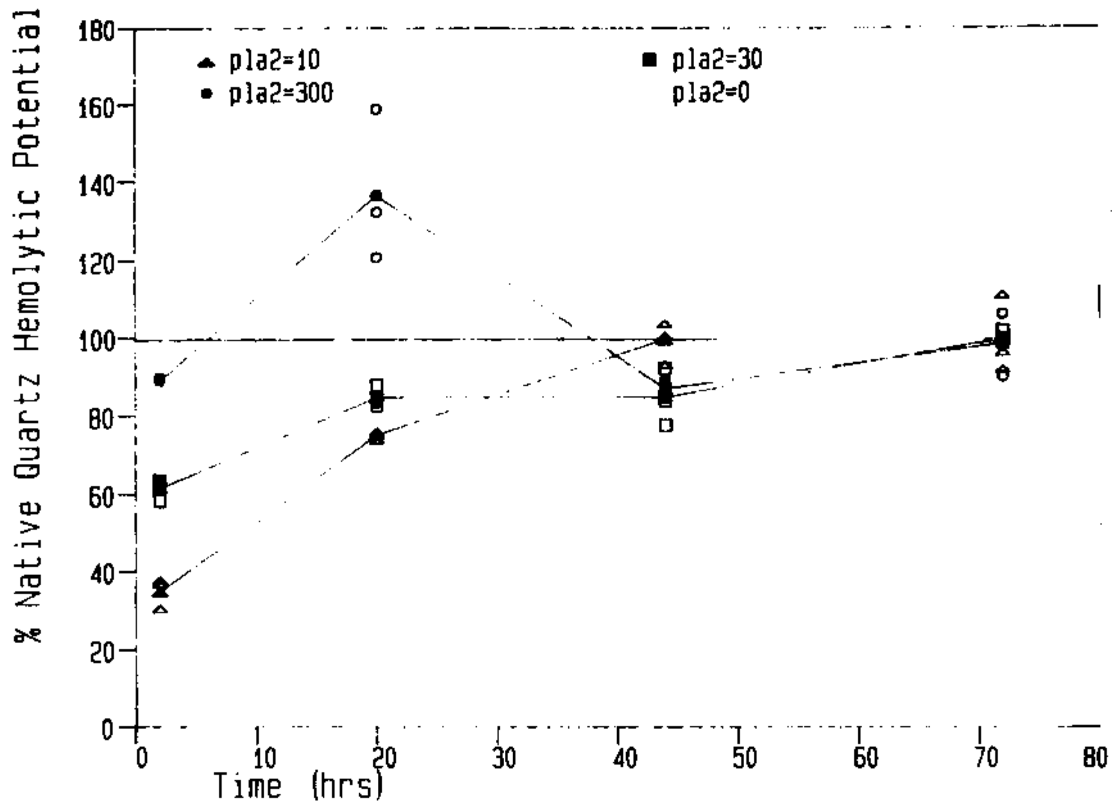


FIGURE 6. Erythrocyte hemolysis by dipalmitoyl lecithin and phospholipase A2 treated quartz versus time of incubation with the lipase. Data is shown for different levels of applied enzyme activity, expressed in terms of "activity equivalents" defined in the text.

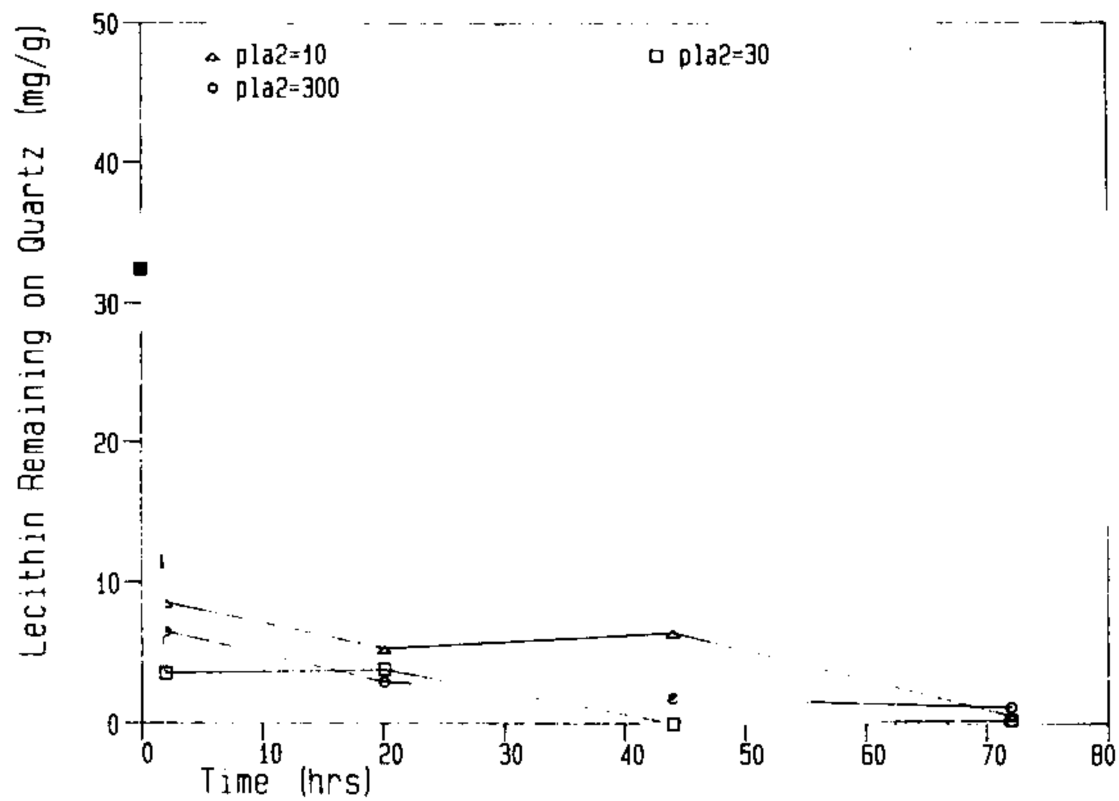


FIGURE 7. Dipalmitoyl lecithin retained on quartz following treatment with phospholipase A2 versus time of incubation with the lipase. Data is shown for different levels of applied enzyme activity expressed as "activity equivalents."

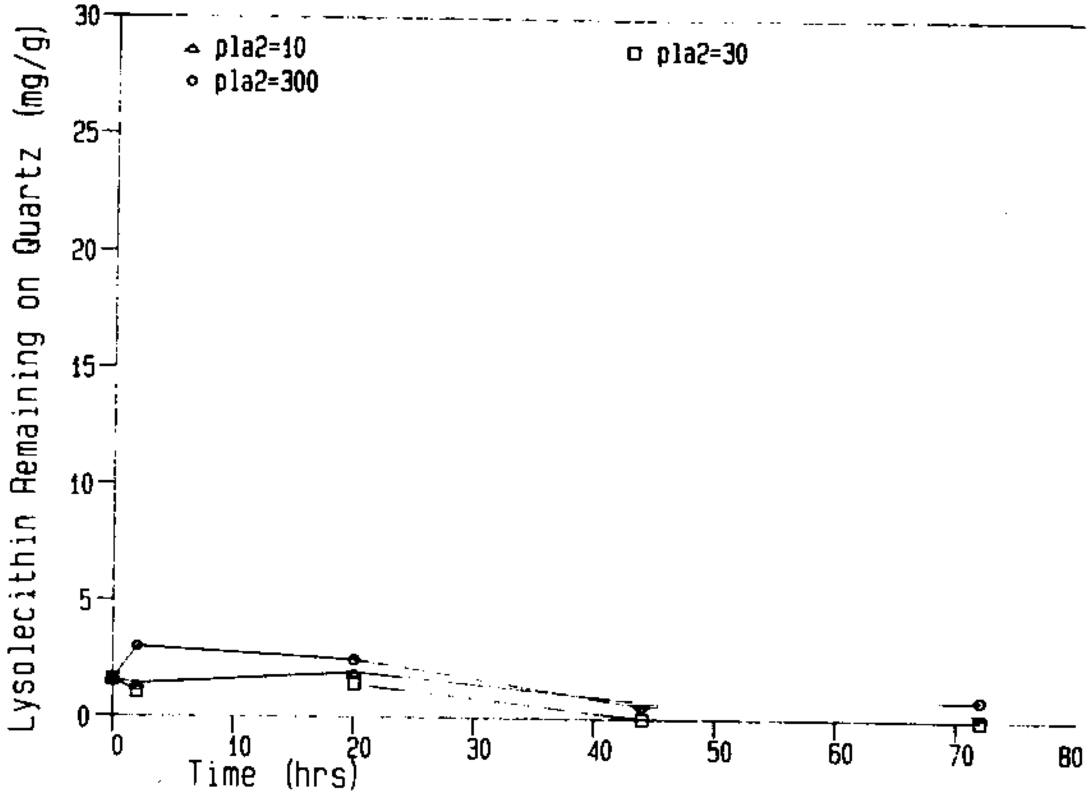


FIGURE 8. Lysolecithin retained on quartz following treatment with phospholipase A2 versus time of incubation with the lipase. Data is shown for different levels of applied enzyme activity expressed as "activity equivalents."

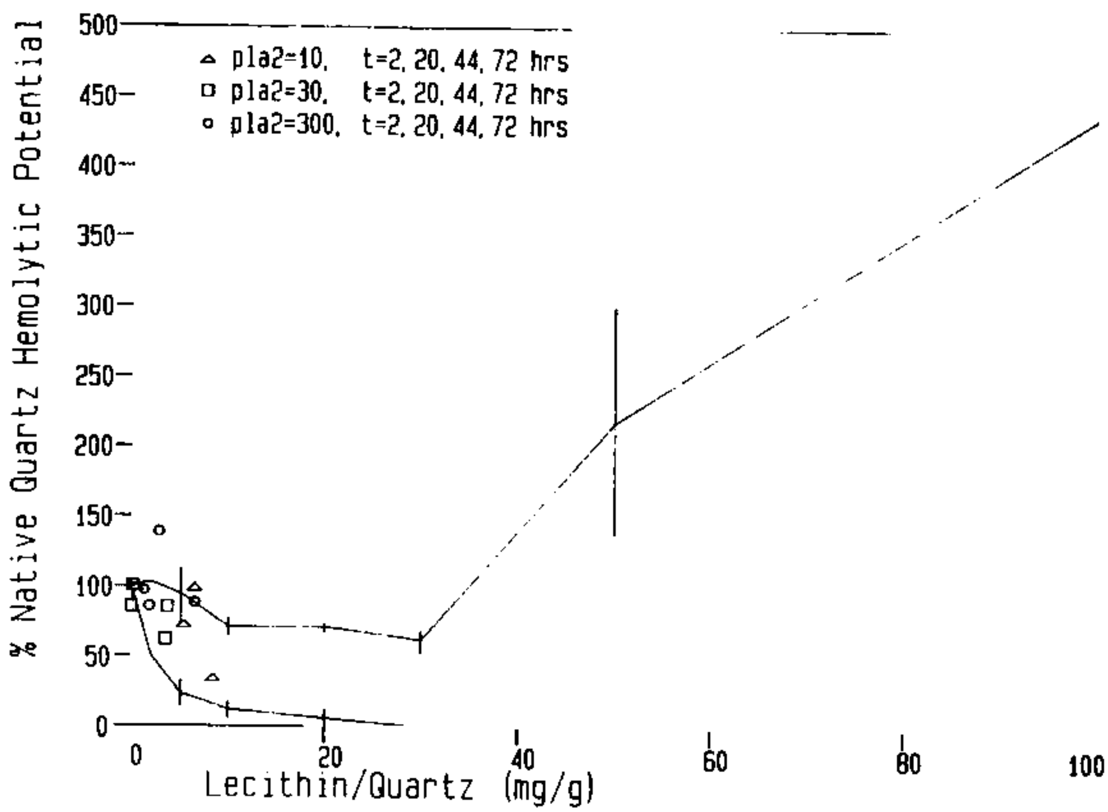


FIGURE 9. Erythrocyte hemolytic potential and retained dipalmitoyl lecithin for lecithin and phospholipase A2 treated quartz. Data from Figures 6 and 7 are presented on the map of quartz hemolytic potential versus lecithin and lysolecithin treatment from Figures 1 and 3.

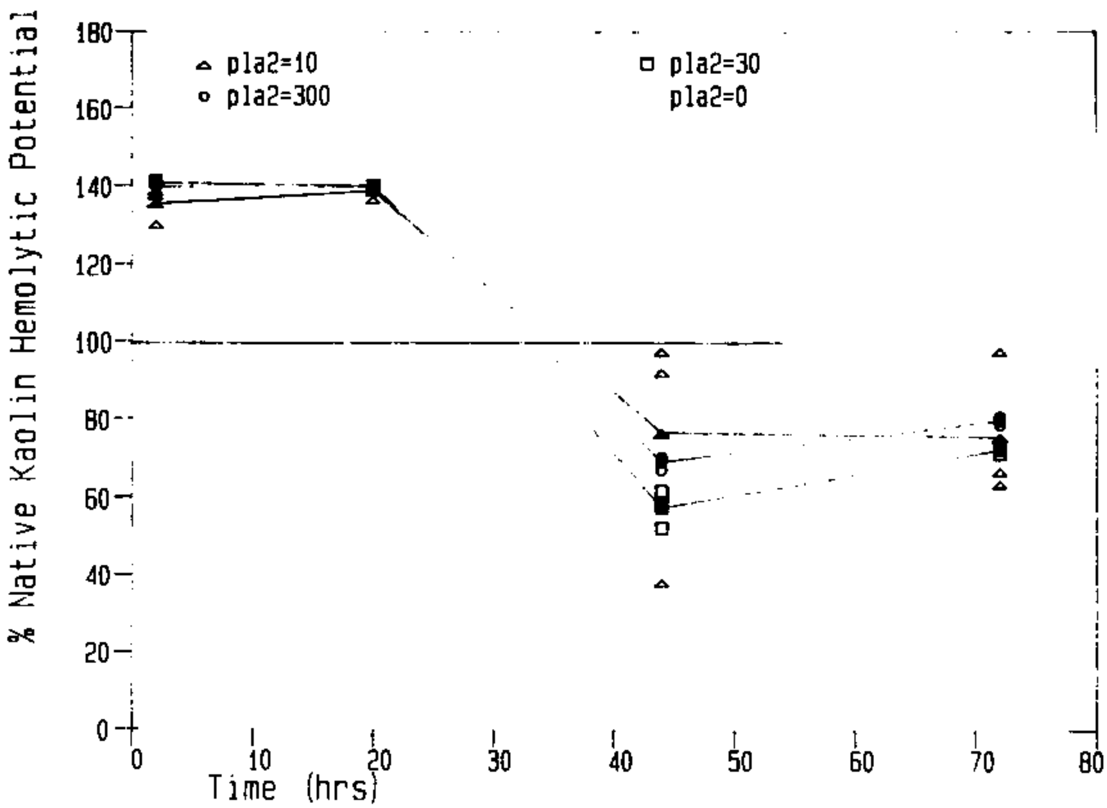


FIGURE 10. Erythrocyte hemolysis by dipalmitoyl lecithin and phospholipase A2 treated kaolin versus time of incubation with the lipase. Data is shown for different levels of applied enzyme activity, expresseed in terms of "activity equivalents" defined in the text.

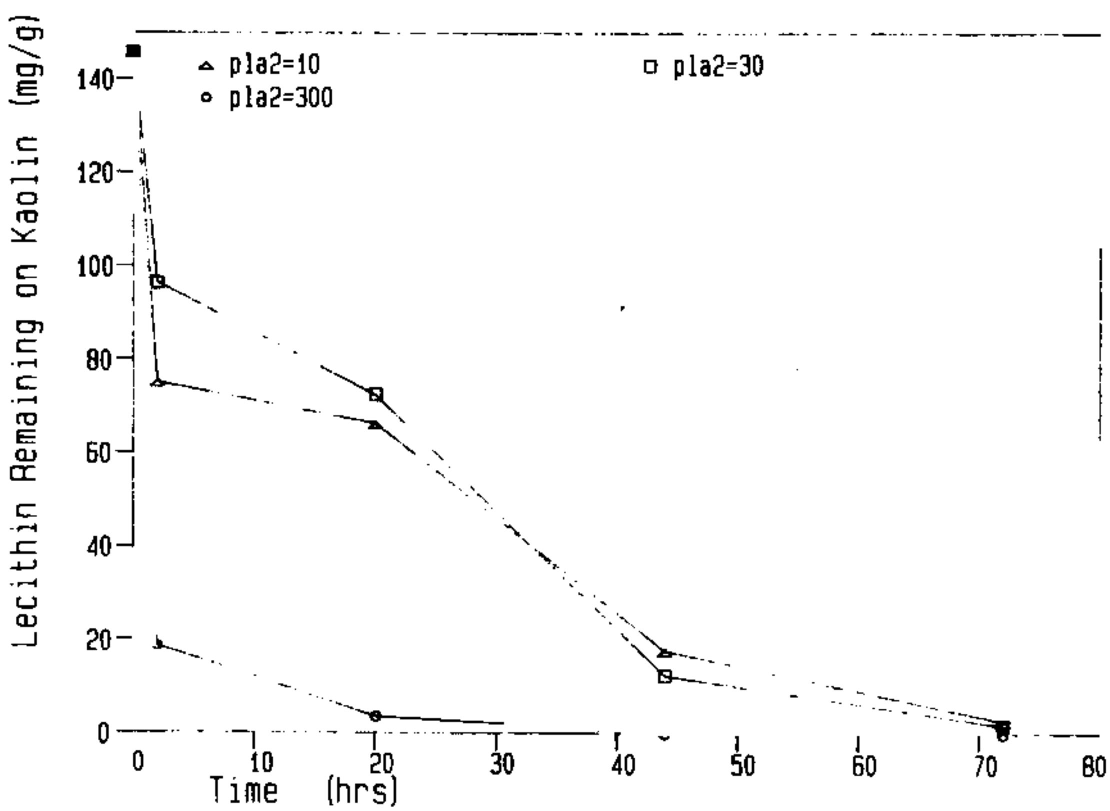


FIGURE 11. Dipalmitoyl lecithin retained on kaolin following treatment with phospholipase A2 versus time of incubation with the lipase. Data is shown for different levels of applied enzyme activity expressed as "activity equivalents."

nificantly greater than that of untreated kaolin. Somewhere between 20 and 44 hours these potentials drop to values below that of native kaolin. At 72 hours, the potential is rising back toward the native dust levels. Figure 11 shows the amounts of DPL remaining on the kaolin as a function of enzyme activity and of time of digestion. This is measured by elution, chromatography, and phosphate analysis as for the quartz. Relatively high levels of DPL are retained on the kaolin to 44 hours as shown, in contrast to the quartz behavior. Figure 12 shows the corresponding lysolecithin retention data. Again, in contrast to quartz, high levels are retained in general out to the 44-hour data point. Figure 13 displays the hemolytic potential and retained DPL data for kaolin on the map of potential versus adsorbed DPL and lysolecithin for kaolin. Lower enzymatic activities and digestion times are seen to result in potentials which can be attributed to enzymatically produced lysolecithin. Longer digestion times result in potentials which might be attributed at least in part to surface effects. That the high hemolytic potentials above those of native kaolin can be attributed to adherent lysolecithin has been demonstrated by additional mixed enzyme studies to those previously reported,[12] comparing the effects of one hour digestions with 300 activity equivalents of phospholipase A2, from Crotalus adamanteus venom, and mixtures of it with equal activities of phospholipase C. The double enzyme treatment reduces the hemolytic potentials and adsorbed DPL levels from system saturation values for kaolin to values consistent with fractional exposed surface toxicity with little lysolecithin contribution. The quartz potential after double lipase treatment is partially reduced from levels manifesting some combined effects of surface and lysolecithin to values consistent with activity due principally to exposed surface activity.

Development is underway in our lab on a system to challenge pulmonary macrophages *in vitro* with dusts treated with pulmonary surfactant, radiolabeled components of pulmonary surfactant, or proposed prophylactic agents. The attempt will then be to maintain the cells in culture long enough to measure any restoration of cytotoxic effects above those displayed by negative controls, that is, by cells not dosed with dusts. Figures 14 and 15 demonstrate, in part, the method and its major difficulty — maintaining viable control cells. The figures show the percentage of lactate dehydrogenase and beta-N-acetyl glucosaminidase which is released from the cells as a function of time since dust exposure. The top line is the release from cells challenged with untreated quartz. Cell damage or death is presumed to be indicated if both enzymes are released. The partial suppression of quartz hemolytic potential for the first 3 days is attributed to prophylactic effects of various biochemicals in the culture nutrient media. The bottom line shows the attrition of cells treated identically except that they have not been challenged with quartz. The data for cells challenged with DPL-treated quartz are initially at the levels for the negative controls. This may be due principally to the prophylactic effects of DPL on phagocytized dusts; we have observed that the DPL treatment also slows uptake of quartz by the cells. The high attrition rates in this experiment do not permit un-

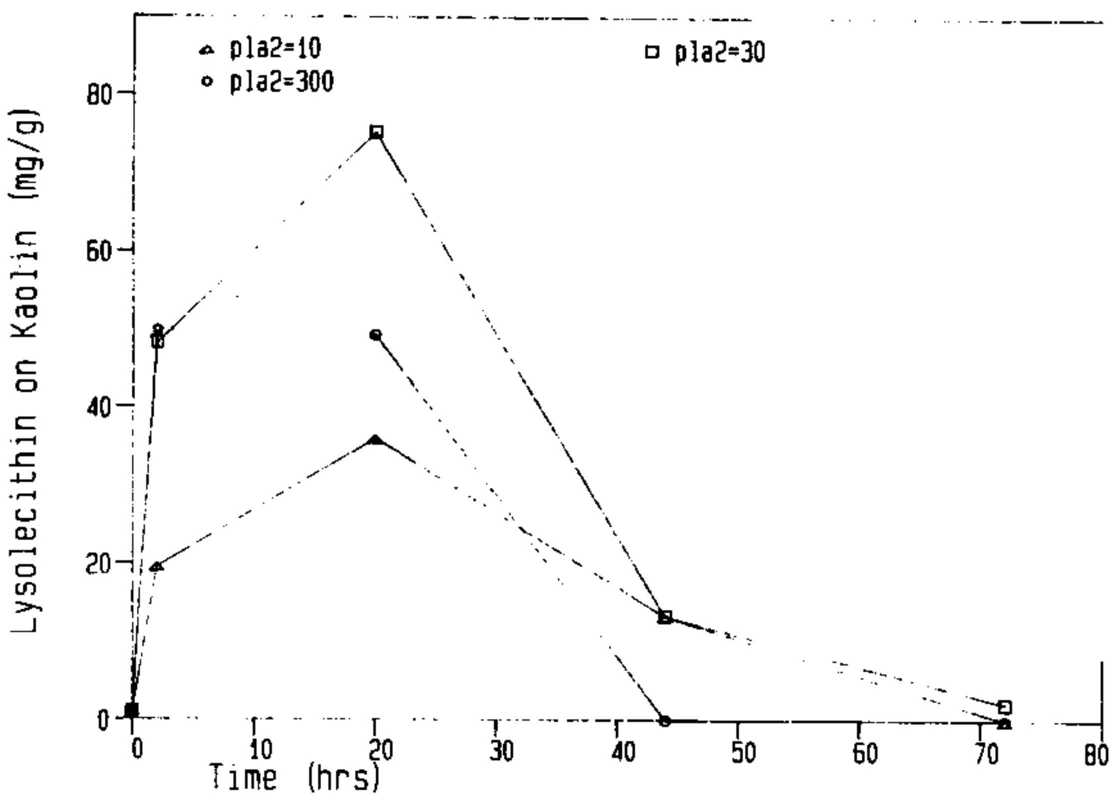


FIGURE 12. Lysolecithin retained on kaolin following treatment with phospholipase A2 versus time of incubation with the lipase. Data is shown for different levels of applied enzyme activity expressed as "activity equivalents."

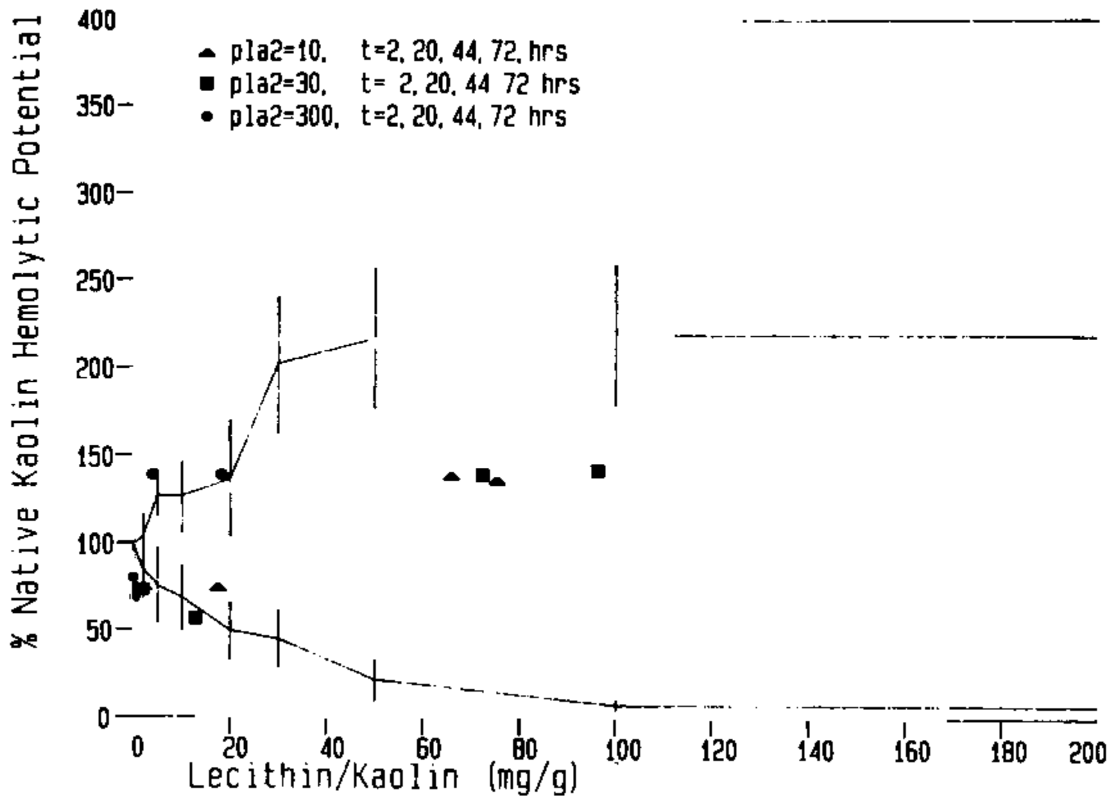


FIGURE 13. Erythrocyte hemolytic potential and retained dipalmitoyl lecithin for lecithin and phospholipase A2 treated kaolin. Data from Figures 10 and 11 are presented on the map of kaolin hemolytic potential versus lecithin and lysolecithin treatment from Figures 2 and 4.

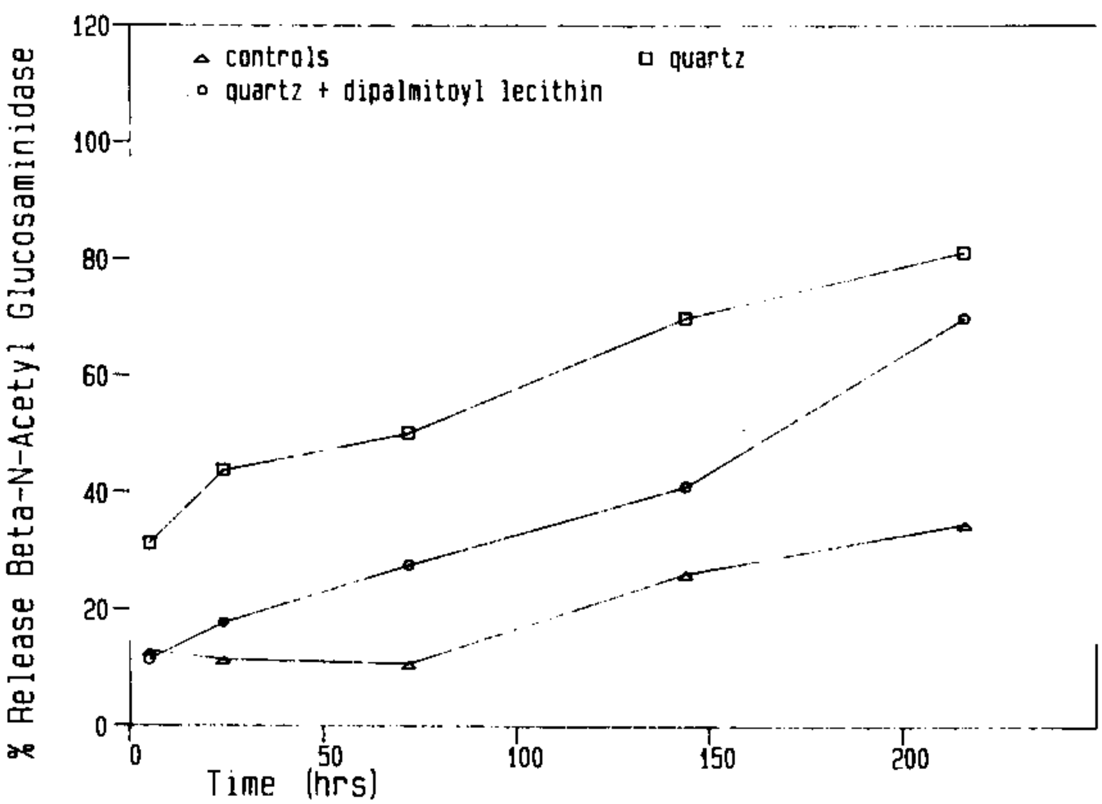


FIGURE 14. Release of lysosomal enzyme versus time following quartz dust challenge for rabbit pulmonary macrophages in culture. Data is shown for negative controls, i.e., macrophages not challenged with quartz; for positive controls, i.e., for challenge with untreated quartz; and for challenge with lecithin treated quartz.

equivocal interpretation of the longer time values. We currently are testing modifications of the system to improve the viability of the controls.

Discussion

Adsorption of pulmonary surfactant by a respired particle may suppress prompt cytotoxic damage to alveolar macrophages and epithelial cells in the lung. Dipalmitoyl lecithin, a major component of pulmonary surfactant, suppresses the *in vitro* hemolytic potential of both quartz and kaolin, and also suppreses their potential to cause major damage to pulmonary macrophages *in vitro* as measured by cytosolic and lysosomal enzyme release. Comparison of estimated amounts of surfactant in a healthy lung and DPL adsorption data indicate *in vivo* pulmonary surfactant levels are adequate to provide a defense against the prompt lytic effects of silicate or aluminosilicate dusts at typical occupational exposure levels.[11] Instillation of quartz and kaolin in animal lungs does not produce prompt permanent damage;[22] acute but transient inflammatory cellular response *in vivo* which is observed for both dusts[22] indicate some non-mineral specific effect of respired dusts. The effect or lack of effect of surfactant on dust induced release of antigenic factors by pulmonary macrophages has not been investigated.

Phospholipase A2 enzymatic digestion in vitro of DPL-coated quartz or kaolin can remove all or most of the adsorbed DPL over the period of a few days for the enzymatic activities used. There appear to be mineral specific differences in the rates of digestion and in the degree of adherence of lipase-produced lysolecithin to the DPL-dust complex at intermediate stages of digestion. Mineral specific rate differences might result from differing free energies of adsorption or from conformational differences in adsorbed DPL which provide different levels of steric hinderance to the lipase action. Phospholipase activity is affected by the physical state of its phospholipid substrate.[23]

Adsorption of lecithin to aluminosilicate dust surface may involve electrostatic and hydrogen bonding. Alumina surface is a better catalyst than silica for hydrolysis of lecithin in organic media,[24] indicating more effective interaction of alumina surface hydroxyls with the ester bonds to the glycerol moiety of lecithin. Lecithin is a zwitterion with the choline head group cationic and the phosphate group anionic. Silanol groups on the surface of quartz in aqueous media partially dissociate to produce negatively charged surface sites, with an isoelectric point around pH 1.5;[25] that is, part of the adsorption of DPL to quartz may be attributed to electrostatic interaction between the choline group at the tip of the DPL and the dissociated silanol groups on the quartz surface.[26] Kaolin has a structure of alternate layers of silica tetrahedra and alumina octahedra. Hydroxyl groups on the surface of alumina have an isolectric point of about pH 9.4,[25] the surface of alumina bearing a net positive charge. Adsorption of DPL to kaolin should involve in part electrostatic interaction between the alumina octahedra positively charged surface sites and the negatively charged phosphate

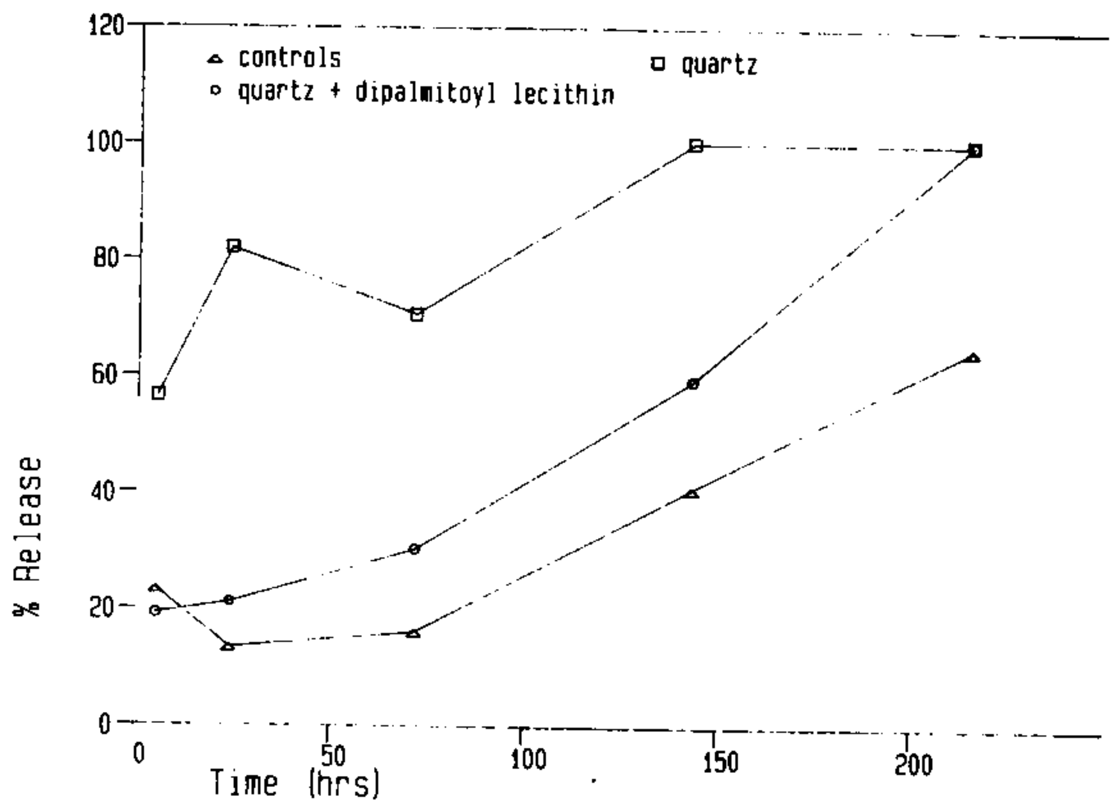


FIGURE 15. Release of cytosolic enzyme versus time following quartz dust challenge for rabbit pulmonary macrophages in culture. Data is shown for macrophages not challenged with quartz, challenged with untreated quartz, or challenged with lecithin treated quartz.

moiety of DPL. The phosphate-glycerol bond is hydrolyzed under the enzymatic action of Phospholipase C and the adjacent ester linkage of glycerol to a fatty acid acyl group is hydrolyzed by the action of Phospholipase A2. An adsorbed phospholipid conformation in which phosphate groups are directed toward alumina surface groups of aluminosilicate dust might hinder enzymatic hydrolysis of the target ester linkages.

Lysolecithin is adsorbed to a more limited extent than DPL by both quartz and kaolin in single compound adsorption isotherm measurements. Adsorption of lysolecithin at intermediate stages of the phospholipase A2 digestion of DPL on dusts may be due in part to lysolecithin association with adsorbed DPL. Lysolecithin on quartz and kaolin decreases as DPL is digested away. We have not determined yet the degree of mineral adsorption of hydrolysis produced fatty acids or their contribution to cytotoxicity suppression. In the phagolysosome of a pulmonary macrophage, a number of enzymes would act upon a surfactant coated particle. Our limited experiments with phospholipase A2 and C in combination indicate that the mixed activity can significantly diminish the lysolecithin contribution to the hemolytic potential compared to the single enzyme treatment result. To provide a useful basis for analysis of physiologic effects, these *in vitro* digestion studies must be extended to use lavaged surfactants, full lysosomal enzyme applied at acidic conditions representative of the phagolysosomal interior, and representative relative amounts of surfactant, enzyme activity, and dusts. We are currently measuring the DPL-digesting activity of full lysosomal enzyme, which we obtain by density gradient centrifugation methods[28] from rat liver homogenate.

Complementary to these *in vitro* digestion experiments, the long-term macrophage challenge system is an attempt to obtain time course information on the suppression of dust cytotoxic properties after challenge and phagocytosis of surfactant treated dusts. If macrophages can be maintained viable in culture long enough to unequivocally distinguish dust induced effects, then the possible correlation of induced effects with the fate of the initial coating of labeled surfactant will be tested. Comparing the time course for retoxification of kaolin with that of quartz should indicate whether or not these interactions are significant in distinguishing the pathogenicity of respirable quartz dust.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

References

1. **Morgan, W.K.C. and A. Seaton:** *Occupational Lung Diseases*, Saunders, Philadelphia (1975).

2. **Hamilton, A. and H.L. Hardy:** *Industrial Toxicology*, 3rd ed., p. 448. Publishing Sciences Group, Acton, MA (1974).

3. **Parker, W.R.:** *Occupational Lung Disorders*, p. 338. Butterworths, London (1974).

4. **Hunter, D.:** *The Diseases of Occupations*, 5th ed., p. 992. English Universities Press, London (1975).

5. **Sheers, G.:** Prevalence of Pneumoconiosis in Cornish Kaolin Workers. *Br. J. Ind. Med. 21*:218 (1964).

6. **Warraki, S. and Y. Herant:** Pneumoconiosis in China-Clay Workers. *Br. J. Ind. Med. 20*:226 (1963).

7. **Lynch, K. and F.A. McIver:** Pneumoconiosis from Exposure to Kaolin Dust: Kaolinosis. *Am. J. Path. 30*:1117 (1954).

8. **Wallace, W.E., M.J. Keane, V. Vallyathan et al:** Pulmonary Surfactant Interaction with Respirable Dust. *Proceedings -- Generic Mineral Technology Center for Respirable Dust, Coal Mine Dust Conference*, pp. 180-187. S. Peng, Ed. (1984). Report No. BP86 169380/AS. National Technical Information Service, Springfield, VA (1986).

9. **Wallace, W.E., V. Vallyathan, M.J. Keane and V. Robinson:** *In vitro* Biologic Toxicity of Native and Surface-modified Silica and Kaolin. *J. Toxicol. Environ. Health 16*:415 (1985).

10. **Clements, J.A., J. Nellenboger and H.J. Trahan:** Pulmonary Surfactant and Evolution of the Lungs. *Science 169*:603 (1970).

11. **Wallace, W.E., Jr., L.C. Headley and K.C. Weber:** Dipalmitoyl Lecithin Surfactant Adsorption by Kaolin Dust *in vitro*. *J. Colloid Interface Sci. 51*:535 (1975).

12. **Wallace, W.E., M.J. Keane, V. Vallyathan et al:** Supression of Inhaled Particle Cytotoxicity by Pulmonary Surfactant and Re-Toxification by Phospholipase--Distinguishing Properties of Quartz and Kaolin. *Proceedings -- British Occupational Health Society, Inhaled Particles Conference, 1985.* (To be published).

13. **Nolan, R.P., A.M. Langer, J.S. Harington et al:** Quartz Hemolysis as Related to its Surface Functionalities. *Environ. Res. 26*:503 (1981).

14. **Marks, J.:** The Neutralization of Silica Toxicity *in vitro*. *Br. J. Ind. Med. 14*:81 (1957).

15. **Stalder, K. and W. Stober:** Haemolytic Activity of Suspensions of Different Silica Modifications and Inert Dusts. *Nature 207*:874 (1965).

16. **Allison, A.C.:** *Respiratory Defense Mechanisms, Part II*, pp. 1075-1102. J.D. Brain, D.F. Proctor and L.M. Reid. Eds. Marcel Dekker, Inc., New York (1977).

17. **Harington, J., K. Miller and G. Macnab:** Hemolysis by Asbestos. *Environ. Res. 4*:95-117 (1971).

18. **Reeves, W.J. and G.M. Fimignari:** An Improved Procedure for the Preparation of Crystalline Lactic Dehydrogenase from Hog Heart. *J. Biol. Chem. 238*:3853 (1963).

19. **Lockard, V. and R. Kennedy:** Alterations in Rabbit Alveolar Macrophages as a Result of Traumatic Shock. *Lab. Invest. 35*:501-506 (1976).

20. **Sellinger, O.Z., H. Beaufay, P. Jacques et al:** Intracellular Distribution and Properties of beta-N-Acetylglucosaminidase and beta-N-

galactosidase in Rat Liver. *Biochem. J. 74*:450-456 (1960).

21. **Bartlettt, G.R.**: Phosphorus Assay in Column Chromatography. *J. Biolog. Chem. 234*:466 (1959).

22. **Vallyathan, V., D. Schwegler, M. Reasor et al**: Comparative *in vitro*. Cytotoxicity and Relative Pathogenicity of Mineral Dusts. *Proceedings – British Occupational Health Society, Inhaled Particles Conference, 1985* (to be published).

23. **Matsuzawa, Y., and K.Y. Hostetler**: Properties of Phospholipase C Isolated from Rat Liver Lysosomes. *J. Biolog. Chem. 255*:646 (1980).

24. **Renkonen, O.**: Breakdown of Lecithin on Aluminum Oxide Columns. *J. Lipid Res. 3*:181 (1962).

25. **Ginn, M.E.**: Adsorption of Cationic Surfactants on Mineral Substrates. *Cationic Surfactants*, Chap. 10, p. 347. E. Jungerman, Ed. Marcel Dekker, Inc., New York (1977).

26. **Langer, A.M.**: Crystal Faces and Cleavage Planes in Quartz as Templates in Biological Processes. *Q. Rev. Biophysics 11*:543 (1978).

HEALTH EFFECTS – INHALATION STUDIES

Effect of Silica Inhalation on Pulmonary Alveolar Macrophages (PAM) and Microsomal Cytochrome P450 Activities

W. PAILES,[A] J. RABOVSKY,[A] D. JUDY,[A] J. TUCKER,[A] V. CASTRANOVA[A,B] and R.C. LANTZ[C]

[A]Division of Respiratory Disease Studies, NIOSH, Morgantown, West Virginia 26505; [B]Department of Physiology, West Virginia University; [C]Department of Anatomy, West Virginia University

Rats were exposed to either filtered air (controls) or filtered air containing 20 mg/m^3 α quartz (Min-U-Sil 10, 95% of particles < 5 um), 16 hours per day, five days per week, for four weeks. Within five days following termination of the exposure, various functional or morphological parameters were examined by determining number of lavaged PAM, mean PAM volume, PAM viability, PAM purity, PAM oxygen metabolism (both resting and zymosan-stimulated), PAM surface properties and whole lung microsomal EPhase and ECase activities (constitutive and inducible). Mean cell volume of PAM was significanrly increased in quartz versus control animals. Scanning electron microscopic examination of PAM also indicated significant alteration in surface morphology, i.e., less spreading of alveolar macrophages when attached to a surface was noted after exposure to α quartz. In addition, non-significant decreases in PAM number and constitutive ECase were noted after silica exposure. All other parameters were unaffected by exposure. These results indicate that although α quartz may cause some focal alteration in a limited number of PAM and in microsomal P450 activities, the percentage of cells and the amount of enzyme involved immediately following a four week exposure was not sufficiently large to significantly affect the average cellular function of the entire population of lavaged PAM or whole lung P450 dependent enzyme activities.

Introduction

Pulmonary alveolar macrophages (PAM) are free lung cells located on the surface of the small airways and the alveoli.(1) These cells play an important role in phagocytosis, thus, cleansing the lung of airborne bacteria and particles.(2) Upon contact with foreign particles, alveolar macrophages release superoxide anion (O_2^-) which may be involved in the detoxification of these foreign substances.(3-6) The release of superoxide anion, as well as other reactive species, can be monitored by measurement of chemiluminescence.(7) Exposure to silica may result in hypersecretion of reactive species or loss of membrane integrity and thus release of lysosomal enzymes which may lead to damage of lung tissue.(8-10) In addition, particle-induced activation of alveolar macrophages can result in secretion of fibrogenic factors.(11,12) Therefore, characterization of the responses of alveolar macrophages to silica exposure could be essential to an understanding of the development of silicosis.

Phagocytosis of inhaled particulates by alveolar macrophages may also affect pulmonary defense mechanisms associated with nonphagocytic cells. Such a defense mechanism would be the active metabolic detoxication system associated with the microsomal cytochrome P450 pathway in alveolar type II and bronchiolar Clara cells.(13) The cytochrome P450 pathway is responsible for the metabolism of foreign substances (xenobiotics) to less toxic materials.(14) In the lung, as in other tissues, this pathway is sensitive to environmental contaminants. Such sensitivity may be expressed as an induction of P450-dependent enzyme activity(15-18) and is often specific for the inducing agent. For example, phenobarbital induces activities associated with constitutive activities, whereas ß-naphthoflavone (BNF) induces activities that metabolize xenobiotics.(19)

Phagocyte-derived factors or mediators have been shown to influence cytochrome P450-dependent activity. For example, activation of liver macrophages by particulates resulted in the release of factor(s) that decreased cytochrome P450 activity in hepatocytes.(20) Similarly, when mice and rats were injected with a supernatant liguid from endotoxin-treated peritoneal macrophages, the hepatic cytochrome P450 content decreased.(21) Hence, exposure of the lung to substances which alter macrophage function may affect the ability of the lung to detoxify foreign organic material. For example, silica-induced changes in macrophage function may result in the reduced capacity of the lung to detoxify organic substances associated with diesel fumes which may be found in the coal mine environment.

As discussed above, exposure to various toxicants can adversely affect the phagocytic and secretory activity of alveolar macrophages as well as subsequent detoxication of organic compounds through the cytochrome P450 pathway. Thus, an understanding of functional alterations in alveolar macrophages and in microsomal P450 activity following toxicant inhalation is important to understanding the development of pneumoconiosis and the susceptibility to pulmonary disease. In the study described herein, functional alterations in alveolar macrophages and in the microsomal P450 enzyme activities, ethoxyphenaxazone (EPh'ase) and ethoxycoumarin deethylase (EC'ase), were tested following exposure of male Sprague-Dawley rats to a toxic substance (α quartz) known to cause fibrosis.

Methods

Exposure System

Rats were exposed to silica in the West Virginia University inhalation facility. The facility consists of two Hazelton HIC-1000 chambers. Both chambers received air (10 l/min) which had been filtered, cooled, dehumidified, and reheated and humidified to 70°F, 45 percent relative humidity. Animals were selected at random and placed in either the control chamber, which received only the filtered air, or the exposure chamber, which received silica in addition to filtered air. Silica (Min-U-Sil 10, 95% of particles < 5 um) was aerosolized using a TSI 9310 fluidized bed aerosol generator and animals were exposed to 20 mg/m^3 of silica 16 hours per day, five days per week for four weeks. Within five days following the termination of the exposure functional and morphological parameters were examined.

Isolation of Macrophages and Functional Studies

Alveolar macrophages were obtained by pulmonary lavage.[22] Briefly, male Sprague-Dawley rats, either filtered air control or silica-exposed, were anesthetized with sodium pentobarbital and exsanguinated by cutting the renal artery. The trachea was cannulated and the lungs lavaged 12 times with a total of 80 ml of ice-cold, Ca^{2+} and Mg^{2+}-free phosphate-buffered medium (145 mM NaCl, 5 mM KCl, 1.9 mM NaH_2PO_4, 9.35 mM Na_2HPO_4, and 5.5 mM glucose; pH = 7.4). Cells were separated from lavage fluid by centrifugation at 500 g for five minutes at 2°C. Then the cell pellet was washed twice by alternate centrifugation and resuspension in HEPES-buffered medium (140 mM NaCl, 5 mM KCl, 10 mM Na HEPES, 1 mM $CaCl_2$, and 5.5 mM glucose; pH = 7.4).

Cell count, mean cell volume, and purity of alveolar macrophages obtained by lavage were determined with an electronic cell counter (Coulter Counter Model ZB) equipped with a cell sizing attachment (Channelyzer II) (Coulter Electronics, Inc., Hialeah, FL). The percent of alveolar macrophages in the samples was calculated as the number of cells with a cellular volume identifiable as that of an alveolar macrophage divided by the total number of cells in the sample.

Membrane integrity of alveolar macrophages was determined by trypan-blue exclusion.[23] Alveolar macrophages (1.2–1.6 x 10^6 cells) were suspended in HEPES-buffered medium containing 0.4 percent trypan blue. After four minutes, the cells were observed under a light microscope and the fraction of cells excluding blue dye determined.

Superoxide anion release was determined by measuring superoxide-dependent reduction of cytochrome C.[24] Alveolar macrophages (8 x 10^6 cells) were preincubated in HEPES-buffered solution for 15 minutes at 37°C. At zero time, cells were suspended in HEPES-buffered medium (final 5 ml) containing 0.12 mM cytochrome C. Then a zero-time sample was taken, centrifuged at 6000 g for one minute at 2°C, and the optical density of the supernatant measured at 550 nm with a spectrophotometer. Twenty minutes later a second sample was taken and optical density measured. Superoxide release was proportional to the difference in optical density measurements over this time period. Resting superoxide release was cytochrome C reduction in the absence of particles while zymosan-stimulated superoxide release was cytochrome C reduction following the addition of zymosan (6 mg/ml) to the cell suspension at zero time, i.e., just prior to taking the first sample.

Chemiluminescence (CL) was measured as counts per minute in the tritium channel of a liquid scintillation counter operated in the out-of coincidence mode.[7] Alveolar macrophages (4 x 10^6 cells) were suspended in 5 ml of HEPES-buffered medium and preincubated at 37°C for 15 minutes. After preincubation, CL measurements were made at five-minute intervals. CL was expressed as the total number of counts over a 30 minute time period. Resting CL, measured in the absence of particles, was enhanced with luminol (10^{-6} M) Zymosan-stimulated CL was measured without luminol after the addition of zymosan (6 mg/ml) at zero time.

Scanning Electron Microscope

Monolayers of lavaged alveolar macrophages were prepared using 15 mm plastic tissue culture cover slips (Lux Scientific) placed in the flat bottom wells (1.7 x 1.6 cm) of Linbro Multi-well Tissue Culture plates. One milliliter of cell suspension containing approximately 1 x 10^6 cells was pipetted into each of six wells for each exposure group. The cells were incubated at 37°C in 5 percent CO_2 for two hours to allow adherence and spreading of the cells onto the cover slips and then rinsed two times with phosphate buffer to remove non-adherent cells.

The macrophage monolayers were fixed in 2 percent glutaraldehyde-phosphate-buffered fixative (pH 7.2 +/- 0.1), followed by 2 percent tannic acid for 1/2 hour and then postfixed with 2 percent osmium tetroxide (OsO_3). The cells were dehydrated through a graded series, 10 to 100 percent ethanol with 10 percent gradations and then transferred through graded concentrations of amyl acetate-ethanol solutions to 100 percent amyl acetate for critical point drying. A Denton DCP-1 critical point drying apparatus using liquid CO_2 was used for drying the cell monolayers. After drying, the cover slips with adhering cells were glued to pure carbon planchets and mounted on aluminum SEM studs and coated with gold/palladium (200A) or carbon. A Polaron E5100 series II sputter coater or a Polaron E6100 vacuum evaporator was used for coating the samples.

Scanning electron microscopic (SEM) examination of the macrophage monolayer was performed using an ETEC Autoscan SEM operating at 20KV and using secondary imaging (SEI).

Measurement of Cytochrome P450 Enzymes

Four treatment regimens were used for each enzyme analysis. They were 1) Filtered-air (FA)-controls, corn-oil(CO)-injected, 2) FA, BNF-injected, 3) silica-exposed, CO-injected, and 4) silica-exposed, BNF-injected. BNF in CO was administered i.p., one time, at 80 mg/kg rat. Control animals received an equivalent amount of CO. Forty-eight hours after injection, the animals were sacrificed by phenobarbital injection. The excised lungs were perfused with physiological saline, and microsomes were prepared from the lung homogenate by differential centrifugation.[25]

The two cytochrome P450-dependent monooxygenase activities used in this study were ethyoxyphenoxazone deethylase (EPh'ase), also referred to as ethoxyresorufin

TABLE I

Properties of Alveolar Macrophages Lavaged from Rats after a Four-week Exposure to Silica*

	Cell Count (AM/rat)	Cell Volume (um3)	Purity (% AM)
Control	7.05 (+/- 0.83) x 10^6	1521 +/- 4	72 +/- 9
Silica	6.14 (+/- 0.37) x 10^6	1746 +/- 22**	68 +/- 13

* Values are means +/- SEM of three experiments.

** Significantly different from control ($p < 0.05$).

deethylase (ERase), and ethoxycoumarin deethylase (EC'ase). EPh'ase was assayed in a direct fluorometric procedure that measures the formation of the highly fluorescent product, resorufin.[26] EC'ase was measured by the procedure of Greenlee and Poland[27] in which the fluorescent product, hydroxycoumarin, was separated from the reaction contents by an extraction step. The cofactor NADPH required in the EPh'ase and EC'ase assays, was supplied by a generating system consisting of $NADP^+$, MgC_{12}, glucose-6-phosphate and glucose-6-phosphate dehydrogenase.[28]

Data are expressed as specific activity (nmoles produced per minute per mg protein) and the values presented are averages obtained from three experimental groups. Induction values were obtained by dividing the specific activity of EPh'ase or EC'ase for BNF-treated rats by the activity found in CO-treated rats for the silica or filtered air groups. Protein was determined by the method of Lowry *et al.*[29]

Statistical analysis

Statistical differences between experimental groups were determined using analysis of variance with $P < 0.05$ being considered as significant.[30]

Results

The effects of inhalation of silica on the physical properties of alveolar macrophages obtained by pulmonary lavage are given in Table I. Exposure to silica did not affect the purity of alveolar macrophages in the lavage fluid. Silica exposure did tend to decrease the number of alveolar macro-

TABLE II

Functional Parameters of Rat Alveolar Macrophages after Four Weeks Exposure to Silica[A]

	TryPan-blue Exclusion (% cells excluding dye)
Control	93 +/- 1
Silica	88 +/- 4

	Superoxide Release[B] (% of control)	
	Resting	Zymosan-Stimulated
Silica	111 +/- 32	95 +/- 15

	Chemiluminescence[C] (% of control)	
	Resting	Zymosan-Stimulated
Silica	132 +/- 35	103 +/- 12

A Values are means +/- SEM of three experiments.

B In control cells, zymosan increased superoxide release by 11 fold.

C In control cells, chemiluminescence was enhanced with luminol. Zymosan-stimulated chemiluminescence was measured without luminol.

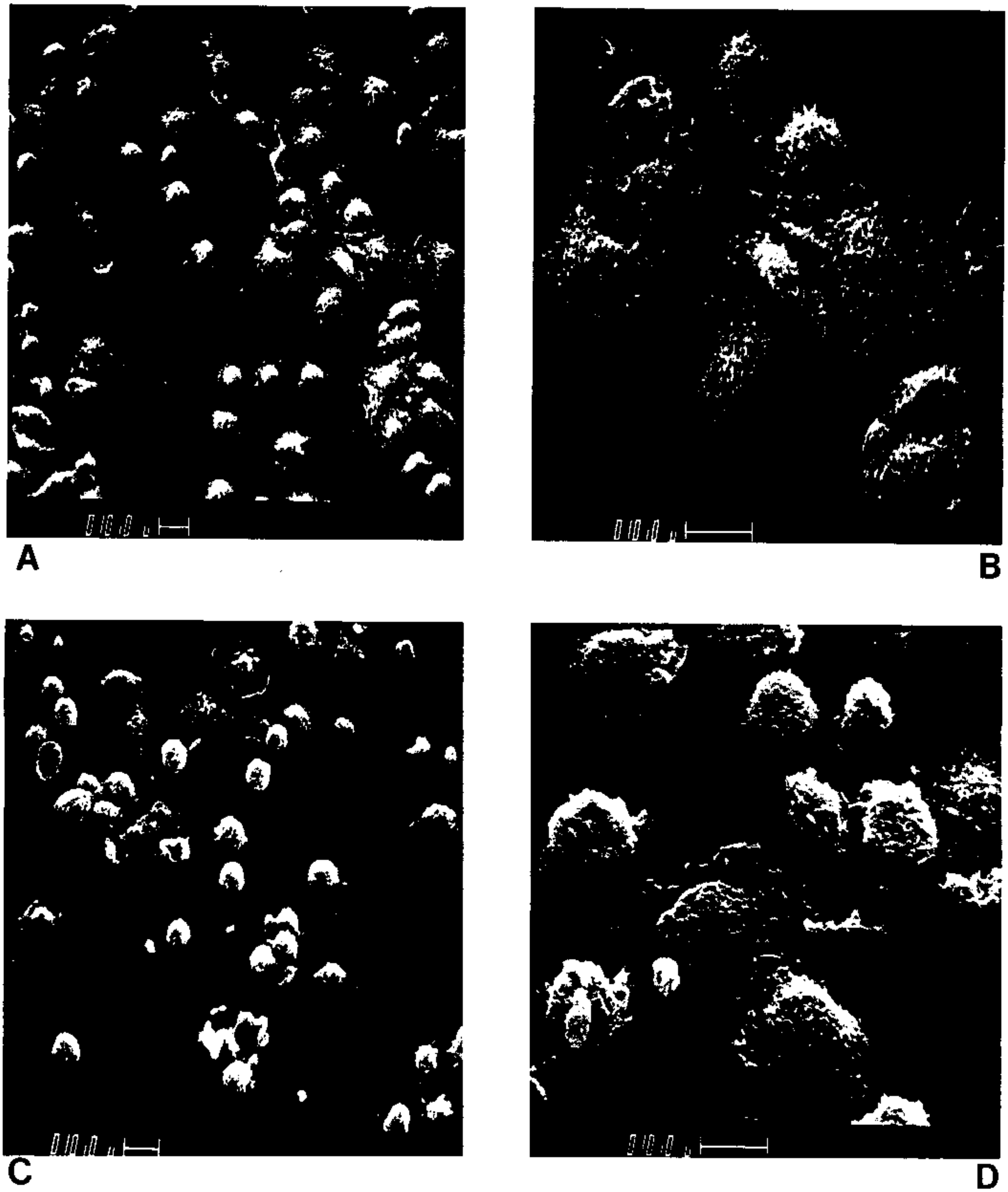


FIGURE 1. A and B are low and high power scanning electron micrographs of alveolar macrophages lavaged from rats exposed to filtered air. C and D are low and high power scanning electron micrographs of alveolar macrophages lavaged from rats exposed to 20 mg/m3 of silica for 16 hr/day, 5 day/week for 4 weeks.

phages obtained by pulmonary lavage. However, statistical analysis revealed that this trend was not statistically significant. In contrast, a statistically significant increase in mean cellular volume of alveolar macrophages was noted following inhalation of silica.

Table II lists the effect of inhalation of silica on various functional parameters of alveolar macrophages. Exposure to silica by inhalation did not alter the ability of alveolar macrophages to exclude trypan-blue dye. Therefore, membrane integrity of these phagocytes was unaffected by exposure. In addition, silica exposure did not affect the secretion of superoxide anion, or the generation of chemiluminescence either at rest or in response to zymosan particles. These data indicate no evidence of hyperactivity or loss of function of alveolar macrophages from silica exposed rats. However, scanning electron microscopy demonstrated some loss of surface activity following exposure to silica (Figure 1A-D). Following silica inhalation, alveolar macrophages exhibited less spreading and less surface ruffling, i.e., many exposed cells appeared rounded with fewer membrane projections. In addition, silica-exposed cells appeared larger than control alveolar macrophages.

The results of the analysis of the two cytochrome P450-dependent enzyme activities are summarized in Table III. EPh'ase activity, in its constitutive as well as induced state, was unaltered by exposure to silica. EC'ase, on the other hand, appeared to exhibit an increased induction value following silica exposure, and the increase was due to a decreased level of activity of the constitutive form. Statistical analysis revealed, however, the trend so described cannot be considered statistically significant.

Discussion

Inhalation of silica should result in phagocytosis and thus accumulation of silica within alveolar macrophages. Therefore, several models for silicosis center around the effects of silica on these pulmonary phagocytes. One theory proposes that silica causes lytic damage to alveolar macrophages.(10,31) Such damage would release lysosomal enzymes which would damage alveolar epithelial cells. Another theory proposes that silica-exposed alveolar macrophages are hyperactive, i.e., secreting excessive quantities of lysosomal enzymes and reactive forms of oxygen.(32-33) Such hypersecretion would also result in lung damage. To test these hypotheses, we measured the membrane integrity and secretory activity of alveolar macrophages after inhalation exposure to 20 mg/m^3 silica for four weeks (Table II). We found no evidence for lytic activity of silica inhalation, i.e., exposure did not result in any change in the ability of alveolar macrophages to exclude trypan-blue dye. Also we found no significant hypersecretion of reactive species either at rest or upon exposure to zymosan particles. Jackson *et al*(34) also found little decrease in viability of macrophages exposed to silica *in vitro*. However, they found that silica decreased the ability of alveolar macrophages to secrete superoxide in response to stimulation. A closer examination of our data reveals a similar trend. That is, although silica caused no significant change in mean values for either superoxide release or chemiluminescence, in two out of three experiments a decrease in secretory activity was noted.

Our data indicated that the yield and purity of alveolar macrophages was not affected by silica inhalation (Table I). These data contrast with reports that silica exposure increased the yield of alveolar macrophages and leukocytes from the lung.(35-37) However, exposure in these studies was via intratracheal instillation and the cellular response varied widely depending on time after exposure.

The data with electronic cell sizing (Table I) and scanning electron microscopy (Figure 1) indicate that alveolar macrophages enlarged as a result of exposure to silica. These data agree with results from intratracheal exposure.(35-36)

Scanning electron microscopY indicates that alveolar macrophages exhibited decreased cellular spreading and surface ruffling following inhalation exposure to silica

TABLE III

Effect of Silica Exposure on Induction of Cytochrome P450-dependent Enzyme Activity[A]

Exposure[B]	Specific Activity[C]	EPh'ase Induction Valued	Specific Activity[C]	EC'ase Induction Value[D]
FA - CO	0.019 +/- 0.007	16.0 +/- 5.7	0.330 +/- 0.036	1.2 +/- 0.6
- BNF	0.280 +/- 0.100		0.410 +/- 0.190	
Si - CO	0.019 +/- 0.006	14.0 +/- 2.9	0.190 +/- 0.019	2.1 +/- 0.3
- BNF	0.250 +/- 0.046		0.400 +/- 0.092	

[A]Values are means +/- SEM of three experiments.

[B]After the rats were exposed to silica (Si) or filtered-air (FA), they were then injected with ß-naphthoflavone (BNF) or corn oil (CO). Details may be found in Methods.

[C]Specific activity in nmoles/min/mg protein.

[D]The induction values are averages of individual values obtained from each group.

(Figure 1). Such surface features have been related to decreased phagocytic activity of alveolar macrophages.(38-39) In agreement, Beck *et al*[37] have reported a decrease in the phagocytotic ability of alveolar macrophages after intratracheal exposure to silica while Martin *et al*[40] have reported a decrease in the chemotactic activity of alveolar macrophages after inhalation of quartz.

We also evaluated the *in vivo* effect of silica exposure on normal metabolic detoxication reactions catalyzed by two cytochrome P450-dependent enzymes, EPh'ase and EC'ase, in pulmonary tissue. Lung EPh'ase is associated with the xenobiotic metabolizing, nonconstitutive class of activities,[26] whereas EC'ase activity appears to represent a mixed class of monooxygenase activities. The enzyme from untreated rat lung responds to *in vitro* inhibitors as a constitutive, phenobarbital-induced, form.[41] Data from our laboratory (unpublished) suggest not only that lung EC'ase from untreated rats is the constitutive form but the activity from BNF-treated rats is the xenobiotic metabolizing form. Thus, in the current study, we are monitoring the BNF-associated increase in lung xenobiotic metabolizing enzymes and a change in enzyme form.

It is important to recognize that it is not necessary to assume a direct effect of silica on P450-mediated metabolism. An effect could be mediated by factors released from phagocytes which are activated in response to silica exposure. In liver, cytochrome P450-dependent reactions in hepatocytes are modulated by particle-stimulated Kupffer cells[20] and the extracellular contents of endotoxin-treated peritoneal macrophages.[21] Alterations in normally occurring cellular or extracellular phospholipid also have consequences for cytochrome P450 activity.[42] Since silica exposure induces pulmonary lipidosis,[43] such a mode of action may be important in silica-exposed lungs.

Studies on the relationship between silica exposure and microsomal P450-mediated reactions have taken many directions. During their study on membrane uptake of benzo(a)pyrene (BaP), Lakowicz and Bevan[44] observed silica enhanced uptake of the particle-bound compound. In an in vitro study, Kandaswami and O'Brien[45] found no effect of silica on the liver microsomal metabolism of BaP. In the study described herein, we investigated the *in vivo* effect of exposure to silica by inhalation on the levels of two cytochrome P450-dependent enzyme activities. The results suggest the constitutive level of lung EC'ase may have diminished following the four-week exposure. The extent of decrease, however, was too small to be statistically significant with the number of animals available for the study.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

References

1. **Weibel, E.R.:** Morphological Basis of Alveolar Capillary Gas Exchange. *Physiol. Rev. 53*:419-495 (1973).
2. **Green, G.M.:** Amberson Lecture: In Defense of the Lung. *Am. Rev. Resp. Dis. 102*:691-700 (1970).
3. **Drath, D.B., A.A. Harper and M.L. Karnovsky:** *Biochemical Characteristics of Alveolar Macrophages. Lung Cells in Disease*, pp. 153-161. A. Bouhuys, Ed. North-Holland Publishing Company, New York (1976).
4. **Drath, D.B., A.A. Harper, J. Gharibian et al:** The Effect of Tobacco Smoke on the Metabolism and Function of Rat Macrophages. *J. Cell. Physiol. 95*:105-113 (1978).
5. **Sweeney, T.D., V. Castranova, L. Bleigh and P.R. Miles:** Factors Which Affect Superoxide Anion Release from Rat Alveolar Macrophages. *Exp. Lung Res. 2*:85-96 (1981).
6. **Sagone, A.L., G.W. King and E.M. Metz:** A Comparison of Metabolic Response to Phagocytosis in Human Granulocytes and Monocytes. *J. Clin. Invest. 57*:1352-1358 (1976).
7. **Miles, P.R., V. Castranova and P. Lee:** Reactive Forms of Oxygen and Chemiluminescence in Phagocytizing Rabbit Alveolar Macrophages. *Am. J. Physiol. 235*:C103-C108 (1978).
8. **Goldstein, E.:** Hydrolytic Enzymes of Alveolar Macrophages. *Rev. Inf. Dis. 5*:1078-1092 (1983).
9. **Fridovich, I.:** The Biology of Oxygen Radicals: The Superoxide Radical is an Agent of Oxygen Toxicity; Superoxide Dismutases Provide an Important Defense. *Sci. 201*:875-880 (1975).
10. **Wallace, W.E., M.J. Keane, V. Vallyathan et al:** Pulmonary Surfactant Interaction with Respirable Dust. *Proceedings of Coal Mine Dust Conference*, S. Peng, Ed. Mogantown (1984).
11. **Heppleston, A.G. and J.A. Styles:** Activity of a Macrophage Factor in Collagen Formation by Silica. *Nature 214*:521-522 (1967).
12. **Bitterman, P.B., S.I. Rennard, G.W. Hunninghake, and R.G. Crystal:** Human Alveolar Macrophage Growth Factor for Fibroblasts Regulation and Partial Characterization. *J. Clin. Invest. 70*:806-822 (1982).
13. **Minchin, R.F. and M.P. Boyd:** Localization of Metabolic Activation and Deactivation Systems in the Lung: Significance to the Pulmonary Toxicity of Xenobiotics. *Ann. Rev. Pharmacol. Toxicol. 23*:217-238 (1983).
14. **Wislocki, P.G., G.T. Miwa and A.Y.H. Lu:** Reactions Catalyzed by the Cytochrome P450 System. *Enzymatic Basis of Detoxication,* Vol. I, pp. 137-182. W.B. Jakoby, Ed. Academic Press, New York (1980).
15. **Matsubara, T., R.A. Prough, M.D. Burke and R.W. Estabrook:** The Preparation of Microsomal Fractions of Rodent Respiratory Tract and Their Characterization. *Cancer Res. 34*:2196-2203 (1974).
16. **Morgan, D.D., D. Warshawsky, R.W. Niemeier and E.B. Bingham:** The Pharmacokinetics of Benzo[a]pyrene in the Isolated Perfused Rabbit

Lung: The Influence of Benzo[a]pyrene, N-Dodecane, Particulate or Sulfur Dioxide. *Toxicology 33*:275-289 (1984).

17. **Serabjit-Singh, C.J., P.W. Albro, I.G. Robertson and R.M. Philpot:** Interactions Between Xenobiotics that Increase or Decrease the Levels of Cytochrome P450 Isozymes in Rabbit Lung and Liver. *J. Biol. Chem. 258*:12827-12834 (1983).

18. **Ueng, T.-H. and A.P. Alvarez:** Selective Induction and Inhibition of Liver and Lung Cytochrome P450-dependent Monooxygenases by the PCBs Mixtures, Anoclor 1016. *Toxicology 35*:83-84 (1985).

19. **Weibel, F.J.:** *Activation and Inactivation of Carcinogens by Microsomal Monooxygenases: Modification by Benzoflavones and Polycyclic Aromatic Hydrocarbons. Modifiers of Chemical Carcinogenesis,* pp. 57-84. T.J. Slaga, Ed. Raven Press, New York (1980).

20. **Petersen, T.C. and K.W. Renton:** Depression of Cytochrome P450 Dependent Drug Biotransformation in Hepatocytes after the Activation of the Reticulo-endothelial System by Dextran Sulfate. *J. Pharmacol. Exp. Ther. 229*:299-304 (1984).

21. **Williams, J.F.:** Induction of Tolerance in Mice and Rats to the Effect of Endotoxin to Decrease the Hepatic Microsomal Mixed-Function Oxidase System: Evidence for a Possible Macrophage-derived Factor in the Endotoxin Effect. *Int. J. Immunopharmacol. 7*:501-509 (1985).

22. **Myrvik, Q.N., E.S. Leake and B. Fariss:** Lysozyme Content of Alveolar and Peritoneal Macrophages from the Rabbit. *J. Immunol. 86*:133-136 (1961).

23. **Phillips, H.J.:** Dye Exclusion Tests for Cell Viability. *Tissue Culture Methods and Applications,* pp. 406-408. P.R. Kruse and M.K. Patterson, Eds. Academic Press, New York (1973).

24. **Babior, B.M., R.S. Kipnes and J.T. Curnette:** Biological Defense Mechanisms: The Production by Leukocytes of Superoxide, a Potential Bacterial Agent. *J. Clin. Invest. 52*:741-744 (1973).

25. **Danner-Rabovsky, J. and R.D. Groseclose:** Stability of Rat Lung and Liver Microsomal Cytochrome P450 Enzyme Activities to Storage: Purified Microsomal Fraction, Postmitochondrial Fraction and Whole Tissue. *J. Toxicol. Environ. Health 10*:601-611 (1982).

26. **Burke, M.D., R.A. Prough and R.T. Mayer:** Characteristics of a Microsomal Cytochrome P448-Mediated Reaction, Ethoxyresorufin O-Deethylation. *Drug Met. and Dispos. 5*:1-8 (1977).

27. **Greenlee, W.F. and A. Poland:** An Improved Assay of 7-Ethoxycoumarin O-Deethylase Activity: Induction of Hepatic Enzyme Activity in C57BL/GJ and DBA/2J Mice by Phenobarbital, 3-Methylcholanthrene and 2,3,7,8-Tetracholodibenzo-P-Dioxin. *J. Pharmacol. Exp. Ther. 205*:596-605 (1978).

28. **Rabovsky, J., D.J. Judy and W.H. Pailes:** *In Vitro* Effects of Straight-Chain Alkanes (n-Hexane through n-Dodecane) on Rat Liver and Lung Cytochrome P450. *J. Toxicol. Environ. Health 18*:408-421 (1986).

29. **Lowry, O.H., N.J. Rosenbrough, A.L. Farr and R.J. Randall:** Protein Measurements with the Folin Reagent. *J. Biol. Chem. 193*:265-275 (1951).

30. **Winer, B.J.:** *Statistical Principles in Experimental Design.* McGraw-Hill, New York (1971).

31. **Nolan, R.P., A.M. Langer, J.S. Harington et al:** Quartz Hemolysis as Related to Its Surface Functionalities. *Environ. Res. 26*:503-520 (1981).

32. **Weiss, S.J. and A.F. LoBuglio:** Biology of Disease: Phagocyte Generated Oxygen Metabolites and Cellular Injury. *Lab. Invest. 47*:5-18 (1982).

33. **Kaw, J.L., E.G. Beck and J. Burch:** Studies of Quartz Cytotoxicity on Peritoneal Macrophages of Guinea Pigs Pretreated with Polyvinylpyridine N-oxide. *Environ. Res. 9*:313-320 (1975).

34. **Jackson, M.V., A. Holian and R.P. Daniele:** Effect of Silica Exposure on the Release of Superoxide Anion by Alveolar Macrophages. *Am. Rev. Respir. Dis. 127*:162A (1983).

35. **Morgan, A., S.R. Mores, A. Holmes et al:** The Effect of Quartz, Administered by Intratracheal Instillation on Rat Lung. *Environ. Res. 22*:1-12 (1980).

36. **Sykes, S.E., A. Mogan, S.R. Moore et al:** Dose-dependent Effects in the Subacute Response of the Rat Lung to Quartz. I. The Cellular Response and the Activity of Lactate Dehydrogenase in the Airways. *Exp. Lung Res. 5*:229-243 (1983).

37. **Beck, B.D., J.D. Brain and D.E. Bohannon:** An *in vivo* Hamster Bioassay to Assess the Toxicity of Particulates for the Lung. *Tox. Appl. Pharmacol. 66*:9-29 (1982).

38. **Hill, J.O., R.H. Gray, B. DeNee and G.J. Newton:** Comparative Damage to Alveolar Macrophages after Phagocytosis of Respirable Particles. *Environ. Res. 27*:95-109 (1982).

39. **Castranova, V., L. Bowman, M.J. Reasor et al:** The Response of Rat Alveolar Macrophages to Chronic Inhalation of Coal Dust and/or Diesel Exhaust. *Environ. Res. 36*:405-419 (1985).

40. **Martin, T.R., E.Y. Chi, D.S. Covert et al:** Comparative Effects of Inhaled Volcanic Ash and Quartz in Rats. *Am. Rev. Respir. Dis. 128*:144-152 (1983).

41. **Lorenz, J., H.R. Glatt, R. Fleishmann et al:** Drug Metabolism and Its Relationship to that in Three Rodent Species: Monooxygenase, Epoxide Hydrolase, and Glutathione S-Transferase Activities in Subcellular Fractions of Lung and Liver. *Biochem. Med. 32*:43-56 (1984).

42. **Ingelman-Sundberg, M. and I. Johansson:** Catalytic Properties of Purified Forms of Rabbit Liver Microsomal Cytochrome P450 in Reconstituted Phospholipid Vesicles. *Biochem.*

19:4004-4011 (1980).

43. **Dethloff, L.A., L.B. Gilmore, B.C. Gladden et al:** Effects of Silica on the Composition of the Pulmonary Extracellular Lining. *Toxicol. Appl. Pharmacol.* *84*:66-83 (1986).

44. **Kandaswami, C. and P.J. O'Brien:** Effect of Chrysotile Asbestos and Silica on the Microsomal Metabolism of Benzo[a]pyrene. *Environ. Health Perspec.* *51*:311-314 (1983).

45. **Lackowicz, J.R. and D.R. Bevan:** Effects of Asbestos, Iron Oxide, Silica, and Carbon Black on the Microsomal Availability of Benzo[a]pyrene. *Biochem.* *18*:1570-1576 (1979).

Development of Alterations in the Lung Induced by Inhaled Silica: a Morphometric Study

R. CLARK LANTZ,[A] CHARLES STANLEY[B] and DAVID E. HINTON[A]
[A]Department of Anatomy, West Virginia University, Morgantown, West Virginia 26506; [B]Department of Mechanical Engineering, West Virginia University, Morgantown, West Virginia 26506

Morphometric examination of lung alterations following exposure to toxic and pathogenic substances is invaluable in detecting subtle changes which might otherwise be overlooked. Results, from evaluation of initial structural alterations, support and guide subsequent non-morphological techniques and, when coupled appropriately, can lead to a better understanding of the pathogenesis of a disease. Morphometry is a technique which can be used to determine, quantitatively, the site, extent, development, and progression of a disease state. Determination of the extent of tissue and cellular involvement in the response to inhalation of silica has been performed in order to gain a better understanding of the development of fibrosis following inhalation of this toxicant. In addition, since silica has been postulated as one of the important pathogenic minerals in coal mine dust, it is important to understand the lung tissue response to silica prior to evaluating the effects of inhaled coal mine dusts. Male Syrian golden hamsters were placed in Hazelton 1000 inhalation chambers and were exposed to either filtered air (controls, n = 24) or filtered air plus 30 mg/m^3 silica (Min-U-Sil 10, 95% of particles < 5 um, n = 24) for 16 hours per day, five days per week, for two weeks. Animals were returned to the animal quarters prior to subsequent tissue processing at 1, 4, and 12 weeks following exposure. This schedule was designed to allow time for the development of fibrosis. Lungs were fixed by intratracheal perfusion of 1/2 strength Karnovsky's fixative at a pressure of 20 cm H_2O and tissues were taken for embedment and analysis at the light level. Determination of site, extent, and development of alterations was performed using a multitiered approach. Changes in large structures (airways, blood vessels) was determined prior to evaluation of changes at the septal tissue level. Data will be presented outlining the progression of changes. Results indicate the usefulness of morphometric analysis of lungs following inhalation of toxic substances in quantitatively defining the structural alterations.

Introduction

Silica is a known fibrogenic agent when inhaled alone and has also been postulated as an important causative agent in coal workers' pneumoconiosis. Although efforts have been made to elucidate the mechanism of pathogenesis of silicosis, the events which lead to the deposition of collagen and fibrosis in the lung following silica exposure are not completely understood. Several investigators have attempted to describe the tissue and cellular responses following silica exposure either following intratracheal instillation or inhalation.[1-4] However, these studies have used relatively high doses and have only been concerned with qualitative evaluation of the morphological alterations. The purpose of this report is to describe, in quantitative terms using morphometric techniques, the structural alterations in the lung following inhalation of silica. Use of these techniques permits objective evaluation of structural alteration, permits statistical testing of differences between control and exposed animals, allows structural data to be correlated with other biochemical and physiological data, and can be a sensitive method for detection of subtle differences in structural alteration.

Materials and Methods

Animals

Male Syrian golden hamsters (90-110 g body weight obtained from Engle Laboratories, Farmersburg, IN) were used throughout the study. When not in the inhalation chambers, animals were housed in the WVU Basic Science animal quarters, given food and water ad lib and maintained on a 12 hour on — 12 hour off light/dark cycle.

Inhalation Exposure

Hamsters were exposed to silica in the West Virginia University inhalation facility. The facility consists of two Hazelton HIC-1000 chambers. Both chambers received air (10 l/min) which had been filtered, cooled, dehumidified, and reheated and humidified to 70°F, 45 percent relative humidty. Animals were selected at random and placed in either the control chamber, which received only the filtered air, or the exposure chamber, which received silica in addition to filtered air. Silica (Min-U-Sil 10, 95% of particles < 5 um) was aerosolized using a TSI 9310 fluidized bed aerosol generator and animals were exposed to 30 mg/m^3 of silica 16 hours per day, five days per week for two weeks. At one week (N = 7), four weeks (N = 7) and 12 weeks (N = 8) following the end of exposure animals were processed for morphological and morphometric examination. Control animals (N = 10) were also taken at each time point.

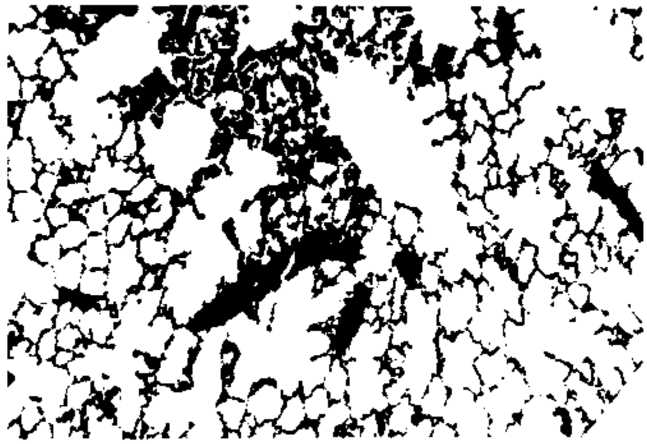


FIGURE 1. Light micrograph of hamster distal lung. Note cellular accumulation in alveoli. Silica treated animal 12 weeks postexposure. H & E stained paraffin section. X80.

General Morphologic Methods

All animals were anesthetized by a single i.p. injection (0.6 ml/100 g body weight) of 1.0 percent aqueous Brevital sodium (Lilly). After exposure of the trachea, a catheter was inserted between the second and third tracheal cartilaginous rings. The catheter was connected to a three way valve allowing maintenance of a patent airway. At this time the anterior abdominal wall was opened and the diaphragm was punctured permitting collapse of the lung against atmospheric pressure and flow of fixative (1/2 strength Karnovsky's fluid containing 0.01 percent picric acid in 0.1M phosphate buffer, pH 7.4) into the lungs was initated. This fixative was selected since it has been shown to be satisfactory for light and electron microscopy. Lungs were inflated against a constant pressure of 20 cm H_2O for one hour at which time the trachea was ligated and lungs, heart and other components of the mediastinum were removed, immersed in fixative and stored at 4°C overnight. Total lung volume (via fluid displacement) and weights of right (apical, middle, caudal and infracardiac lobes) and left (left lobe) lungs of each animal were recorded.

After fixation, each lobe was dissected free and sliced along the axis of the major intrapulmonary airway from the hilus to the periphery.[5] Slices were taken from each lobe for routine light microscopy (LM) (paraffin embedment and staining of 5 um sections, taken at 1 mm intervals, with hematoxylin and eosin. Slices from right caudal and left lung lobes of each animal were used for high resolution light microscopy (HRLM). These were gently minces into 1 mm^3 pieces, rinsed in phosphate buffer as above, postfixed in OsO_4 for one hour, dehydrated in graded ethanol solutions, passed through propylene oxide and embedded in Epon-Araldite. Semithin sections (1 um) of Epon-Araldite embedded material were cut with glass knives and stained with toluidine blue for HRLM. Randomization was assured at the lung lobe level[6] since approximately 100 pieces from individual lobes were mixed in vials of fixative prior to removal of ten pieces for HRLM.

Morphometric Procedures

Standard point counting techniques as described for the lung[7] were used. Point counting of all light microscopic material was performed directly from glass slides using a drawing tube attachment which superimposed an image of the square lattice over the image of the tissue section. Analysis of H & E — stained, paraffin embedded sections, from each lobe of each lung was performed using a grid overlay of 100 points with an interpoint distance (as determined by stage micrometer) of 0.2 mm. The number of points overlying structures of interest was used to estimate volume densitites (V_V) for large blood vessels and airways as well as distal lung (respiratory bronchiole, alveolar ducts, sacs and alveoli) in 10 fields/animal. The second level of analysis was HRLM material. Slides were viewed at 625X and a grid overlay of 100 total points with interpoint distance of 20 um was used. Points over air space and alveolar septal tissue were used to estimate V_V of each. Surface density of alveolar epithelium was estimated by counting intercepts of test lines with the epithelial surface.

Arithmetic mean barrier thickness of alveolar septa was calculated by dividing the volume density of septal compartment by the epithelial surface densities. Alveolar mean linear intercept length was calculated from the volume density of distal lung airspace and surface density of alveolar epithelial cells.

Statistics

Statistical differences between experimental groups were determined by using analysis of variance[8] with $P < 0.05$ being considered as significant.

Results

Qualitative evaluation of light micrographs from animals exposed to silica show responses typical of toxic dust exposures. Examination of tissue demonstrated cellular accumulations in the alveolar spaces (Figures 1 and 2) and apparent thickening of the alveolar septa (Figure 2). These changes were present in animals at 1, 4, and 12 weeks following the termination of the two week exposure to silica.

FIGURE 2. High resolution light micrograph of hamster distal lung. Cellular accumulation in alveoli and apparent thickening of alveolar septa are present. Silica treated animal 12 weeks postexposure. Toluidine blue stained epon embedded tissue. X600.

TABLE I

Effect of Silica Exposure on Hamster Lung

Parameter	Control	Time After Silica Exposure		
		1 week	4 weeks	12 weeks
Total lung volume (cm^3)	4.99 +/- 0.19	4.36 +/- 0.17	4.79 +/- 0.16	5.84 +/- 0.30[a]
Large airways (cm^3)	0.46 +/- 0.05	0.30 +/- 0.02	0.49 +/- 0.07	0.39 +/- 0.05
Large blood vessels (cm^3)	0.39 +/- 0.03	0.36 +/- 0.03	0.49 +/- 0.03	0.44 +/- 0.05
Distal lung (cm^3)	4.14 +/- 0.18	3.70 +/- 0.16	3.81 +/- 0.20	5.01 +/- 0.25[a]
Distal lung airspace (cm^3)	3.60 +/- 0.13	3.14 +/- 0.15	3.25 +/- 0.19	4.15 +/- 0.20[a]
Alveolar septa (cm^3)	0.54 +/- 0.07	0.55 +/- 0.04	0.56 +/- 0.03	0.86 +/- 0.09[a]
Alveolar mean linear intercept (um)	55.5 +/- 2.6	55.1 +/- 2.5	57.3 +/- 2.3	50.6 +/- 2.9
Septal thickness (um)	1.99 +/- 0.15	2.45 +/- 0.15[b]	2.47 +/- 0.07[b]	2.55 +/- 0.19[b]

Values are mean +/- SEM

[a]Significantly different from all other groups ($p < 0.05$).

[b]Significantly different from control ($p < 0.05$).

Light microscopic morphometric data are presented in Table I. Values for volumes are presented as absolute values so that any change in various tissue compartment volumes could be detected. Although control animals were examined at all three time points following the end of exposure, no significant differences were seen between any of the controls and therefore all control animal values were placed in a single group.

Twelve weeks following silica exposure significant increase in total lung volume was seen versus all other groups. When the total lung volume was divided into its constitutive parts it was determined that the increase in lung volume was caused by increases in both the distal lung airspace and alveolar septal volumes (Table I).

In order to determine if the changes in volume of distal lung compartments represents septal thickening and/or emphysema, alveolar mean linear intercept (the average distance between alveolar septal walls) and the septal thickness were calculated. No significant differences were seen in alveolar mean linear intercept. Alveolar septa were thicker in the 12 week group but significant increases in this parameter over controls were also seen in the one and four week postexposure groups.

Discussion

Qualitative descriptions of the response of the lung to inhaled silica have been previously reported by numerous investigators.[1-4] Although descriptive accounts of the progression of the tissue responses is useful, quantitative determinations of the site and extent of alteration cannot be obtained by these methods. Morphometric examination of lung alterations following exposure to toxic and pathogenic substances is invaluable in detecting subtle changes which might otherwise be overlooked. Results, from evaluation of initial structural alterations, support and guide subsequent nonmorphological techniques and, when coupled appropriately, can lead to a better understanding of the pathogenesis of a disease. Morphometry is a technique which can be used to determine, quantitatively, the site, extent, development and progression of a disease state. Determination of the extent of tissue and cellular involvement in the response to inhalation of silica has been performed in order to gain a better understanding of the development of fibrosis following inhalation of this toxicant.

Data presented in this light microscopic study support and extend the findings of qualitative evaluation of pulmonary tissue following silica exposure. Wehner *et al*[4] reported that inhalation of silica lead to increases in lung volume as early as four months postexposure. They did not however, present data as to the exact cause and site of the increase in lung volume. Our study has also found a similar increase in lung volume in silica exposed animals at 12 weeks postexposure but by using morphometric techniques it was determined that the increase is due to changes in both the distal lung airspace and septal volumes.

Alteration in these volumes may be expected if, as is well documented, silica exposure leads to fibrosis and also to emphysema. However, this conclusion is not substantiated by our data. If emphysema were present in the silica exposed animals, alveolar mean linear intercept values should increase. No significant differences were seen in this parameter at 12 weeks postexposure. In addition, if increases in septal lung volume is due only to increases in the septal thickness, then increases should only be present in the 12 week group and not in all groups of exposed animals. Since tissue volume and air space have increased without an increase in alveolar size one interpretation of the data is that the number of alveoli has increased in the silica exposed group 12 weeks after the end of the exposure. Similar increases in alveolar number in response to toxic inhalants has been reported previously by Hyde *et al.*[9]

Increases in septal thickness at all time points following the termination of exposure may be an indication of either interstitial edema, interstitial cellular accumulation and/or fibrosis. The exact nature of the septal response and the cells involved in the response are currently under investigation by performing morphometric examination of the electron microscopic levels. Data obtained at that level of investigation should enhance the understanding of the cellular and tissue responses following silica inhalation.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

References

1. **Martin, J.C., H. Daniel and L. Le Bouffant**: Short- and Long-term Experimental Study of the Toxicity of Coal-mine Dust and Some of Its Constituents. *Inhaled Particles IV*, pp. 361-372. British Occupational Hygiene Society, London (1977).

2. **Dauber, J.H., M.D. Rossman, G.G. Pietra et al:** Experimental Silicosis: Morphologic and Biochemical Abnormalities Produced by Intratracheal Instillation of Quartz into Guinea Pig Lungs. *Am. J. Pathol. 101*:595-612 (1980).

3. **Martin, T.R., E.Y. Chi, D.S. Covert et al:** Comparative Effects of Inhaled Volcanic Ash and Quartz in Rats. *Am. Rev. Resp. Dis. 128*:144-152 (1983).

4. **Wehner, A.P., G.E. Dagle and M.L. Clark**: Lung Changes in Rats Inhaling Volcanic Ash for One Year. *Am. Rev. Resp. Dis. 128*:926-932 (1983).

5. **Dungworth, D.L., L.W. Schwartz and W. Tyler:** Morphological Methods of Evaluation of Pulmonary Toxicity in Animals. *Ann. Rev. Pharmacol. Toxicol. 16*:381-400 (1976).

6. **Rohr, H., M. Oberholzer, G. Bartsch and M. Keller:** Morphometry in Experimental Pathology: Methods, Baseline Data and Applications. *Int. Rev. Exp. Pathol. 15*:233-325 (1976).

7. **Weibel, E.R.:** *Stereological Methods: Practical Methods for Biological Morphometry*. Academic Press, New York, NY (1979).

8. **Winer, B.J.:** *Statistical Principles in Experimental Design*. McGraw-Hill, New York, NY (1971).

9. **Hyde, D.M., M.Y. Stovall, A.Y. Kyhos and D.A. Samuelson:** Estimation of Alveolar and Alveolar Duct Number and Size in Nitrogen Dioxide-Induced Emphysema. *Acta. Stereol. 2*:159-162 (1983).

Noninvasive Magnetopneumographic Studies of Lung Dust Retention and Clearance in Coal Miners

ALLAN P. FREEDMAN, M.D., F.A.C.P., F.C.C.P.[A] and STEPHEN E. ROBINSON, Ph.D.[B]

[A]Director of Pulmonary Laboratories, Presbyterian-University of Pennsylvania-Medical Center, Philadelphia, Pennsylvania; [B]Senior Scientist, Biomagnetic Technologies, Inc., San Diego, California

Coal mine dust has ferrimagnetic properties. In 2289 samples of respirable coal mine dust, we found a concentration of ferrimagnetic mineral (FM) equivalent to 0.45 percent ($\sigma_g = 1.1$) magnetite.

Magnetopneumography (MPG), a noninvasive technique for determining the amount and distribution of ferrimagnetic mineral dust in the lungs, was used to study 53 recently retired underground coal workers. No correlation of lung dust with years underground was found, though we did find an inverse relationship of lung dust burden to smoking history, suggesting reduced alveolar deposition in cigarette smokers.

Twenty-six retired miners were restudied at an interval of one year and 13 measured again at two years. At one year, seven showed no clearance of FM lung dust. The clearance T 1/2 for 19 others was 63 +/- 66 months (range 9 - 134). There was no correlation of T 1/2 with work history, time retired, age, pulmonary function, or degree of X-ray abnormality. Those with cough, phlegm or dyspnea had slowing of clearance of mine dust from deeper lung regions. At two years, seven miners had no detectable clearance, and T 1/2 for six others was 115 +/- 93 months (range 45 - 262 months). These values are similar to animal and autopsy human studies and may suggest a cytotoxic role of coal mine dust in slowing alveolar clearance.

Introduction

Magnetopneumography (MPG) noninvasively measures the relatively small net remanent magnetic field due to the alignment of the individual dipolar magnetic moments of ferrimagnetic particles by a brief DC magnetization.[1] Magnetite ($FeO\ Fe_2O_3$) and maghaemite (γ-Fe_2O_3) are thought to be the predominant ferrimagnetic minerals (FM) present in coal mine dust.[2] None of the body's endogenous organic iron compounds has ferrimagnetic properties. Therefore, it is safe to assume that all measured FM in the body originates from exogenous sources, primarily inhalation of environmental dust particles. Total lung dust content can be derived from measurements of ferrimagnetic dust, when the average fraction of magnetic mineral in the respirable dust of a given occupation is known.

The retention of large amounts of mineral dust in the lung may be associated with lung disease, termed pneumoconiosis. Although lung damage can be medically assessed, actual lung dust content could not be noninvasively measured before the advent of MPG. MPG has been used for assessing the retention of occupationally acquired lung dust in welders, coal miners, foundry workers, and others.[3,4] MPG assessment of asbestos accumulation in the lung has met with variable success.[4-6] Additionally, MPG has been used to estimate the clearance half time of welding fume from cross sectional human studies and to directly measure it in a rat model.[7,8]

Our initial MPG studies found 3 of 14 active bituminous underground coal miners and 11 of 21 retired disabled miners to have elevation of FM compared to 20 rural control subjects.[9] We were also able to discern the accumulation of dust present in the central lymphatic structures. A second cross sectional study showed that 17 of 71 underground bituminous miners (60 active and 11 retired) had FM levels in the lungs greater than 22 of 23 control subjects.[4] No correlation with years mining underground, job category or cigarette smoking history was found. Few of the miners had X-ray changes of pneumoconiosis. Also, there is no way of quantitating their past dust exposure.

We now report measurement of the thoracic burden of FM and its clearance in a larger group of retired coal miners. Analysis of the FM contribution to coal mine dust will also be presented.

Methods

Coal Mine Dust

Two thousand, two hundred and eighty nine (2289) coal mine respirable dust filter samples weighing over 0.5 mg were randomly chosen from all dust samples collected by the Mining Safety and Health Administration over a one-month period in Pennsylvania and West Virginia. The dust laden filter was dissected out and mounted on a nonmagnetic medium. Measurement of FM was carried out on these samples and on similar samples with known concentrations of magnetite. Results were expressed as percent equivalent magnetite. Comparison of groups was performed with a two-tailed test of significance.

Retired Underground Coal Miners

Coal miners were screened to eliminate those with significant exposure to welding fume or other ferrimagnetic dusts. A detailed occupational and smoking history as well as an informed consent were obtained from each subject.

The 53 recently retired miners had a 33 +/- 9 years underground work history and had been retired for an average of 6 +/- 4 months. Although 30 had some degree of pneumoconiotic abnormality, only five were greater than category 1. Their smoking history averaged 14 +/- 25-pack years. Spearman's rank correlation and Student's t test were used to assess statistical significance of observation.

Magnetopneumographic Measurements

MPG measurements were made over the posterior chest on a grid of 3 x 3 points using a 7 cm grid interval. The spinous process of the 7th cervical vertebra was used as a fixed anatomic reference for the scan. A localized-field MPG technique previously described was employed.[10,11] The remanent magnetic field was measured using a 4.4 cm diameter second order SQUID gradiometer of 8 cm baseline. The SQUID, in conjunction with an 11.2 cm diameter water-cooled electromagnet generating 135 milliTesla DC at the skin, had a measured sensitivity of 713 picoTesla/mg/liter. This was based on phantom lung and chest wall models. Partial magnetic erasures were employed to ascertain the distribution of ferrimagnetic mineral within the lung and thereby permit distinction between superficial and deeper concentrations. The values for remanent magnetic field of the nine locations were used to derive mean values for total lung and the contributions of outer, middle and deep lung compartments.

Clearance Calculation

For purposes of clearance calculation, day zero was considered to be the day of retirement. The second measurement of total lung FM was performed either 390 or 430 days after the first and the third measurement was performed 820 days after the first. Twenty six of the 53 initial subjects had a second measurement and 13 had a third measurement performed.

Results

Coal Mine Dust

As can be seen from Figure 1, 2289 coal mine respirable dust samples had a mean FM content expressed as equivalent magnetite of 0.45% +/- 0.90% (mean +/- s.d.). Geometric mean of FM content was 0.22 percent with the geometric standard deviation of 1.20. No significant difference was seen in FM content between Pennsylvania and West Virginia samples.

There was a significant difference in FM content when classified according to job category, as could be seen in Table I. Percent equivalent magnetite of dust breathed by underground face workers was 0.29 percent, of underground nonface workers was 0.71 percent, of transportation workers was 2.31 percent, and of surface occupations was 0.83 percent. A similar distribution was seen when analyzed by sample type with percent magnetite of high risk samples 0.24 percent, of intake air 0.61 percent, of face 0.36 percent, of nonface 0.98 percent, and of surface air 0.82 percent. Mechanics, track men and motormen have the highest percent FM in surrounding air, but these are workers likely to be exposed to welding fumes which are highly ferrimagnetic.

Magnetopneumographic Measurements

The mean value of the remanent field ranged from 9 to 279 picoTesla (pT) with a mean of 48 +/- 53 pT. This is much

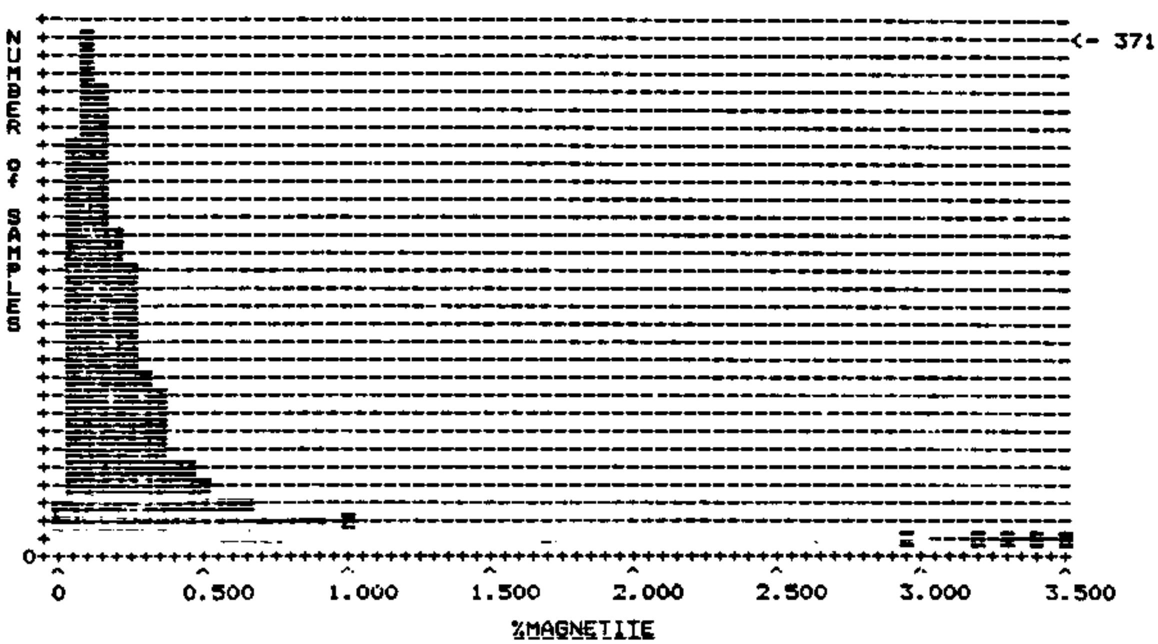


FIGURE 1. Frequency distribution of percent equivalent magnetite in 2289 respirable coal mine dust samples from underground mine in Pennsylvania and West Virginia. Mean, 0.455; Standard deviation, 0.899; Standard mean error, 197.736; Geometric mean, 0.215; and Geometric deviation, 1.199.

higher than the 20 +/- 19 pT obtained from similar measurements of 28 urban dwellers studied by us.

No correlation was found with years underground mining history, despite an attempt to correct MPG measurements for clearance during time retired using mean clearance half time for the group studied serially. A negative correlation was found with pack-years (the product of average packs per day smoked multiplied by years smoking history) of $p < 0.01$. There was no correlation with cigarettes smoked per day or with total years of cigarette smoking. There was no correlation of remanent field measurements with symptoms of cough, sputum production, wheezing or shortness of breath. However, there was a significant negative correlation ($p < 0.05$) with symptoms of sinus disease.

There was a positive correlation between the forced vital capacity expressed as a percent of predicted and the remanent field measurements reaching a significance of $p < 0.05$. No correlation was seen with the forced expiratory volume in one second expressed as a percentage of the forced vital capacity or with the maximal voluntary ventilation. There was no correlation of the remanent field measurements with pneumoconiotic category of the chest X-ray (Table II).

Clearance Calculations

Of the 26 retired miners restudied at an interval of one year, seven showed no clearance of lung dust. The clearance T 1/2 for 19 others was 63 +/- 66 months (range 9 to 134). There was no correlation of T 1/2 with work history, time retired, age, pulmonary function or degree of X-ray abnormality. As can be seen in Table III, the clearance tended to be slower from both superficial and deep lung regions than for the mid lung regions. The T 1/2 from the deep lung was significantly correlated with degree of wheezing.

At two years, 13 miners were measured again and seven miners showed no detectable clearance. The T 1/2 for the six others was 115 +/- 93 months (range 45 to 262).

Discussion

Coal Mine Dust

Since MPG measures the FM fraction of lung dust, extrapolation of MPG measurements to quantitation of total lung dust requires accurate knowledge of lung dust composition. From Table I, it is evident that the FM fraction of respirable coal mine dust is fairly constant within job categories. In a monitoring program, sampling of the dust in the working environment would ideally proceed in tandem with MPG measurements of the worker.

The higher ferrimagnetic activity of dust from nonface sites and the further increase at transportation sites probably reflects contamination with rock strata and welding fume. Since welding fume may contain up to 30 percent FM, its presence in the lung will overshadow the contribution to FM of coal mine dust.[7] Additionally, workers may be exposed to pure magnetite at tipple sites using magnetite for gradient separation of coal.

A final consideration is the *in vivo* stability of the FM fraction of coal mine dust. Though iron oxides are relatively insoluble,[12] there is inferential data suggesting its slow solubilization.[13] Unpublished data from our laboratory regarding measurements on dust extracted from autopsied coal workers' lungs suggest that the contribution of FM may decline with time.

Magnetopneumographic Measurements of Lung FM

Approximately 25 percent of the retired underground coal miners had FM levels outside the 95 percent confidence

TABLE I

Ferrimagnetic Mineral Content by Job Classification

		% Magnetite	S.D	Geom. Mean	Geom. S.D.
All Samples	(2289)	0.46	0.90	0.22	1.22
West VA	(1673)	0.44	0.91	0.20	1.20
Pennsylvania	(616)	0.49	0.87	0.25	1.10
Face Workers	(1707)	0.29	0.39	0.18	0.91
Non-Face	(329)	0.71	1.15	0.33	1.32
Transport	(73)	2.31	2.46	0.61	2.85
Surface	(139)	0.83	1.52	0.26	1.84
Supervisory	(40)	0.80	1.29	0.43	1.05
High Risk	(978)	0.24	0.28	0.16	0.89
Intake Air	(16)	0.61	0.98	0.28	1.26
Face	(711)	0.36	0.48	0.23	0.88
Non-Face	(424)	0.98	1.59	0.37	1.64
Surface	(141)	0.82	1.51	0.26	1.83

can be seen that the magnetite content of respirable coal mine dust is lowest at the face and highest in transportation, with non-face and surface locations having intermediate magnetite levels. Because of the non-gaussian distribution of the data, the geometric S.D. is the best measure of the constancy of magnetite within dust samples from a given job category within the mine.

TABLE II

Retiring Bituminous Coal Miners Study

Code Name	Remanent Field	Years Under	Time Retired	Chest X-Ray**	Smoking Pack-Years
Delbow	279 pT	16	6 Mths	1	0
Xirhen	235	33	9 Mths	2	0
Rayjoh	169	24	3 Mths	2	2
Ewagle	143	39	11 Mths	3	0
Waltyoul	108	36	6 Mths	2	0
Josbaluh	102	29	6 Mths	0	0
Wilshare	88	35	13 Mths	8	3
Samyoul	82	42	6 Mths	0	0
Gerray	74	42	3 Mths	3	5
Fierorga	64	0	5 Mths	1	0
Orlafava	62	40	1 Mth	5	15
Morgeo	55		4 Mths	3	2
Juljesso	54	42	3 Mths	1	1
Jogorohy	52	33	21 Mths	1	2
Mazjoh	51	26	8 Mths	2	0
Robkrich	48	44	6 Mths	3	23
Mikmcke	48	42	9 Mths		0
Paulpetr	48	10	0 Mths	1	1
Henrknig	40	47	3 Mths	3	0
Noacha	40	33	0 Mths	4	6
Jamdevin	39	29	1 Mth	8	0
Koplou	39	41	7 Mths	1	17
Rudmilov	38	44	6 Mths	1	10
Stebasey	37	38	1 Mth	2	10
Frangord	36	35	9 Mths	2	46
Bormik	30	49	2 Mths	6	0
Donashou	29	28	8 Mths	3	0
Vancross	28	13	12 Mths	0	24
Charstre	27	33	6 Mths		11
Simmic	26	42		4	0
Charburk	26	21	3 Mths	1	0
Framayan	25	11	17 Mths		0
Blyken	24	21	0 Mths	2	105
Robcarls	22	15	6 Mths	3	132
Shifor	22	37	3 Mths	5	23
Hajmik	22	32	1 Mth	3	28
Benmik	22	38	7 Mths	2	8
Mckjoh	21	30	7 Mths	0	4
Stevepov	21	41	1 Mth	3	19
Mongeo	21	40	5 Mths	0	28
Donatch	20	40	5 Mths	3	45
Strsta	19	25	7 Mths	2	0
Sharus	17	26	7 Mths	0	13
Richmoro	17	42	0 Mths	2	12
Meageo	16	5	7 Mths	0	9
Giopet	16	32	8 Mths	0	3
Sheste	15	34	7 Mths	2	0
Robebrod	15	31	4 Mths	3	0
Ellihar	12	33	6 Mths	1	10
Chersene	11	36	6 Mths	0	49
Rotjac	10	38	7 Mths	2	11
Andrmcke	9	37	5 Mths	0	9
Johnshab	9	35	2 Mths		26

* Urban control subjects were 20 +/- 19 pT; n = 28.

** Based on a scale of ILO category 1/1 = 3.

interval for urban controls. This is similar to two previously reported groups of workers that we have studied.[4,9] This may be a falsely low prevalence of elevated thoracic FM, as rural dwellers would probably have less FM in their lungs than our urban controls.

The failure of lung FM to be predicted by years underground mining is not surprising. Not only do coal miners have a wide range of past dust exposure levels, but there are individual differences in deposition efficiency and dust clearance kinetics.[11,14,15]

The lack of correlation of lung FM with ILO category of pneumoconiosis is unexpected in view of reported autopsy studies.[16] However, only five of the miners in our study had greater than category 1 abnormality, so the spectrum of coal workers' pneumoconiosis is not adequately represented.

The marked inverse relationship of lung FM to smoking history is most interesting. Decreased alveolar deposition of dust in bronchitic subjects is well known and is thought to be due to airway narrowing and consequent increased deposition in the bronchial tree proximal to the alveoli.[17] This would then represent a sign of airway damage from cigarette smoking, though indices of airway obstruction ($FEV_1/FVC\%$ and maximal voluntary ventilation) were not related to lung FM. There was also no relationship seen of lung FM to subjective symptoms of cough, sputum production or wheezing, though there was correlation with the presence of symptoms of paranasal sinus disease.

Finally, pulmonary function tests were not predictive of FM in the lung, except for the correlation of FM with forced vital capacity as a percent of predicted. The reason for this is unclear, though it may relate to reduction in deposition efficiency of dust in damaged lungs.

Clearance of Lung FM

Lung FM clearance T 1/2 over the first year of observation was 63 +/- 66 months in 19 miners, with seven others having no discernible clearance. This is longer than values from human studies after a single exposure to dust, but we are looking at the final steps of alveolar clearance for dust acquired during the years before retirement.[11,18,19] Our data are consistent with calculations based on autopsy studies,[20,21] and animal data on coal dust clearance.[22] Morrow raised the question of coal mine dust being cytotoxic and impairing its own clearance, but our data in a rat model do not bear this out.[23]

The lung FM clearance T 1/2 based on two years of observation was 115 +/- 93 months in six miners, with seven others having no discernible clearance. This apparent slowing of clearance fits the hypothesized very long phases of alveolar clearance.[15] The lack of correlation of clearance T 1/2 with work history and X-ray abnormality is not unexpected, as there is little physiologic derangement in simple coal workers' pneumoconiosis.[24] Its lack of correlation with cigarette smoking history, respiratory symptoms and pulmonary function tests does not fit with the reported effect of airway obstruction causing slowing alveolar clearance.[4,18,19,25]

Compartmental Analysis of FM Clearance

As can be seen in Table III, clearance from superficial and deep lung regions was slower than from the middle of the lung. This is consistent with the known pattern of dust clearance to subpleural and central lymphatic tissue and was seen in our laboratory studies of magnetite clearance.[11]

Conclusions

1. FM is consistently present in coal mine dust and its concentration is predictable within job categroies.
2. MPG is capable of noninvasively measuring accumulation of lung FM in coal miners, many of whom have higher levels than control subjects.

TABLE III

Compartmental Clearance at 1 Year

Superficial Lung	43 +/- 43 months (n = 12)
Middle Lung	23 +/- 9 months (n = 8)
Deep Lung	44 +/- 39 months (n = 13)

3. MPG is capable of measuring the clearance of lung FM from coal workers.
4. MPG is therefore suitable for the noninvasive monitoring of coal mine dust accumulation of the lung and its clearance.

Acknowledgment

Supported by the ALA of Southwestern Pennsylvania, the Pennsylvania Thoracic Society, Contract 641985 with the Commonwealth of Pennsylvania, and Contract ER60029 with the Department of Energy.

References

1. **Cohen, D. and I. Nemoto:** Ferrimagnetic Particles in the Lung Part I: The Magnetization Process. IEEE Trans. *Biomed. Eng. BME-31*:274-285 (1985).

2. **Bunim, G.:** Magnetic Properties of Mineral Components of Solid Fuels. *Khim. Tverd. Topl.* 2:93-98 (1971).

3. **Kalliomaki, P-L., P.J. Karp, T. Katila et al:** Magnetic Measurements of Pulmonary Contamination. *Scand. J. Work Environ. Health.* 4:232-239 (1976)

4. **Freedman, A.P., S.E. Robinson and F.H.Y. Green:** Magnetopneumography as a Tool for the Study of Dust Retention in the Lungs. *Inhaled Particles V.* Critchlow, Ed. Oxford: Pergamon Press. Ann Occ Hyg. 26:316-335 (1982).

5. **Cohen, D., T.S. Crowther, G.W. Gibbs and M.R. Becklake:** Magnetic Lung Measurements in Relationship to Occupational Exposure in Asbestos Miners and Millers of Quebec. *Env. Res. 26*:535-550 (1981).

6. **Stroink, G., D. Dahn and J. Holland:** Magnetopneumographic Estimation of Lung Dust Loads and Distribution in Asbestos Miners and Millers. *Am. Rev. Respir. Dis. 123 (Part 2)*:144 (1981).

7. **Kalliomaki, P-L., O. Korhonen, V. Vaaranen et al:** Lung Retention and Clearance of Shipyard Arc Welders. *Int. Arch. Occup. Environ. Health 42*:83-90 (1978).

8. **Kalliomaki, P-L., M. Tuomisaari, E-L. Lakomaa et al:** Retention and Clearance of Stainless Steel Shield Gas Welding Fumes in Rat Lungs. *Am. Ind. Hyg. Assoc. J. 44*:649-654 (1983).

9. **Freedman, A.P., S.E. Robinson and R.F. Johnston:** Non-invasive Magnetopneumographic Estimation of Lung Dust Loads and Distribution in Bituminous Coal Workers. J. Occup. Med. 22:613-618 (1980).

10. **Robinson, S.E.:** Non-invasive Imaging of Magnetic Particulate in the Lung and Other Organs. IEEE Trans. *Nucl. Sci. NS-28*:272-274 (1981).

11. **Freedman, A.P., S.E. Robinson and M.R. Street:** Magnetopneumographic Study of Human Alveolar Clearance in Health and Disease. *Inhaled Particles VI.* J. Dodgson and R.I. McCallum, Eds. Pergamon Press, Oxford (In press).

12. **Weast, R.C.:** *CRC Handbook of Chemistry and Physics.* 109 CRC Press, Boca Raton (1981).

13. **Stahlhofen, W., J. Gebhart, J. Heyder et al:** Intercomparison of Regional Deposition of Aerosol Particles in the Human Respiratory Tract and their Long-term Elimination. *Exper. Lung Res. 2*:131-139 (1981).

14. **Albert, R.E. and M. Lippmann:** Factors Influencing Dust Retention in the Pulmonary Parenchyma. *Ann NY Acad Sci 200*:37-45 (1972).

15. **Lauweryne, J.M. and J.H. Baert:** Alveolar Clearance and the Role of the Pulmonary Lymphatics. *Am. Rev. Resp. Dis. 115*:625-83 (1977).

16. **Rossiter, C.E.:** Relation Between Content and Composition of Coal Workers' Lungs and Radiologic Appearances. *Brit. J. Ind. Hyg 29*:31-44 (1972).

17. **Yeates, D.B., T.R. Gerrity and C.S. Garrard:** Characteristics of Tracheobronchial Deposition and Clearance in Man. Inhaled Particles V. Critchlow, Ed. Oxford: Pergamon Press. *Ann Occ Hyg 26*:245-257 (1982).

18. **Bailey, M.R., F.A. Fry and A.C. James:** The Long-term Clearance Kinetics of Insoluble Particles from the Human Lung. *Inhaled Particles V.* Critchlow, Ed. Oxford: Pergamon Press. Ann Occ Hyg 26:273-290 (1982).

19. **Bohning, D.E., H.L. Atkins and S.H. Cohn:** Long-term Particle Clearance in Man: Normal and Impaired. Inhaled Particles V. Critchlow, Ed. Oxford: Pergamon Press. *Ann. Occ. Hyg. 26*:259-271 (1982).

20. **Heppleston, A.G., C.W. Civil and A. Critchlow:** The Effects of Duration and Intermittency of Exposure on the Elimination of Air-borne Dust from High and Low Rank Coal Mines. *Inhaled Particles and Vapours III,* pp. 261-270. W.H. Walton, Ed. London: Unwin (1970).

21. **Stober, W., H.J. Einbrodt and W. Klosterkotter:** Quantitative Studies of Dust Retention in Animal and Human Lungs after Chronic Inhalation. Inhaled Particles and Vapours II, pp. 409-417. C.N. Davies, Ed. Oxford: Pergamon Press (1967).

22. **Morrown, P.E., R.W. Kilpper, E.H. Beiter and F.R. Gibb:** Pulmonary Retention of Neutron Activated Coal Dust. *Arch. Environ. Health 33*:178-183 (1979).

23. **Street, M.R., A.P. Freedman, G. Oberdoerster and F.H.Y. Green:** Clearance of Magnetite Particles from the Lungs of Rats During Exposure to Coal Dust and Diesel Fume. *Proceedings of the Fifth World Conference on Biomagnetism: New York*, pp. 438-442. H. Weinberg, G. Stroink and T. Katila, Eds. Pergamon Press (1985).

24. **Morgan, W.K.C. and N.L. Lapp:** Respiratory Disease in Coal Miners. *Am. Rev. Resp. Dis. 113*:531-559 (1976).

25. **Cohen, D., S.F. Arai and J.O. Brain:** Smoking Impairs Long-term Dust Clearance from the Lung. *Science 204*:514-517 (1979).

Pulmonary Injury in Laboratory Animals Induced by Huai-Nan Coal Mine Respiratory Dust

B.H. CHEN, Z.H. MEN, Y. HUANG, H.Q. MAO and S.Y. WANG
School of Public Health, Shanghai Medical University, Shanghai, China

In recent years there has been increasing interest in the disease mechanism and clinical treatment of silicosis, pneumoconiosis, and silico-pneumoconiosis of miners in China. A lot of *in vivo* and *in vitro* bio-assay methods have been developed to assess the toxicity of various dusts. An *in vitro* method was used by Garrett *et al* to assess the toxicity of coal dust.[1] However, there are still few reports concerning the pulmonary injury induced by coal mine respirable dusts in China. The purpose of this investigation is to assess and compare the toxicity of rock dust and coal dust in an East China coal mine (the Huai-Nan coal mine). Wistar rats and Syrian hamsters were instilled intratracheally with various dusts, their lungs lavaged and the pulmonary damage was evaluated by cellular and biochemical assays of broncho-alveolar lavage (BAL).

Materials and Methods

Collection and Preparation of Samples

Coal dusts and rock dusts were collected in Huai-Nan coal mine at various underground levels, including –410 m (–1,345 ft), –425 m (–1,394 ft), –430 m (–1,410 ft), –480 m (–1,574 ft), –540 m (–1,771 ft), and 9 m (29.5 ft) above ground level. The samples collected from -480 m and -540 m levels were rock dusts and those collected from other levels were coal dusts. The samples were ground, naturally dried and filtered through various meshes. The particulates passing through mesh 110 and mesh 140 were mixed, with their diameters ranging from 0.1–0.15 u. They were used for exposure studies. Saline was used to prepare 0.5 percent dust suspension solution which was sonicated 15 minutes before instillation. After settling in room temperature for 24 hours, the dust suspension solution was centrifuged and the toxicity of dust-free supernatant was assayed. These data were compared with the toxicity of atmospheric suspended particulates collected in Shanghai during this investigation.

Laboratory Animals

Male Wistar rats from the Laboratory Animals Division, Shanghai Medical University and male Syrian hamsters from Shanghai Laboratory Animals Co. were used throughout this study.

Dust Exposure

TABLE I

Cellular and Biochemical Changes in BAL Fluid Induced by Exposure to Coal Dust and Rock Dust (Rats, One Day after Intratracheal Instillation)

	Biochemical Parameters						Cellular Parameters					
	NA (ug/ml)		AkP (King's unit)		AcP (King's unit)		LDH (unit)		Mϕ (10^6)		PMN (%)	
Group	n	$\bar{x}_G$	n	m_d	n	$\bar{x}$	n	m_d	n	$\bar{x}$	n	m_d
Control	14	2.28	14	1.44	1	2.06	14	68.65	14	3.81	14	50
Rock dust	17	3.84	16	2.94	17	3.40	17	127.14	17	2.77	14	85
Coal dust	17	2.70	17	1.11	17	2.07	17	99.78	17	2.82	14	78
Shanghai SP	13	3.63	13	1.55	13	2.83	13	143.87	14	2.19	11	89
Type of test	F		H		F		H		F		H	
P	> 0.05		> 0.05		< 0.05		< 0.05		> 0.05		< 0.05	

* -410 m underground

TABLE II

CTI of Rats Exposed to Coal Dust and Rock Dust (One Day after Intratracheal Instillation)

	AcP		LDH		PMN		
Group	(King's unit)	Number of times over control group	(Activity unit)	Number of times over control group	(%)	Numbe of times over control group	CTI
Rock dust	3.40	1.65	127.14	1.85	85	1.7	5.19
Coal dust*	2.07	1.01	99.78	1.45	78	1.56	2.28
Shanghai SP	2.83	1.38	143.87	2.10	89	1.78	5.15
Control	2.06		68.65		50		

* -410 m undergound.

Laboratory animals were exposed to dust suspension solution of 0.15 ml per 100 gram body weight by a single intratracheal instillation. The exposure dose was 7.5 mg/Kg. Same amount of saline was instilled in the control group.

Cellular and Biochemical Parameters

After anaethesia and exsanguination, the trachea were cannulated and the lungs lavaged with saline. BAL were pooled together and the following parameters measured: the number of pulmonary macrophages, cell differential counting, the activities of lactate dehydrogenase (LDH), acid phosphatase (AcP), alkaline phosphatase (AkP), and the amount of neuraminic acid (NA) in cell-free supernatant.

Data Analysis

All data were examined for their data distribution and homogeneicity and the difference tested for statistical significance by using the F or H test.

Results

The Comparative Toxicity of Rock Dust and Coal Dust in Huai-Nan Coal Mine

The comparative toxicity of rock dust and coal dust in Huai-Nan coal mine is shown in Table I. It can be readily

TABLE III

The Comparative Toxicity of Shanghai SP, Coal Dust and Dust-free Supernatant (Hamsters, One Day after Exposure)

	Biochemical Parameters						Cellular Parameters					
	NA (ug/ml)		AkP (King's unit)		AcP (King's unit)		LDH (unit)		M (10^6)		PMN (%)	
Group	n	x	n	x_G	n	x_G	n	x	n	x	n	m_d
Control	5	1.32	5	3.48	6	1.23	6	44.41	5	3.70	5	4
Shanghai SP	6	3.09	5	4.83	6	3.66	6	83.54	6	7.64	6	85.5
Coal dust	10	2.08	11	6.18	11	3.61	11	69.90	12	5.41	11	76
Supernatant	9	1.45	10	3.14	11	1.76	11	59.02	11	6.73	10	85
Type of test	F		F		F		F		F		H	
P	> 0.05		> 0.05		< 0.05		< 0.05		> 0.05		< 0.05	

seen that there were significant differences in LDH, AcP and polymorphonuclear neutrophils (PMN) between exposure groups and the control group: LDH, $H = 19.137$, $p < 0.05$; AcP, $F = 3.238$, $p < 0.05$; PMN, $H = 21.105$, $p < 0.05$.

LDH is a cytoplasmic enzyme. The release of LDH into the extracellular supernatant of BAL has been broadly used as a measure of cell damage and lysis. As LDH is exhibited in all kinds of cells, increased extracellular LDH in BAL is a nonspecific measure of cell injury and death.

Acid phosphatase is a lysosomal enzyme which is released from cells during phagocytosis, cell injury or cell death. PMNs, macrophages, and type II cells all contain acid phosphatase. Alkaline phosphatase, a plasma membrane-associate enzyme, can be found in BAL from rabbits[2] and hamsters.[3] Alkaline phosphatase could be a useful marker for type II cell injury, especially since it is present at much lower levels in alveolar macrophages. In this investigation, no significant difference was found among exposure groups and the control group.

Comparing the relations between the LDH activity and the counting of PMN, the correlation is significant ($r = 0.95$, $t = 4.32$, $p < 0.01$).

In order to evaluate the general influence of dust exposure, we recommend the use of the cell toxicity index (CTI). CTI is the product of the number of times of meaningful parameters for treated groups compared against controls (LDH, AcP and PMN in this case). The CTI for rock dust and Shanghai SP is 5.19, 2.28 and 5.15 respectively (Table II). Thus the toxicity of rock dust is 1.3 times higher than that of coal dust, and is similar to that of Shanghai SP.

The Comparative Toxicity of Coal Dust Suspension Solution and Dust Free Supernatant

The toxicity of coal dust was evaluated by analysis of components in lavage fluid, as shown in Tables I and II. In order to clarify whether the toxicity was due to dust particle itself or due to substances dissolved in saline, the toxicity of coal dust suspension solution and dust-free supernatant was compared. The results show that the pulmonary injury induced by coal dust suspension solution is more serious than that induced by dust-free supernatant (Table III). The toxicity of coal dust suspension solution comes mainly from the particulate itself. The dust-free supernatant did not induce cell injury, but could induce the PMN influx *in situ*. Whether there is any chemotaxis substance in the supernatant, still needs to be studied.

The Comparative Toxicity of Coal Dust Collected at Various Underground and Ground Levels

The results show that there is no significant difference among the toxicity of coal dust at various underground and ground levels (Table IV).

Discussion

The Comparative Toxicity of Coal Dust, Rock Dust and Shanghai Suspended Particulates

The results presented in this paper show that the toxicity of rock dust in Huai-Nan coal mine is similar to that of atmospheric suspended particulates in Shanghai, but is much higher than that of coal dust in the same mine. The difference in toxicity of various dusts is mainly due to the components of respective dusts. The silica content in rock dust amounts to 65 percent. Silica is well-known as a strong fibrogenic and cytotoxic material. According to Lehtimen,[4] three weeks after a single intratrachel exposure of 50 mg of SiO_2, leads to experimental silicosis. Thus, it is quite apparent that the amount of free silica in rock dust has practical hygienic significance.

On the other hand, the main component of coal dust is carbon which can only induce mild pulmonary fibrosis and simple pneumoconiosis. The three chief sources of atmospheric suspended particulates in Shanghai are coal combustion, industrial air pollution and street dust suspended in the air. The component of Shanghai suspended particulates is highly complex and the toxicity of coal combustion particulates is relatively high. Chen showed that the toxicity of par-

TABLE IV

The Comparative Toxicity of Coal Dust Collected at Various Underground Levels (Rats, One Day after Exposure)

	Biochemical Parameters						Cellular Parameters					
	NA (ug/ml)		AkP (King's unit)		AcP (King's unit)		LDH (unit)		MΦ (10^6)		PMN (%)	
Group	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$
9 m	8	2.56	8	3.79	8	2.14	8	95.62	8	2.31	7	75.4
- 410 m	8	3.38	8	4.01	8	2.04	8	98.33	8	2.25	8	79.4
- 425 m	7	2.82	6	3.38	7	2.10	7	89.80	7	1.76	7	64
- 430 m	8	3.18	8	4.64	8	2.06	8	103.79	8	2.68	8	72.8
P	> 0.05		> 0.05		> 0.05		> 0.05		> 0.05		> 0.05	

ticulates from coal combustion is higher than the toxicity of suspended particulates from other origin.[5,6]

BAL — A Useful Tool in Inhalation Toxicology

During the last decade, BAL has been used increasingly to assess lung injury.[7,8] The lavage fluid contains both cells and molecules harvested from airway and alveolar lining fluids. BAL is a way to biopsy the extensive surfaces of the respiratory tract, all of the surface in a lobe or lung is sampled. The average response of the entire lung can easily be described. However, there is little information regarding the particular area injured. BAL has been employed to discriminate among toxic agents such as metal salts or mineral dusts. BAL has been used as a useful tool in inhalation toxicology and an important complement to histopathologic analysis and pulmonary function in animal studies.

In this investigation, BAL is used as a technique for evaluating the response to coal dust and rock dust exposure. Combined with the cell toxicity index (CTI) developed in this paper, BAL can differentiate not only the comparative toxicity of various dusts, but can also be used to quantitatively assess the general toxicity of respective dusts.

Summary

An *in vivo* short-term bio-assay was developed to assess the pulmonary injury of coal dust and rock dust in Huai-Nan coal mine. Dust suspended in saline and dust-free supernatant were instilled intratracheally to Wistar rats and Syrian hamsters. Saline was used in treating controls. The animals were sacrificed 24 hours after treatment, their lungs lavaged, and the pulmonary damage was evaluated by cellular and biochemical assays of lavage fluid.

Pulmonary injury was expressed by cell toxicity index (CTI). CTI is the product of the number of times of meaningful parameters for treated groups compared against controls (LDH, acid phosphatase and polymorphonuclear neutrophils in this case). The CTI were found to be 5.19, 2.28 and 5.15 for rock dust, coal dust and Shanghai suspended particulates respectively. The toxicity of rock dust is much higher than that of coal dust, but is similar to that of Shanghai suspended particulates. The cell toxicity of dust suspension solution is higher than that of dust-free supernatant. CTI can be used as an indicator of the relative toxicity of respirable dusts in *in vivo* studies.

References

1. **Garrett, N.E., J.A. Campbell and H.E. Stack:** The Utilization of the Rabbit Alveolar Macrophage and Chinese Hamster Ovary Cell for Evaluation of the Toxicity of Particulate Materials. II. Particles from Coal-related Processes. *Environ. Res. 24*:366-376 (1981).

2. **Reasor, M.J., D. Nadean and G. Hook:** Extracellular Alkaline Phosphatase in the Rabbit Lung. *Lung 155*:321-335 (1978).

3. **Mao, H.Q. and B.H. Chen:** Determination of Normal Value of Biochemical Components in Pulmonary Macrophages and Cell-free Lung Lavage Fluid of Laboratory Animals. *Acta. Acad. Med. Xinjiang 8(2)*:174-177 (1985).

4. **Lehtimen, P., S. Aho. and E. Kulonen:** Effect of Silica on the Rat Lung with Special Reference to RNA. *Ann. Occup. Hyg. 27(1)*:81-87 (1983).

5. **Chen, B.H. and Z.H. Men:** Pulmonary Toxicity Induced by Air Suspended Particulates in Different Areas of Shanghai. *Pub. Health Dis. Control 3(2)*:2-8 (1984).

6. **Huang, Y. and B.H. Chen:** Study on the Health Effects on Laboratory Animals Induced by Smoke Due to Coal Combustion. *Acta Academiae Primae Medicinae Shanghai 12(2)*:223-226 (1985).

7. **Chen, B.H.:** The BAL (broncho-alveolar lavage) Assay -- A Methodology Approach in the Study of Maximum Allowable Concentrations of Air Pollutants. *Annual Review on Hygienic Standards*, Vol. I, pp. 60-66. Shanghai (1984).

8. **Witschi, H.P. and J.D. Brain:** *Handbook of Experimental Pharmacology, Vol. 75*, pp. 203-226. Springer-Verlag Berlin Heidelberg (1985).

CHARACTERIZATION I

Standard Respirable Dusts

T.F. DUMM and R. HOGG
Mineral Processing Section, Department of Mineral Engineering, The Pennsylvania State University, University Park, PA 16802

There is a considerable need for standardized respirable dusts with consistent, reproducible characteristics which simulate those of actual mine dust. The availability of such materials should be a significant factor in promoting coordinated research into dust characterization and mine monitoring, dust control, and the biomedical aspects of dust toxicology. The use of an opposed-jet, fluid-energy grinding system in closed circuit with a cross-flow, centrifugal air classifier for preparing bulk quantities of respirable-size dust has been investigated, and appropriate, standardized procedures have been established. By stage-crushing, screening, and fine-grinding with a Donaldson Acucut classifier/mini-grinder system, it is possible to produce bulk quantities of respirable dust at relatively high rates. Using minor modifications to the system, broader or narrower size distributions can be prepared within the respirable range. The system has been shown to reach steady-state with respect to product size distribution very rapidly. However, preferential grinding/classification effects appear to lead to a slow build-up of mineral matter in the circulating load with a corresponding slow change in product composition with time. In those applications where the dust composition is required to match that of the feed coal, it may be necessary to allow considerable time for a true steady-state to be established.

Standard respirable dust samples have been prepared from coals representing the western (high volitile A bituminous), central (medium volatile bituminous) and eastern (anthracite) mining areas of Pennsylvania. Quartz and kaolin clay samples, representing important mineral constituents of coal dust have also been prepared. Extensive characterization studies have been performed on the samples to evaluate chemical and mineralogical composition and the distributions of particle size and specific gravity. Detailed information on the original coals is available from the Penn State Coal Data Base. The standard coal dust samples appear to simulate actual mine dust very well with respect to particle size and shape, but generally have somewhat lower ash content. Samples of these standard dusts have been made available to research groups concerned with respirable dust in mines.

Introduction

Recently, there has been a large coordinated effort in research into finding the causes of Coal Workers' Pneumoconiosis and seeking remedies for it. There is a considerable need for standardized respirable dusts with consistent, reproducible characteristics which simulate those of actual coal mine dusts and can be made available for coordinated research on dust characterization and mine monitoring, dust control, and the biomedical aspects of dust toxicology.

The aim of the work described in this paper was to develop standardized procedures for producing bulk quantities of respirable dust at relatively high rates and to prepare and characterize a variety of such dusts, representing different coal seams and associated minerals.

Preparation of Standard Dusts

Grinding System

The process adopted in this study to produce the standard dust samples uses the Donaldson Acucut Classifier (Donaldson Co., Majac Division, St. Paul, Minnesota), shown in Figure 1, with an auxiliary jet mill grinding attachment. The classifier is a cross-flow device in which large volumes of air are brought through a centrifugal field containing air-entrained particles. Particles are separated on the basis of their aerodynamic diameter into a coarse fraction and a fine fraction with the separation size, or cut size, being determined by the force of the centrifugal field and the quantity of air flowing through the field.

The powder to be ground is fed into the system through a feeder/splitter apparatus as shown in Figure 2. The split stream of air and particles enters a grinder through two hoses connected to opposite ends of the mill. Powder at both ends of the mill then mixes with two opposing high-pressure air streams inside the mill and is comminuted as the particles collide with each other and with the mill surfaces. A pressure drop created by the aspirating action of the high pressure jets inside the mill provides the energy for air/particle flow from the feeder/splitter. All particles then leave the mill and enter the Acucut Classifier at which point particles finer than the desired top size, are separated from the coarser material. The fine powder is collected using an air cyclone to remove the particles from the classifier overflow airstream. The coarse particles are ejected from the classifier and flow into the feeder/splitter assembly, mix with newly introduced powder and return to the jet mill.

The principal advantages of the Donaldson system for preparing standard dusts are that:

1. The process is a continuous, closed-circuit operation combining grinding and classification and is capable of producing dust at reasonably high rates. Fresh coal feed rates up to 3 g/min can be used so that a 500 g sample can be prepared in less than three hours.
2. The maximum particle size in the product can readily be controlled, in the range 1 to 30 um, through the classifier setting.
3. Since grinding is largely by particle impact, contamination of the product can be minimized.

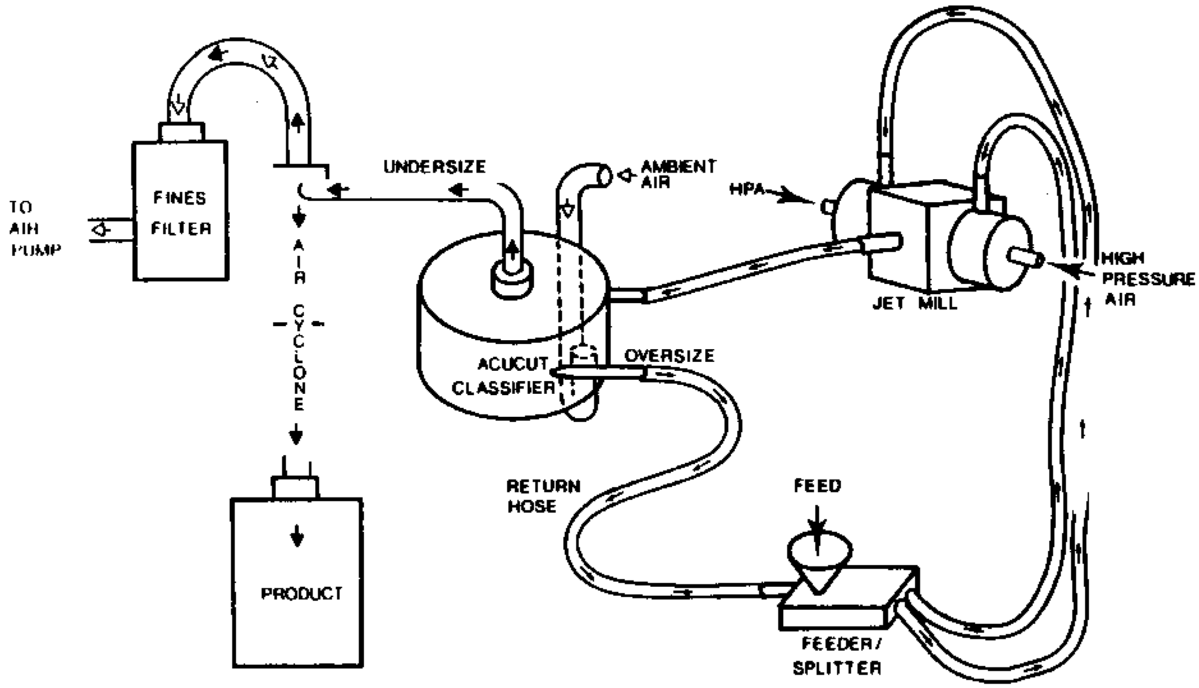


FIGURE 1. Diagram of Donaldson Acucut Classifier with auxiliary jet mill grinding attachment.

4. Since the product is separated on the basis of an aerodynamic particle diameter, it should be possible to simulate airborne dust in mines.

The major disadvantage of the system is that selective grinding and/or classification can lead to concentration of specific organic or inorganic components.

Materials

Standard dusts were prepared from several coals, representing the western, central and eastern mining areas of Pennsylvania, and also from quartz and kaolin clay which are important mineral constituents of coal mine dust. The coals are listed in Table I. The coal designated MP3 was used largely for preliminary test work etc., and was selected on the basis of immediate availability in the laboratory. The PSOC coals were obtained from the Penn State Coal Data Base and were originally collected as channel samples. Detailed information on these coals is given in Appendix A. The kaolin clay was obtained from the Georgia Kaolin Co., Dry Branch, Georgia, and the quartz was obtained from the Ashibor Quarry, Staley, North Carolina.

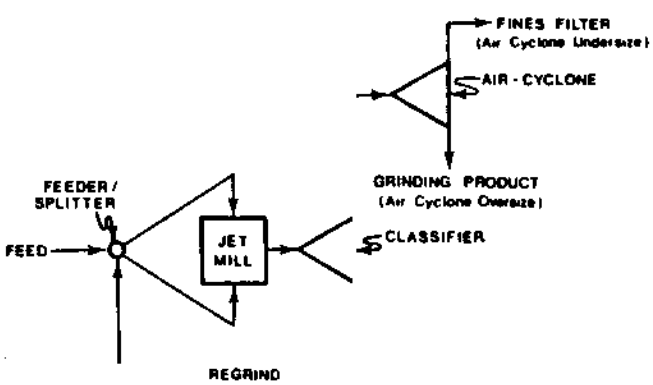


FIGURE 2. Schematic diagram of grinder/classifier system.

FIGURE 3. Schematic diagram of modified grinder/classifier system used for preparation of dusts with broad size distributions (MP3-3, PSOC 1192M).

Procedures

Because of the coarse size of the as-received coal (approximately 50% > 4 mesh) the grinding to respirable size had to be performed in stages. For the initial crushing of all four coals, a Model 4-E Quakertown Mill (coffee grinder) was used. The grind setting was adjusted so as to produce the finest product possible which was typically 80 percent passing 70 mesh and all of the approximately 2500 g of each of the coal samples were ground. This material was then screened in 100-200 g increments using a Tylab Sieve Shaker to remove particles larger than 75 um (half the recom-

TABLE I

Coals Used in These Investigations

Coal Designation	Seam	Seam Location, County	ASTM Rank
MP3	U. Freeport	Armstrong	High Vol. A Bit.
PSOC 1192	L. Kittanning	Clearfied	Medium Vol. A Bit.
PSOC 1361P	U. Freeport	Lawrence	High Vol. A Bit.
PSOC 867	Primrose	Schuylkill	Anthracite

mended top size for the fine grinding). This screened undersize product was ready for fine grinding. The quartz needed no initial crushing, but was prepared for fine grinding by placing about 150 grams into a ceramic Abbe ball mill and grinding for 1 hour and screened to remove the +75 um particles. The kaolin clay required no crushing or fine grinding because the as-received material was already mostly of respirable size.

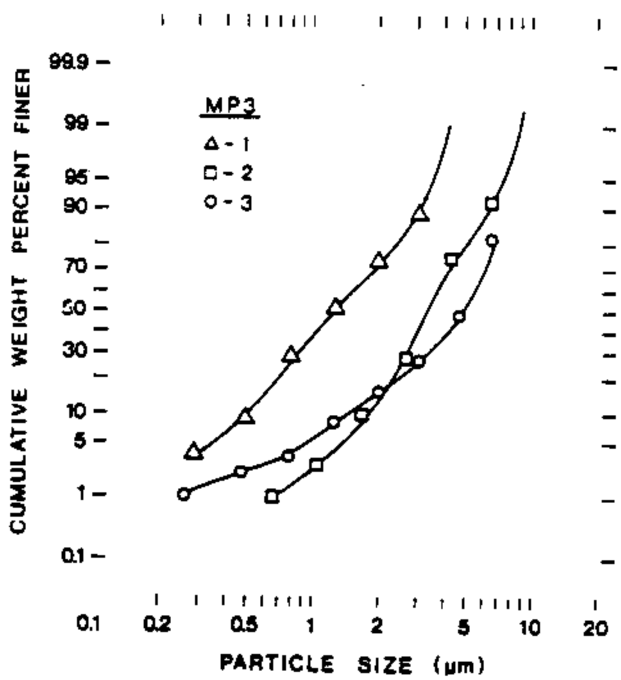


FIGURE 4. Size distributions of respirable dusts as determined by centrifugal sedimentation. MP3-1: air cyclone undersize; MP3-2: air cyclone oversize; MP3-3: air cyclone bypass.

The grinding to produce respirable-size coal or quartz dust was carried out using the Donaldson grinding/classification system described previously. Operation was essentially according, to the manufactures instructions,[1] except that the high pressure air was at about 40 psig rather than 100 psig as recommended, since the higher pressures were not available, at sufficient volume, in our laboratories. The principal effect of the reduced pressure is to lower the system capacity. It is not believed to have significant effects on the overall product size distributions.[2]

The grinding/classification system, actually involves two-stage classification shown in Figure 2. The second stage, the air cyclone, is intended for gas-solid separation, but some size classification is probably inevitable. In order to investigate the influence of the air cyclone on product characteristics, three different circuit configurations were used for grinding of the MP3 coal. This was done by collecting the Acucut classifier undersize stream at the air cyclone inlet, oversize and undersize, (see Figure 2). Collecting the air cyclone oversize and undersize were straightforward. The oversize material falls into a collection jar as the grinding product and was designated MP3-2. The air cyclone undersize material leaves the air cyclone through the vortex finder and enters into a cylindrical, low pressure, high surface area filter where the fine particles become trapped. The fines filter was removed from the machine after grinding, and a snug-fitting collection container was placed around the open end of the filter. High-pressure air was blown through the

TABLE II

Reproducibility of Standard Dust Preparation with Respect to Particle Size Distribution (PSOC 1192)

Upper Limit of Size Interval (um)	Weight Percent in Sample 1 (Nov. 84)	Weight Percent in Sample 2 (June 86)
42.21	0.0	0.0
29.85	0.0	0.0
21.10	0.0	0.0
14.92	0.6	0.0
10.55	4.6	3.7
7.46	24.9	20.9
5.27	30.1	30.5
3.73	18.7	22.0
2.63	10.4	11.4
1.69	5.3	5.8
1.01	3.2	3.4
0.66	1.1	1.2
0.43	0.4	0.5
0.34	0.2	0.2
0.24	0.0	0.0
0.17	0.0	0.0
Mass Median Size:	4.26 um	3.99 um

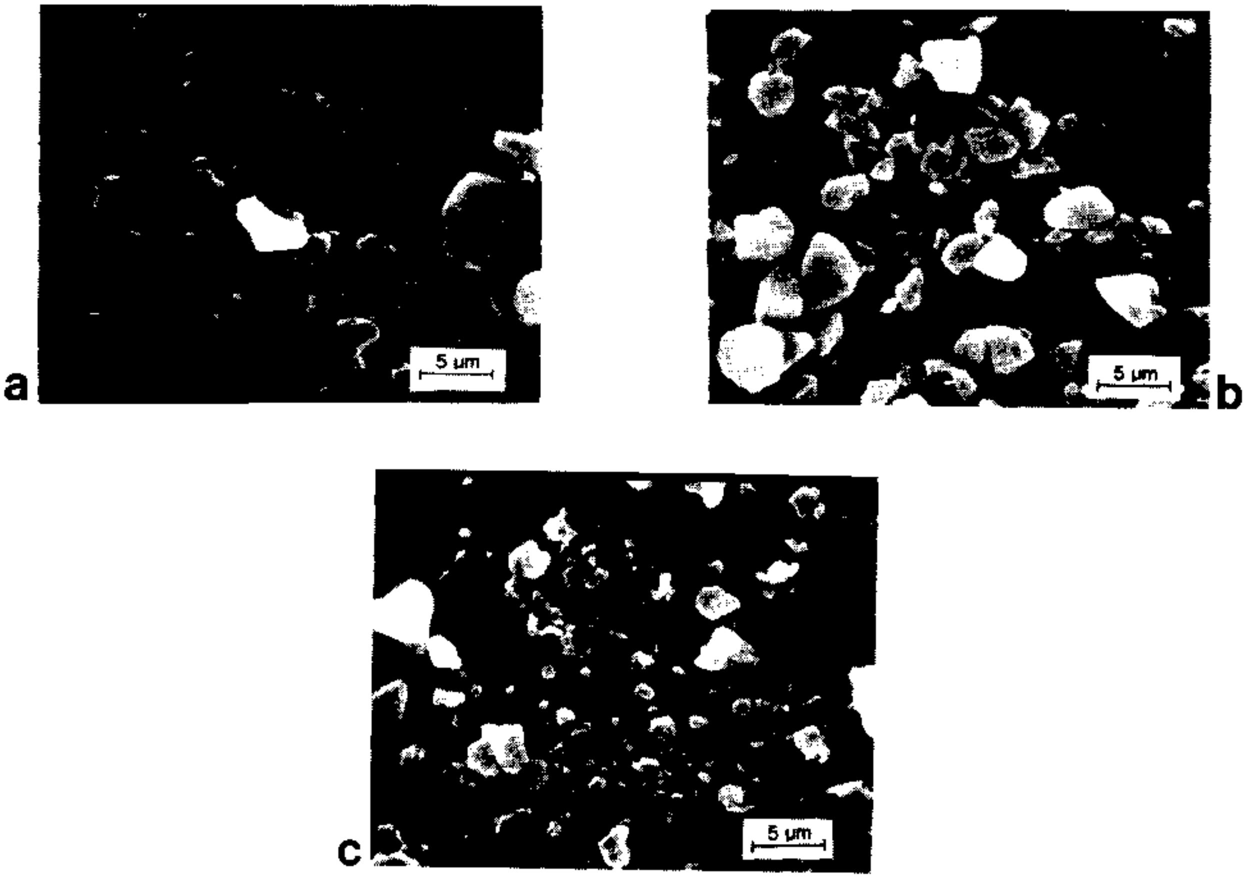


FIGURE 5. Scanning electron micrographs of a) air cyclone undersize (MP3-1) particles, b) air cyclone oversize (MP3-2) particles and c) air cyclone bypass (MP3-3) particles.

clean side of the filter forcing the fine coal particles to fall into the collection container. It was not possible to remove all of the particles from the filter by this technique; usually about 70 weight percent were collected and these were assumed to be representative of the total amount. The particles not collected from the filter remained trapped within the depth of the filter's fibers. The coal sample collected by this procedure was labeled MP3-1. The modified classifier/grinder was then operated at the same conditions to achieve a cut size of 5 um using MP3. When grinding was finished, the filter was removed and the coal sample was collected in the same way as MP3-1. This sample of coal was designated MP3-3. It was assumed that this product has the same properties as the air cyclone inlet, which requires that the classifier performance does not change when the air cyclone is not in place. Figure 3 shows the modified system.

Characterization of Standard Dusts

The standard respirable dusts have been characterized in terms of overall particle size distribution, size-specific gravity distribution, ash content and chemical and mineralogical composition.

Procedures

Particle size distributions were determined by centrifugal sedimentation using a Ladal pipet centrifuge[3] and by light scattering using a Leeds and Northrup Microtrac Small Particle Analyzer. Dumm[4] has investigated the correspondence between these two techniques and demonstrated that the results are quite consistent and can be inter-converted using a simple conversion factor.

Specific gravity distributions were evaluated by sink-float analyses in heavy liquids, using centrifuges. The procedure has been described in detail by Dumm.[4]

Ash analyses were performed by conventional high-temperature methods[4] and also by means of a Branson/IPC Low Temperature Asher.

Chemical (elemental) and mineralogical analyses were carried out by the Mineral Constitution Laboratory at Penn State. Elemental analyses were by plasma arc emission spectrometry and the mineralogical composition was determined by pressed KBr pellet infrared spectroscopy and powder X-ray diffraction techniques.

Results

Evaluation of the Grinding/Classification System

The effects of the air cyclone on the final product size distribution are shown in Figures 4 and 5. The normal circuit product, the cyclone oversize, (MP3-2) has the coarsest, narrowest size distribution, with very little submicron material. Apparently, the cyclone does indeed classify the dust, preferentially removing fine particles. As expected, the cyclone undersize contains the finest material (MP3-1), while the cyclone by-pass (MP3-3), which is intended to represent the feed to the cyclone, has the broadest distribution,

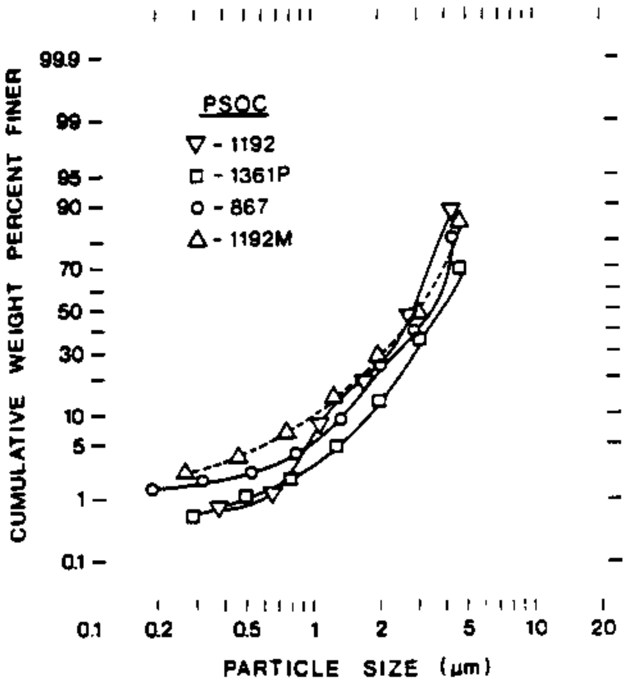


FIGURE 6. Size distributions of standard respirable dusts as determined by centrifugal sedimentation.

being a combination of the other two products. It is apparent that these different circuit configurations can be used to prepare different size distributions, in the respirable range, from the same starting material. The cyclone by-pass arrangement has been used to prepare a modified dust from PSOC 1192 coal. This modified dust has been designated PSOC 1192 M.

Reproducibility of the Dust Preparation

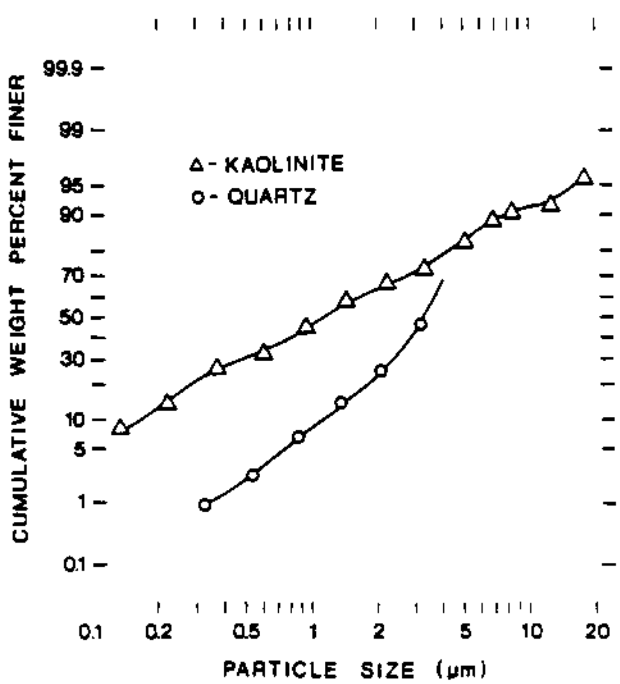


FIGURE 7. Size distributions of kaolinite and quartz standard respirable dusts as determined by centrifugal sedimentation.

For the standard respirable dusts to be useful in dust research, it is vital that the procedure used in their preparation be highly reproducible. An example of the reproducibility is given in Table II, in which the size distribution of a dust prepared in November 1984, is compared with that of a second sample prepared in June 1986 from the same coal. It is clear from the results that the differences are quite small, essentially within experimental error, and that the procedure is indeed reproducible.

Particle Size Distribution

The particle size distributions of the standard dusts are shown in Figures 6 and 7. The three standard coal samples

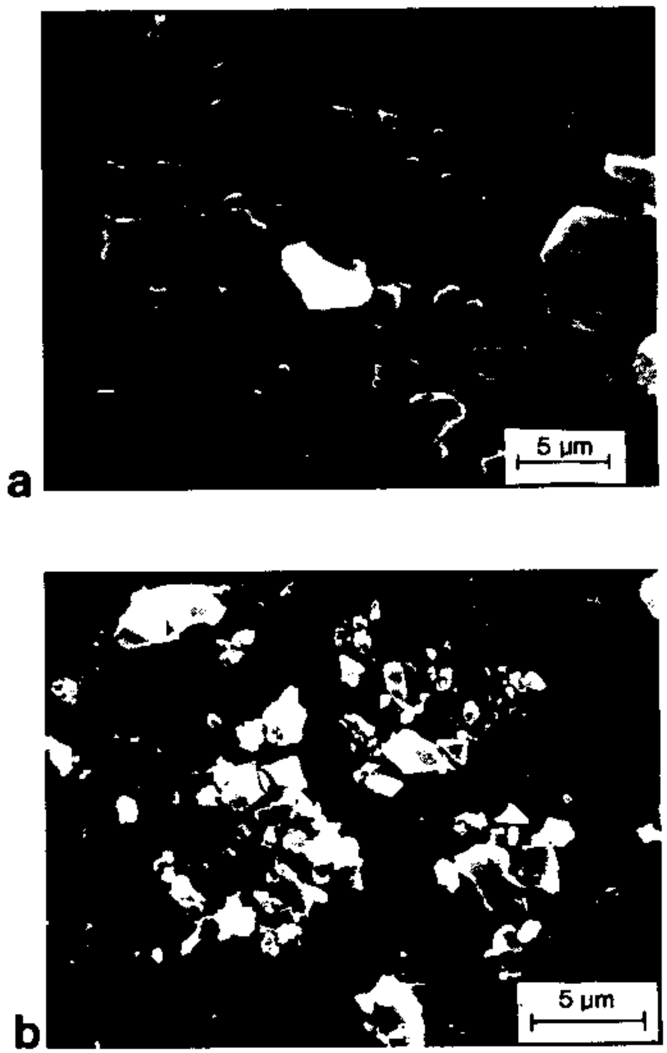


FIGURE 8. Scanning electron micrographs of a) standard respirable dust from Upper Freeport seam and b) actual coal mine dust from Brookville seam.

have similar distributions to one another and to sample MP3-1 (see Figure 4) sample PSOC 1192M has a somewhat broader size distribution, containing more submicron material, and is generally similar to MP3-1. The size distributions for the two mineral samples are shown in Figure 7. The distribution for quartz is quite similar to those for the coals.

The kaolin clay has a much broader size distribution and contains considerably more very fine particles than the other materials. This particular dust was not processed in any way

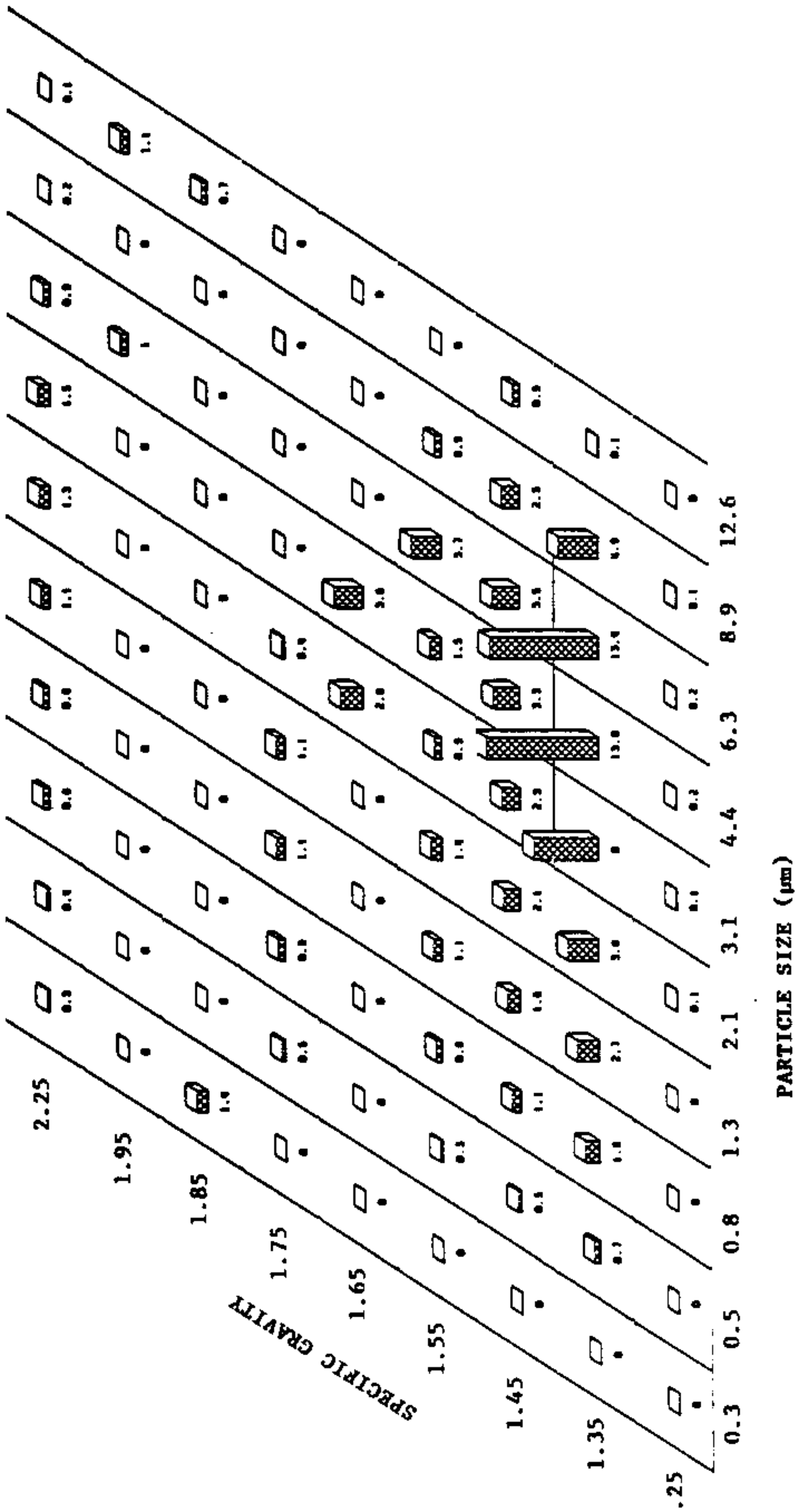


FIGURE 9. Size-specific gravity distribution of standard respirable dust PSOC 1192M.

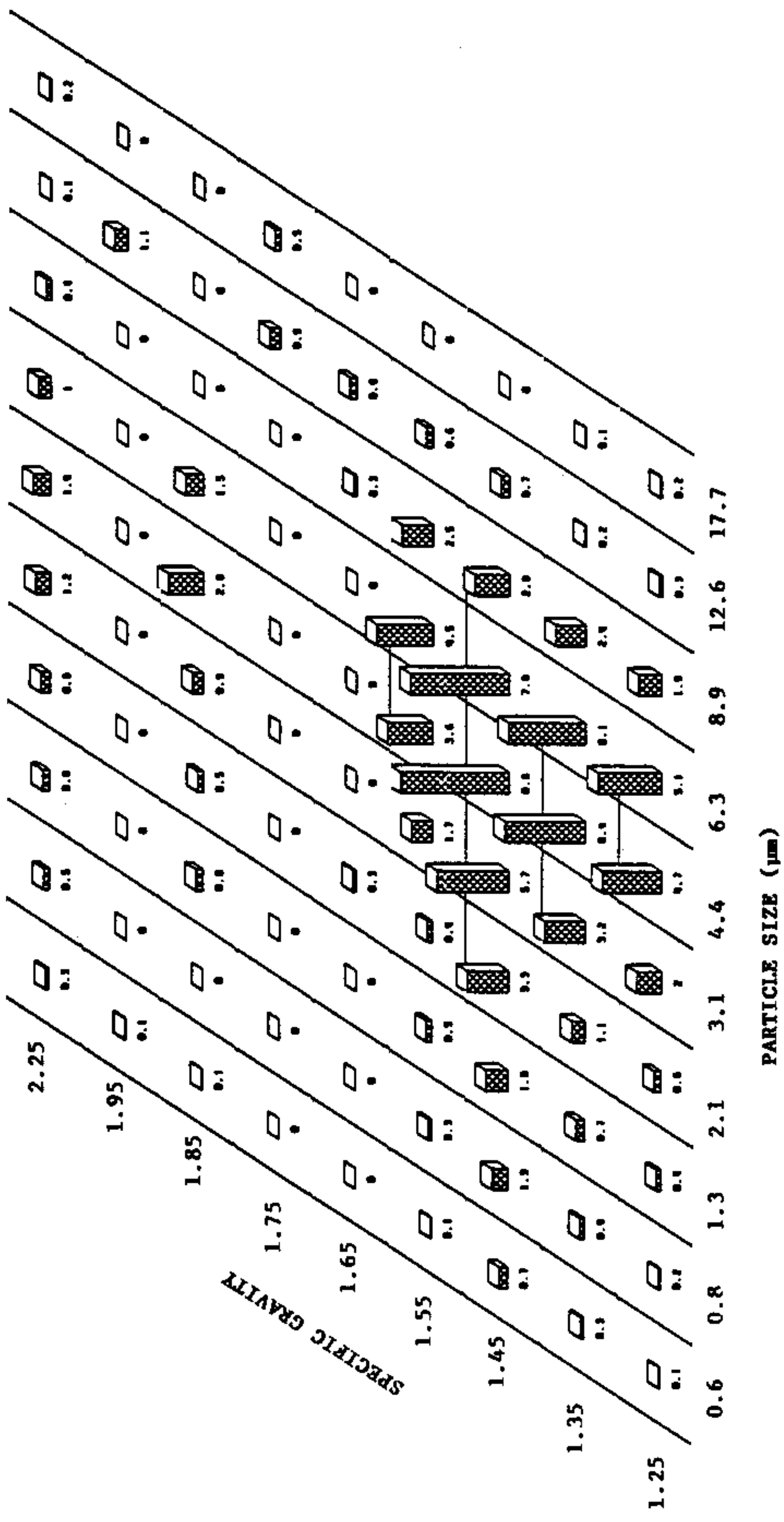


FIGURE 10. Size-specific gravity distribution of standard respirable dust PSOC 1361P.

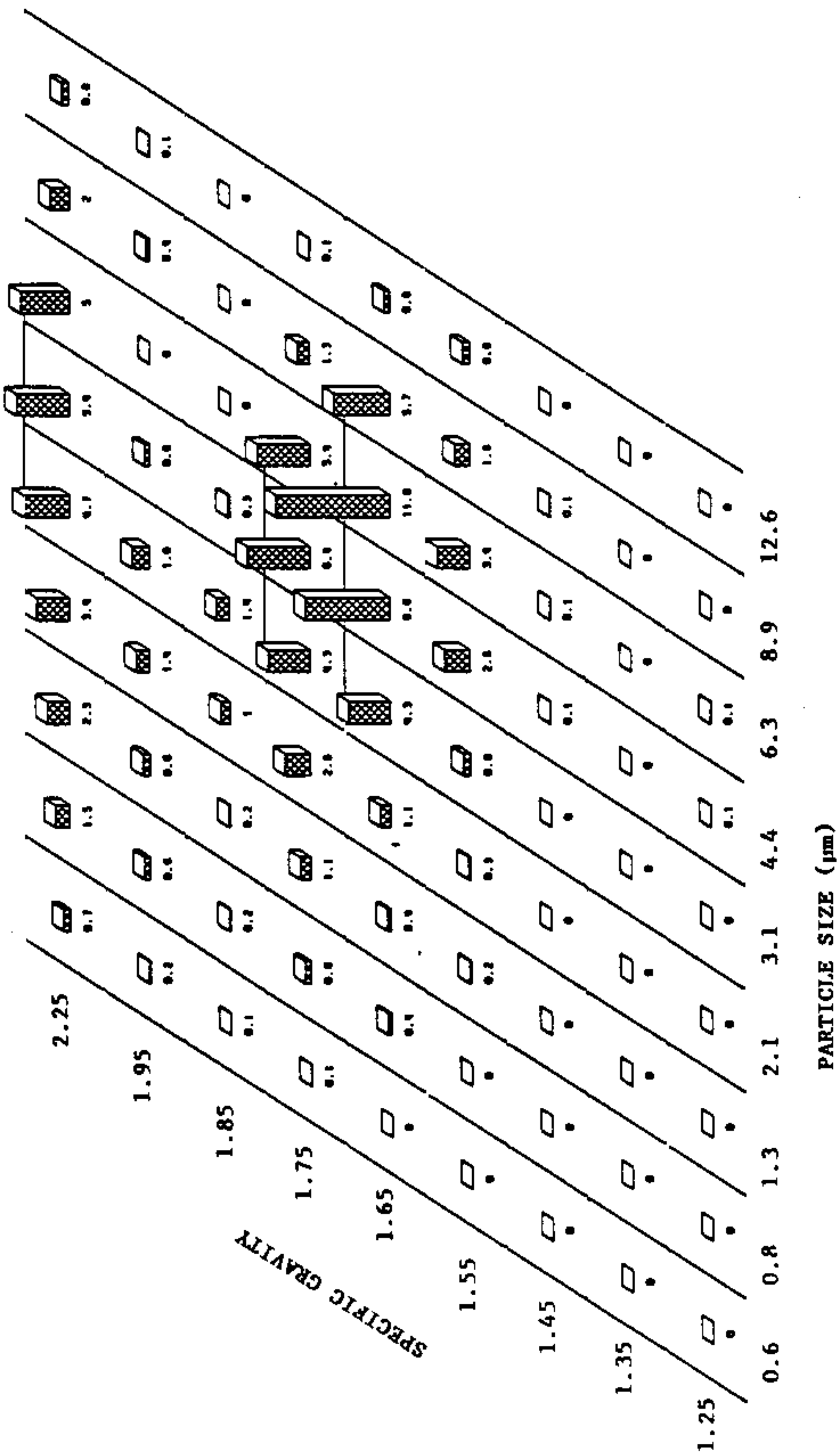


FIGURE 11. Size-specific gravity distribution of standard respirable dust PSOC 867.

and was used simply as-received. It should be emphasized that the mineral dusts were not intended to be directly representative of the mineral constituents in actual mine dusts.

A comparison of one of the synthetic dusts (MP3) with a sample of actual mine dust is shown in Figure 8. There appear to be no noticeable differences in particle size and shape between the two, indicating that the synthetic dusts may indeed be appropriate for research into coal mine dust and Coal Workers' Pneumoconiosis.

Particle size-specific gravity distributions for the PSOC 1192M, PSOC 1361P and PSOC 867 dusts are shown in Figures 9-11. The three distributions are distinctly bimodal, consisting of relatively clean coal (specific gravity < 1.7) and a very high ash fraction (specific gravity > 2). In other words, the dusts show a high degree of liberation between the organic material and mineral matter, as would generally be expected at such fine sizes. It can also be seen from the figures that the mineral matter tends to be slightly finer than the organic material.

Ash Content

The results of ash analyses on the standard respirable coal dusts and the corresponding feed coals are shown in Table III. It is clear that there is considerable discrepancy between the feed and the dust in each case. For the bituminous coals,

TABLE III

Ash Contents of Feed Coals and Corresponding Respirable Dusts

	Percent Ash	
Coal	Feed	Respirable Dust
MP3-2	7.99	6.74
PSOC 1192	10.93	7.20
PSOC 867	12.65	21.2
PSOC 1361P	7.77	6.27

the ash content of the dust is significantly lower than that of the original coal. It appears that the mineral matter does not break as rapidly as the organic coal constituents. This results in a larger than average amount of mineral particles remaining in the circulating load of the classifier/grinder system and a lower than average amount reporting to the respirable product container. For the anthracite, the opposite phenomenon is seen. The higher ash content of this respirable product compared to the feed is probably due to a large amount of very small clay particles that are already less than respirable size within the feed. These particles would pass immediately to the respirable product container along with a lower than average amount of comminuted organic particles. Given sufficient time, of course, the system should eventually reach a steady-state with the composition of the product identical to that of the feed. However, further experimentation has shown that the approach to such a steady-state is very slow. It is possible that this is a consequence of the reduced air pressure used in the grinding system.

Composition

Chemical and mineralogical analyses have been performed on each of the standard dusts.[5] The results are given in Appendix B.

Summary

By stage-crushing, screening, and fine grinding with the Donaldson Acucut classifier/grinder, it is possible to produce bulk quantities of respirable dust in relatively short periods of time. With certain modifications to the classifier/grinder, it is possible to produce different size distributions of a feed material without changing the top size of the products. The technique has been shown to be very reproducible as far as size distribution is concerned.

Although it appears that the product size distribution from the classifier/grinder reaches steady-state quickly, the composition does not. Differences in ash content between the feed coal and respirable coal dust product from the Donaldson Acucut classifier have been observed. These differences are attributed to differing breakage rates between the mineral and organic constituents of the coal. In addition, since the Acucut classifier is density dependent the varying densities between coal constituents will also contribute to differences in ash between the feed and product. If it is important that the composition of the standard respirable dust match the coal seam, or feed composition, considerably more time may be required to produce a standard respirable dust.

Standard dusts have been prepared from three different Pennsylvania coals and two minerals, quartz and kaolin, commonly associated with coal. Samples of these dusts can be made available for research. Their characteristics are listed in Appendix B.

Acknowledgments

The work described in this paper was supported by the Mineral Institutes program by Grant No. G1135142 from the Bureau of Mines, U.S. Department of Interior, as part of the Generic Mineral Technology Center for Respirable Dust.

References

1. *Instruction Manual*, Donaldson Acucut Classifier. St. Paul, Minnesota (1978).
2. Personal Communication, Donaldson Corp., November (1983).
3. Allen, T.: *Particle Size Measurement*, 3rd Edition. Chapman and Hall (1981).
4. Dumm, T.F.: *An Evaluation of Techniques for Characterizing Respirable Coal Dust.* M.S. Thesis, The Pennsylvania State University (1986).
5. *ASTM Annual Book of Standards*, Designation D3174 (1982).

APPENDIX A

Characteristics of Coals Used to Prepare Standard Dusts

Coal Identification: MP3

Coal Seam: Upper Freeport

Location: Plumcreek Township
Armstron County, PA
Mine: Margaret No. 11

Collection: Hand-mined channel sample from freshly prepared face. Sealed in plastic-lined burlap bags. Returned to the laboratory at University Park.

Collection Date: September 27, 1979.

** PENN STATE COAL DATA BASE **

```
******************
*                *
* SAMPLE HISTORY *
*                *
******************
```

PENN STATE NUMBER	PSOC-1192
COLLECTED BY	PENNSYLVANIA STATE UNIVERSITY
COLLECTION DATE	10/16/79
COLLECTOR'S NUMBER	1192
REPORTED RANK	
SAMPLE TYPE	CHANNEL WHOLE SEAM
OTHER SAMPLE INFORMATION	
SAMPLE RESERVE	150
SEAM NAME	LOWER KITTANNING
ALTERNATE SEAM NAME	B SEAM
TOTAL SEAM THICKNESS	1 FT. 10 IN.
THICKNESS OF SEAM SAMPLED	1 FT. 10 IN.
PORTION RECOVERED IN CORE	
DIAMETER OF CORE	

SEAM NAME LOWER KITTANNING
APPARENT RANK MEDIUM VOLATILE BITUMINOUS (MVB)

```
***********************
*                     *
* GEOLOGIC INFORMATION *
*                     *
***********************
```

SYSTEM (AGE)	PENNSYLVANIAN
SERIES	
GROUP	
FORMATION	ALLEGHENY
OVERBURDEN LITHOLOGY	SHALE
FLOOR LITHOLOGY	SHALE

****
* CHEMICAL DATA 1 *
****

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF (PARR)	DMMF (PARR-G)	DMMF (DIR MM)
% MOISTURE	0.67					
% ASH	11.40	11.48				
% VOLATILE MATTER	24.08	24.24	27.38	25.46	25.53	
% FIXED CARBON	63.85	64.28	72.62	74.54	74.47	

****
* CHEMICAL DATA 2 *
****

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF(PARR)
				(14.55 %MM)
% ASH	11.40	11.48		
% CARBON	76.08	76.59	86.52	89.64
% HYDROGEN	4.50*	4.53	5.12	5.30
% NITROGEN	1.42	1.43	1.62	1.67
% SULFUR	3.89	3.92	4.43	
% CHLORINE	0.08	0.09	0.10	0.10
% OXYGEN(DIFF)	1.95*	1.97	2.23	3.30

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	3.14	0.02	0.76	3.92
DAF	3.55	0.02	0.86	4.43
OPTICAL				

ELEMENTAL ANALYSIS	DRY	DMMF(MOD.P)	DMMF(DIR.)
		(14.49%MM)	(%MM)
% CARBON	76.41	89.36	
% HYDROGEN	4.32	5.05	
% NITROGEN	1.43	1.67	
% ORGANIC SULFUR	0.76	0.89	
% OXYGEN(DIFF)	2.59	2.94	
% CHLORINE	0.09	0.10	
% MINERAL MATTER	14.49		
(INCLUDES 5.87 % FES2)			

```
******************
*                *
* CHEMICAL DATA 3 *
*                *
******************
```

% MOISTURE IN COAL = 0.40
% HIGH TEMPERATURE ASH = 11.70 AT 750 DEGREES C

TRACE ELEMENT ANALYSIS	PPM HTA	PPM TOTAL COAL	MAJOR ELEMENT ANALYSIS	OXIDE % OF HTA	ELEMENT % OF TOTAL DRY COAL
AG			SIO2	34.20	1.87
B			AL2O3	23.10	1.43
BA	780	91	TIO2	0.90	0.06
BE	35	4	FE2O3	38.50	3.15
BI			MGO	0.45	0.03
CE			CAO	1.12	0.09
CO			NA2O	0.21	0.02
CR	170	20	K2O	1.06	0.10
CU	95	11	P2O5	0.12	0.01
GA			SO3	1.20	0.06
GE					
LA					
LI					
MN					
MO					
NI	140	16			
NB					
PB					
RB	50	6			
SC					
SN					
SR	370	43			
TH					
U					
V	250	29			
Y					
YB					
ZN	220	26			
ZR	220	26			

VOLATILES	PPM TOTAL COAL
AS	
BR	
CD	
CL	
F	
HG	
SB	
SE	

PETROGRAPHIC DATA

MACERAL COMPOSITION WHITE ANALYSIS ONLY

	DRY VOLUME %	DMMF VOLUME %	DRY WEIGHT %
VITRINITE (CALC.)	80.5	87.1	74.4
INERTINITE (CALC.)	11.8	12.8	10.9
LIPTINITE (CALC.)	0.1	0.1	0.1
MINERAL MATTER (CALC.)	7.6		14.6
VITRINOIDS			
VITRINITE	79.4	85.9	73.4
PSEUDOVITRINITE	1.1	1.2	1.0
FUSINITE	2.5	2.7	2.3
SEMI-FUSINITE	7.0	7.6	6.5
MACRINITE	0.6	0.6	0.5
MICRINITE	1.8	1.9	1.6
SCLEROTINITE	0.0	0.0	0.0
SPORINITE			
CUTINITE			
EXINITE (ANAL.)	0.1	0.1	0.1
RESINITE	0.0	0.0	0.0
SUBERINITE			
EXUDATINITE			
FLUORINITE			
BITUMINITE			
ALGINITE	0.0	0.0	0.0
LIPTODETRINITE			
MINERAL MATTER(ANAL.)			
INERTINITE(ANAL.)			
LIPTINITE(ANAL.)			

REFLECTANCE DATA (%.IN OIL)	HIGH	LOW	RANGE	MEAN MAX	STAND.DEV.
VITRINITE	1.49	1.20	0.29	1.32	0.05
PSEUDOVITRINITE					
VITRINOIDS					

% VITRINOID REFLECTANCE	HALF-TYPE	VOLUME PERCENT	% VITRINOID REFLECTANCE	V-TYPE	VOLUME PERCENT
1.20-1.24	VHT 1.225	7.00			
1.25-1.29	VHT 1.275	20.00	1.20-1.29	V12	27.00
1.30-1.34	VHT 1.325	41.00			
1.35-1.39	VHT 1.375	17.00	1.30-1.39	V13	58.00
1.40-1.44	VHT 1.425	4.00			
1.45-1.49	VHT 1.475	3.00	1.40-1.49	V14	7.00

** PENN STATE COAL DATA BASE **

```
******************
*                *
* SAMPLE HISTORY *
*                *
******************
```

PENN STATE NUMBER	PSOC-1361P
COLLECTED BY	PENNSYLVANIA STATE UNIVERSITY
COLLECTION DATE	2/24/82
COLLECTOR'S NUMBER	
REPORTED RANK	
SAMPLE TYPE	CHANNEL WHOLE SEAM
OTHER SAMPLE INFORMATION	PREMIUM SAMPLE
SAMPLE RESERVE	80
SEAM NAME	UPPER FREEPORT
ALTERNATE SEAM NAME	E SEAM
TOTAL SEAM THICKNESS	0 FT. 26 IN.
THICKNESS OF SEAM SAMPLED	0 FT. 26 IN.
PORTION RECOVERED IN CORE	
DIAMETER OF CORE	

SEAM NAME UPPER FREEPORT
APPARENT RANK HIGH VOLATILE A BITUMINOUS (HVAB)

```
***********************
*                     *
* GEOLOGIC INFORMATION *
*                     *
***********************
```

SYSTEM (AGE)	PENNSYLVANIAN
SERIES	
GROUP	ALLEGHENY
FORMATION	
OVERBURDEN LITHOLOGY	BLACK SHALE
FLOOR LITHOLOGY	CLAY

CHEMICAL DATA 1

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF (PARR)	DMMF (PARR-G)	DMMF (DIR MM)
% MOISTURE	1.90					
% ASH	8.31	8.47				
% VOLATILE MATTER	37.43	38.16	41.69	40.88	40.85	
% FIXED CARBON	52.36	53.37	58.31	59.12	59.15	

CHEMICAL DATA 2

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF(PARR) (10.21 %MM)
% ASH	8.31	8.47		
% CARBON	73.57	75.00	81.94	83.53
% HYDROGEN	5.12*	5.22	5.70	5.81
% NITROGEN	1.38	1.41	1.54	1.57
% SULFUR	1.90	1.94	2.12	
% CHLORINE				
% OXYGEN(DIFF)	7.81*	7.96	8.70	9.08

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	1.17	0.05	0.72	1.94
DAF	1.28	0.05	0.79	2.12
OPTICAL				

ELEMENTAL ANALYSIS	DRY	DMMF(MOD.P) (10.12%MM)	DMMF(DIR.) (%MM)
% CARBON	74.87	83.31	
% HYDROGEN	5.09	5.66	
% NITROGEN	1.41	1.57	
% ORGANIC SULFUR	0.72	0.80	
% OXYGEN(DIFF)	7.79	8.66	
% CHLORINE	-		
% MINERAL MATTER (INCLUDES 2.19 % FES2)	10.12		

CHEMICAL DATA 3

% MOISTURE IN COAL = 1.90
% HIGH TEMPERATURE ASH = 8.27 AT 750 DEGREES C

TRACE ELEMENT ANALYSIS	PPM HTA	PPM TOTAL COAL
AG		
B		
BA	1000	83
BE	20	2
BI		
CE		
CO		
CR	150	12
CU	190	16
GA		
GE		
LA		
LI		
MN		
MO		
NI	150	12
NB		
PB		
RB	90	7
SC		
SN		
SR	1050	87
TH		
U		
V	160	13
Y		
YB		
ZN	280	23
ZR	230	19

MAJOR ELEMENT ANALYSIS	OXIDE % OF HTA	ELEMENT % OF TOTAL DRY COAL
SIO2	42.40	1.64
AL2O3	23.20	1.02
TIO2	1.02	0.05
FE2O3	26.40	1.53
MGO	0.74	0.04
CAO	1.15	0.07
NA2O	0.38	0.02
K2O	2.36	0.16
P2O5	0.48	0.02
SO3	0.80	0.03

VOLATILES	PPM TOTAL COAL
AS	
BR	
CD	
CL	
F	
HG	
SB	
SE	

PETROGRAPHIC DATA

MACERAL COMPOSITION WHITE ANALYSIS ONLY

	DRY VOLUME %	DMMF VOLUME %	DRY WEIGHT %
VITRINITE (CALC.)	74.4	78.5	70.5
INERTINITE (CALC.)	15.1	15.9	14.3
LIPTINITE (CALC.)	5.3	5.6	5.0
MINERAL MATTER (CALC.)	5.2		10.2
VITRINOIDS			
VITRINITE	71.1	75.0	67.3
PSEUDOVITRINITE	3.3	3.5	3.1
FUSINITE	4.2	4.4	3.9
SEMI-FUSINITE	4.3	4.5	4.0
MACRINITE	0.9	0.9	0.8
MICRINITE	5.8	6.1	5.5
SCLEROTINITE	0.0	0.0	0.0
SPORINITE			
CUTINITE			
EXINITE (ANAL.)	4.7	5.0	4.5
RESINITE	0.6	0.6	0.5
SUBERINITE			
EXUDATINITE			
FLUORINITE			
BITUMINITE			
ALGINITE	0.0	0.0	0.0
LIPTODETRINITE			
MINERAL MATTER(ANAL.)			
INERTINITE(ANAL.)			
LIPTINITE(ANAL.)			

REFLECTANCE DATA , (%.IN OIL)	HIGH	LOW	RANGE	MEAN MAX	STAND.DEV.
VITRINITE	0.93	0.73	0.20	0.83	0.04
PSEUDOVITRINITE					
VITRINOIDS					

% VITRINOID REFLECTANCE	HALF-TYPE	VOLUME PERCENT	% VITRINOID REFLECTANCE	V-TYPE	VOLUME PERCENT
0.70-0.74	VHT 0.725	2.00			
0.75-0.79	VHT 0.775	12.00	0.70-0.79	V7	14.00
0.80-0.84	VHT 0.825	55.00			
0.85-0.89	VHT 0.875	25.00	0.80-0.89	V8	80.00
0.90-0.94	VHT 0.925	6.00			
0.95-0.99	VHT 0.975		0.90-0.99	V9	5.00

```
** PENN STATE COAL DATA BASE **

                          *****************
                          *               *
                          * SAMPLE HISTORY *
                          *               *
                          *****************

PENN STATE NUMBER         PSOC-867

COLLECTED BY              PENNSYLVANIA STATE UNIVERSITY
COLLECTION DATE            8/29/76
COLLECTOR'S NUMBER            867

REPORTED RANK             ANTHRACITE (AN)

SAMPLE TYPE               CHANNEL WHOLE SEAM
OTHER SAMPLE INFORMATION
SAMPLE RESERVE                329

SEAM NAME                 PRIMROSE
ALTERNATE SEAM NAME

TOTAL SEAM THICKNESS          16 FT.   0 IN.
THICKNESS OF SEAM SAMPLED     16 FT.   0 IN.
PORTION RECOVERED IN CORE
DIAMETER OF CORE


SEAM NAME       PRIMROSE
APPARENT RANK   ANTHRACITE (AN)
                          ***********************
                          *                     *
                          * GEOLOGIC INFORMATION *
                          *                     *
                          ***********************

SYSTEM (AGE)              PENNSYLVANIAN
SERIES
GROUP
FORMATION                 LLEWELLYN

OVERBURDEN LITHOLOGY      SHALE
FLOOR LITHOLOGY           SHALE
```

```
*******************
*                 *
* CHEMICAL DATA 1 *
*                 *
*******************
```

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF (PARR)	DMMF (PARR-G)	DMMF (DIR MM)
% MOISTURE	3.77					
% ASH	13.39	13.91				
% VOLATILE MATTER	3.57	3.71	4.31	2.82	1.88	
% FIXED CARBON	79.27	82.38	95.69	97.18	98.12	

```
*******************
*                 *
* CHEMICAL DATA 2 *
*                 *
*******************
```

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF(PARR) (15.31 %MM)
% ASH	13.39	13.91		
% CARBON	78.76	81.85	95.07	96.65
% HYDROGEN	1.02*	1.06	1.23	1.25
% NITROGEN	0.64	0.66	0.77	0.78
% SULFUR	0.50	0.52	0.60	
% CHLORINE	0.02	0.03	0.03	0.03
% OXYGEN(DIFF)	1.90*	1.97	2.30	1.30

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	0.05	0.01	0.46	0.52
DAF	0.06	0.01	0.53	0.60
OPTICAL				

ELEMENTAL ANALYSIS	DRY	DMMF(MOD.P) (15.75%MM)	DMMF(DIR.) (%MM)
% CARBON	81.65	96.92	
% HYDROGEN	0.88	1.04	
% NITROGEN	0.66	0.78	
% ORGANIC SULFUR	0.46	0.55	
% OXYGEN(DIFF)	0.59	0.68	
% CHLORINE	0.03	0.03	
% MINERAL MATTER (INCLUDES 0.09 % FES2)	15.75		

```
*******************
*                 *
* CHEMICAL DATA 3 *
*                 *
*******************
```

% MOISTURE IN COAL = 1.23
% HIGH TEMPERATURE ASH = 13.67 AT 750 DEGREES C

TRACE ELEMENT ANALYSIS	PPM HTA	PPM TOTAL COAL	MAJOR ELEMENT ANALYSIS	OXIDE % OF HTA	ELEMENT % OF TOTAL DRY COAL
AG			SIO2	55.00	3.51
B			AL2O3	31.60	2.29
BA	1440	197	TIO2	1.93	0.16
BE	6	1	FE2O3	3.30	0.32
BI			MGO	0.86	0.07
CE			CAO	0.65	0.06
CO			NA2O	1.01	0.10
CR	260	36	K2O	3.38	0.38
CU	180	25	P2O5	0.26	0.02
GA			SO3	0.60	0.03
GE					
LA					
LI					
MN					
MO					
NI	160	22			
NB					
PB					
RB	180	25			
SC					
SN					
SR	670	92			
TH					
U					
V	220	30			
Y					
YB					
ZN	110	15			
ZR	340	46			

VOLATILES	PPM TOTAL COAL
AS	
BR	
CD	
CL	
F	
HG	
SB	
SE	

```
********************
*                  *
* PETROGRAPHIC DATA *
*                  *
********************
```

MACERAL COMPOSITION WHITE ANALYSIS ONLY

	DRY VOLUME %	DMMF VOLUME %	DRY WEIGHT %
VITRINITE (CALC.)	71.7	77.9	66.0
INERTINITE (CALC.)	20.3	22.1	18.7
LIPTINITE (CALC.)		0.0	0.0
MINERAL MATTER (CALC.)	8.0		15.3
VITRINOIDS			
VITRINITE	71.7	77.9	66.0
PSEUDOVITRINITE	0.0	0.0	0.0
FUSINITE	0.7	0.8	0.7
SEMI-FUSINITE	19.5	21.2	17.9
MACRINITE	0.1	0.1	0.1
MICRINITE	0.0	0.0	0.0
SCLEROTINITE	0.0	0.0	0.0
SPORINITE	0.0	0.0	0.0
CUTINITE	0.0	0.0	0.0
EXINITE (ANAL.)			
RESINITE	0.0	0.0	0.0
SUBERINITE			
EXUDATINITE			
FLUORINITE			
BITUMINITE			
ALGINITE	0.0	0.0	0.0
LIPTODETRINITE			
MINERAL MATTER(ANAL.)			
INERTINITE(ANAL.)			
LIPTINITE(ANAL.)			

REFLECTANCE DATA (%.IN OIL)	HIGH	LOW	RANGE	MEAN MAX	STAND.DEV.
VITRINITE	5.80	4.86	0.94	5.77	0.38
PSEUDOVITRINITE					
VITRINOIDS					

APPENDIX B

Characteristics of Standard Respirable Dusts

TABLE 1
Size Distribution of Standard Respirable Dusts as Determined by Ladal Pipet Centrifuge

MP3-1		MP32		MP3-3		PSOC 1192		PSOC 1192M		PSOC 867		PSOC 1361P		Kaolinite		Quartz	
X†	F+	X	F	X	F	X	F	X	F	X	F	X	F	X	F	X	F
4.63	100.0	9.80	100.0	6.55	82.1	6.55	100.0	4.63	86.2	4.33	81.3	4.63	71.6	17.5+	95.7	3.14	46.8
3.08	89.1	6.56	91.3	4.63	48.2	4.34	88.3	2.97	43.8	2.88	39.0	3.08	34.7	12.5+	91.9	2.09	25.8
1.99	73.4	4.21	75.2	3.07	26.8	2.79	45.6	1.88	23.9	2.03	24.4	1.99	12.8	8.4+	90.8	1.35	14.4
1.27	52.4	2.65	28.4	1.98	15.4	1.77	19.2	1.18	12.2	1.32	9.0	1.27	4.7	6.9+	88.5	0.86	6.6
0.79	28.3	1.69	9.6	1.25	8.3	1.10	7.1	0.74	6.0	0.84	3.9	0.79	1.9	5.0+	82.7	0.54	2.3
0.49	9.0	1.05	2.8	0.77	3.4	0.66	1.1	0.46	3.0	0.52	2.4	0.49	1.1	3.35+	73.1	0.33	0.94
0.28	3.7	0.66	1.0	0.47	2.2	0.39	0.68	0.26	1.3	0.32	1.9	0.29	0.59	2.22	67.4		
				0.27	1.0					0.19	1.4			1.48	58.8		
														0.96	45.2		
														0.61	32.5		
														0.38	26.5		
														0.23	13.7		
														0.14	8.2		

† Size of particle in um.
* Cumulative weight percent finer than size.
+ Anaysis extended with Andreasen Pipet.

TABLE 2

Size Distribution of Standard Respirable Dusts as Determined by Microtrac Small Particle Analyser

Particle	Weight Percent Finer Than Size								
Size, um	MP3-1	MP3-2	MP3-3	PSOC 1192	PSOC 1192M	PSOC 1361P	PSOC 867	Kaolinite	Quartz
42.21	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
29.85	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
21.10	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.7	100.0
14.92	100.0	100.0	93.2	100.0	99.1	100.0	100.0	92.4	97.5
10.55	100.0	100.0	84.7	99.3	97.5	100.0	100.0	85.4	90.9
7.46	98.7	87.9	67.2	94.6	88.8	89.2	88.6	65.4	75.2
5.27	97.1	60.0	44.7	69.7	67.6	61.6	60.3	62.8	52.7
3.73	92.2	34.0	28.6	39.6	45.4	35.7	36.5	50.1	35.6
2.63	77.6	18.5	19.1	20.9	29.7	20.2	21.7	37.4	23.0
1.69	59.6	9.8	12.6	10.4	19.3	11.1	10.8	27.2	13.5
1.01	37.8	4.7	7.3	5.1	11.7	5.7	4.1	17.7	6.7
0.66	17.2	1.9	3.3	1.8	5.4	2.3	1.3	11.2	2.4
0.43	7.0	0.7	1.3	0.7	2.2	0.8	0.1	8.5	0.8
0.34	2.2	0.2	0.4	0.2	0.7	0.2	0.0	7.2	0.3
0.24	0.8	0.0	0.1	0.0	0.2	0.0	0.0	6.8	0.1
0.17	0.2	0.0	0.0	0.0	0.1	0.0	0.0	6.4	0.0

TABLE 3
Mineralogical Composition of Standard Respirable Dusts
as Determined by the Mineral Constitution Laboratory of the Pennsylvania State University

Sample	PSOC 867	PSOC 1192M	PSOC 1361P	MP3-2
LTA	25.7%	9.58%	9.03%	10.1%
Quartz	14	4	8	12
Pyrite	n.d.	22	32	16
Kaolinite	35-45	30-40	30-40	25-35
Illite*	--	10-20	10-20	20-30
Illite plus mixed-layer clays*	20-30	--	--	--
Chlorite*	5-15	n.d.	n.d.	n.d.
Feldspars*	5-10	n.d.	n.d.	n.d.

n.d. = not detected.

* = estimated value based on normative analysis.

TABLE 4
Spectrochemical Analysis of Standard Respirable Dusts Expressed as Oxides

Percent of High Temperature Ash

Oxide	PSOC 867	PSOC 1192	PSOC 1192M	PSOC 1361P	MP3-2	Kaolinite	Quartz
SiO_2	53.4	33.5	36.9	43.1	47.3	45.2	95
Al_2O_3	33.1	25.2	27.6	27.7	27.6	38.1	2.06
TiO_2	1.46	1.02	1.27	1.12	1.35	1.36	< 0.1
Fe_2O_3	5.30	34.4	27.7	22.5	14.7	0.34	0.50
MgO	1.23	0.49	0.58	0.84	1.00	< 0.1	< 0.1
CaO	0.60	1.56	1.74	1.25	2.07	< 0.1	< 0.1
MnO	0.02	0.02	0.02	0.088	0.012	< 0.01	< 0.01
Na_2O	0.93	0.17	0.21	0.27	0.26	0.05	0.10
K_2O	2.84	1.24	1.38	1.77	2.60	0.12	0.39
P_2O_5	0.17	0.18	0.21	0.44	0.75	--	--
SO_3	0.2	0.5	0.3	0.1	0.6	--	--
TOTAL	99.3%	98.3%	97.9%	99.1%	98.3%	85.2%*	98.0%

* Loss of H_2O on ignition (750°C) < 15.2%.

TABLE 5
Size-specific Gravity Distribution of PSOC 1192M as a Percentage of the Total Coal

Size, um	% Total	Sink/Float 1.3	1.3 x 1.4	1.4 x 1.5	1.5 x 1.6	1.6 x 1.7	1.7 x 1.8	1.8 x 1.9	1.9 x 2.0	2.0
42.21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29.85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21.10	2.1	0.0	0.1	0.4	0.0	0.0	0.0	0.5	1.0	0.1
14.92	0.8	0.0	0.0	0.5	0.0	0.0	0.0	0.2	0.1	0.0
10.55	8.3	0.1	4.9	2.3	0.9	0.0	0.0	0.0	0.0	0.2
7.42	22.7	0.2	13.4	3.5	2.7	0.0	0.0	0.0	1.0	0.9
6.27	23.9	0.2	13.8	3.3	1.5	3.6	0.0	0.0	0.0	1.5
3.73	15.8	0.1	8.0	2.3	0.9	2.8	0.4	0.0	0.0	1.3
2.63	9.6	0.1	3.8	2.1	1.4	0.0	1.1	0.0	0.0	1.1
1.69	7.3	0.0	2.7	1.6	1.1	0.0	1.1	0.0	0.0	0.8
1.01	5.4	0.0	1.8	1.1	0.8	0.0	0.9	0.0	0.0	0.8
0.66	2.5	0.0	0.7	0.5	0.3	0.0	0.5	0.6	0.0	0.4
0.43	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.2
0.34	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0
0.24	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
0.17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 6

Size-specific Gravity Distribution of PSOC 1361P as a Percentage of the Total Coal

Size, um	% Total	Sink/Float 1.3	1.3 x 1.4	1.4 x 1.5	1.5 x 1.6	1.6 x 1.7	1.7 x 1.8	1.8 x 1.9	1.9 x 2.0	2.0
42.21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29.85	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
21.10	0.8	0.2	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.2
14.92	4.5	0.3	0.2	0.7	0.6	0.6	0.9	0.0	1.1	0.1
10.55	10.3	1.9	2.4	2.8	2.5	0.3	0.0	0.0	0.0	0.4
7.42	26.1	5.1	6.1	7.8	4.5	0.0	0.0	1.5	0.0	1.0
6.27	27.4	4.7	6.4	8.6	3.6	0.0	0.0	2.8	0.0	1.0
3.73	14.7	2.0	3.2	5.7	1.7	0.0	0.0	0.9	0.0	1.4
2.63	7.0	0.6	1.1	3.3	0.4	0.0	0.0	0.5	0.0	1.2
1.69	4.6	0.4	0.7	1.8	0.5	0.0	0.0	0.6	0.0	0.8
1.01	2.8	0.2	0.4	1.3	0.3	0.0	0.0	0.0	0.0	0.5
0.66	0.9	0.1	0.2	0.4	0.1	0.0	0.0	0.0	0.0	0.2
0.43	0.4	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.1
0.34	0.3	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0
0.24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 7
Size-specific Gravity Distribution of PSOC 867 as a Percentage of the Total Coal

		Sink/Float								
Size, um	% Total	1.3	1.3 x 1.4	1.4 x 1.5	1.5 x 1.6	1.6 x 1.7	1.7 x 1.8	1.8 x 1.9	1.9 x 2.0	2.0
42.21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29.85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21.10	0.6	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3
14.92	2.0	0.0	0.0	0.0	0.5	0.6	0.1	0.0	0.1	0.6
10.55	11.2	0.0	0.0	0.1	1.6	5.7	1.3	0.0	0.4	2.0
7.42	25.7	0.1	0.0	0.1	3.4	11.6	5.4	0.0	0.0	5.0
6.27	24.0	0.1	0.0	0.1	2.6	8.6	6.4	0.3	0.6	5.4
3.73	17.3	0.0	0.0	0.0	0.8	4.3	4.3	1.4	1.8	4.7
2.63	9.9	0.0	0.0	0.0	0.3	1.1	2.6	1.0	1.4	3.4
1.69	5.0	0.0	0.0	0.0	0.2	0.4	1.1	0.2	0.8	2.3
1.01	3.3	0.0	0.0	0.0	0.0	0.0	0.6	0.2	0.6	1.5
0.66	0.9	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.5
0.43	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
0.34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Detection of Organic Free Radicals in Coal-dust Exposed Lung Tissue and Correlations with Their Histopathological Parameters

B. JAFARI,[A] N.S. DALAL,[A] V. VALLYATHAN[B] and F.Y.H. GREEN[B]
[A]Chemistry Department, West Virginia University, Morgantown, West Virginia 26506; [B]National Institute of Occupational Safety and Health, Morgantown, West Virginia 26505

Using electron spin resonance (ESR) spectroscopy we have carried out a systematic study of the measurement of concentrations of organic free radicals in freeze-dried lung tissue. Sixty-six tissue samples were obtained from the National Coal Workers' Autopsy Study (NCWAS). The samples were characterized in terms of the concentration per gram of the free radicals, and examined in relationship to the histopathological parameters such as age, numbers of years in the mining atmosphere, the degree of disease, and smoking history. Preliminary results indicate a positive correlation between the free radicals in the lung tissue and the severity of pneumoconiosis.

Introduction

This paper summarizes our electron spin resonance (ESR) measurements of the concentration of organic free radicals in the freeze-dried lung tissue of autopsied coal miners. This work was undertaken because it is well known that most coals contain carbon-centered organic free radicals,[1,2] and recent studies from our laboratories indicated that reactive free radicals might play a role in the biochemical mechanism of coal workers' pneumoconiosis (CWP).[3] Thus we obtained 144 lung-tissue samples from the National Institute for Occupational Safety and Health (NIOSH) in Morgantown. The samples came from the data bank of the National Coal Workers' Autopsy Study (NCWAS). This selection was unique because fairly detailed histopathological information was available for each sample.

Other recent studies in this field are those of Ohta *et al*[4] who conducted ESR measurements on black dust deposited in autopsied human lungs, but no coal miner was included therein. Earlier Retcofsky[2] had examined one lung-tissue sample via ESR spectroscopy and had concluded that the free radicals in the lung tissue reflected simply the fusain (narrow component) ESR signals. The present study was thus undertaken to complement the earlier work[2-4] and the results indicate a positive correlation with the disease severity fairly strongly.

Methodology

ESR measurements were made with an X-band, IBM-Bruker ER 200D, ESR spectrometer in conjunction with an Aspect 2000 microcomputer. The lung tissue samples were all used as thin slices, as received from NIOSH, and inserted into the microwave absorption cell (cavity) of the ESR Spectrometer using quartz sample tubes. Detailed ESR measurements were made at room temperature on all 144 samples, in a blind study. Of these 66 samples were used for statistical analysis since detailed histopathological data were available only for these samples from NIOSH. The average age was 55 +/- 8 years at time of death, with an average un-

TABLE I

Concentrations of Free Radicals in Coal Miners' Lungs With and Without Disease

Number of Cases	Age	Mining Tenure	Smoking History	Type of Disease	Free Radical Conc./GM
22	63 +/- 7	29 +/- 15	40 +/- 26	No disease	0.42 +/- 0.72
15	74 +/- 8	26 +/- 14	33 +/- 20	Macular disease	0.85 +/- 0.58
10	70 +/- 8	33 +/- 16	30 +/- 26	Progressive massive fibrosis	1.27 +/- 1.04
4	71 +/- 6	41 +/- 5	non-smokers	Progressive massive fibrosis	4.50 +/- 2.90
11	65 +/- 10	24 +/- 16	28 +/- 13	Cancer of the lung	3.76 +/- 2.23

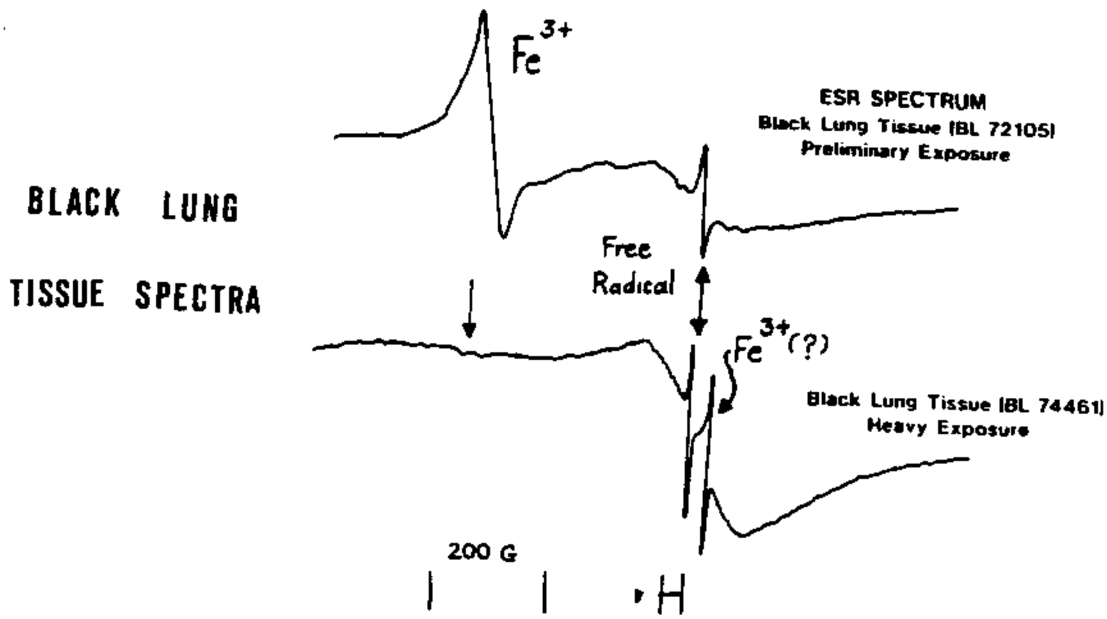


FIGURE 1. Typical ESR spectra of freeze-dried lung tissue (a) with preliminary exposure (b) with heavy exposure.

derground mining history of 31 +/- 13 years. Among these 94 percent were smokers and 6 percent non-smokers.

Results

Figure 1 shows typical ESR spectra from two lung-tissue samples, Figure 1(a) is for a sample with only a preliminary coal dust exposure whereas 1(b) is that for a heavily-exposed tissue. These spectra were obtained over a wide range of magnetic field in order to measure both the free radicals and any paramagnetic transition-metal ions, such as Fe^{3+}, as marked in the figure. The free radical spectra occur only in a narrow magnetic field range around 3400 G at X-band, as indicated by arrowheads in the figure. Since the focus of the present study was only the free radicals and not metal ions, detailed measurements were made only on the free radical features.

As is well known the concentration of the free radicals is proportional to the area under the free radical ESR signal.[1,2] The free radical concentration was thus measured per gram of the tissue sample used. Table I gives the details of the free radical concentration along with the histopathological data on the specimen studied. Here no disease refers to coal workers who had been classified to have no CWP. Macular refers to cases of simple pneumoconiosis whereas progressive massive fibrosis (PMF) refers to the most advanced stage of the disease. It is seen that the free-radical concentration is the highest in samples with PMF and the lowest in those with "no disease." A graphical representation of the findings is given in Figure 2. Here the horizontal scale used is from zero to 14 as devised by NIOSH; zero corresponding to no disease and 14 to the highest PMF. It is again seen that the free radical concentration in the lung tissue increases sharply with the severity of CWP.

The results of Table I and Figure 2 also show that, for roughly the same degree of CWP, the free radical concentration is higher in the cases of non-smokers than smokers. This was surprising at first because cigarette smoke itself is known to contain organic free radicals.[5] Hence if there were no reaction between the free radicals in the coal dust and those in cigarette smoke, then one might expect that the total free radical concentration to be higher in the smokers, contrary to our findings. Thus while at present the nature of interactions between the various types of free radicals in the lung tissue is not clear, it is apparent that these radicals are not inert.

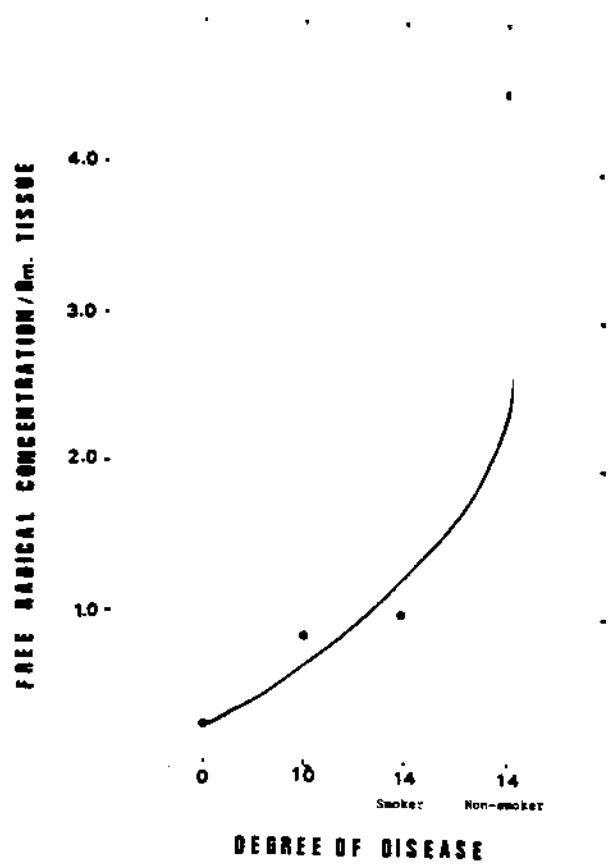


FIGURE 2. Correlation between the degree of CWP and the measured organic free radical concentration.

Conclusions

Preliminary conclusions from this study is that the amount of stable, carbon-centered free radicals in autopsied lung-tissue increases with the severity of CWP. We are in the process of comparing ESR signals from coal dust obtained from the same mines, to examine whether or not the free radicals in the lung tissue are the same as those found in the specific coal mine dust. It is hoped that the results would provide further clues to reactivity of the free radicals in the coal mine dust with lung tissue and cigarette smoke and thereby the pathogenicity of CWP.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

References

1. **Petrakis, L. and D.W. Grandy**: *Free Radicals in Coal and Fossil Fuels*. Elsevier (1983).
2. **Retkofsky, H.L.**: Magnetic Resonance Studies of Coal. Coal *Science 1*:43-82 (1982).
3. **Dalal, N., M.M. Suryan, B. Jafari et al**: *Detection of Reactive Free Radicals in Fresh Coal Mine Dust and Its Implications to Pneumoconiosis*. Paper presented at the Sixth International Symposium on Inhaled Particles. Cambridge, England (1985).
4. **Ohta, Y., H. Shiraishi and Y. Tabata**: An Electron Spin Resonance Study of Free Radicals in Black Dust Deposited in Human Lungs. *Arch. Environ. Health 40*:279-282 (1985).
5. **Pryor, W.A., B.J. Hales, P. Premovic and D. Church**: The Radicals in Cigarette Tars: Their Nature and Suggested Physiological Implications. *Science 220*:425-427 (1983).

Mineral Fiber Toxicity: Further Evidences for an Involvement of the Surface Chemistry.

DENIS NADEAU, Ph.D.,[A] LOUISE FOUQUETTE-COUTURE, B.Sc.,[A] JALEH KHORAMI, Ph.D.[B] and DANIEL PARADIS, B.Sc.[A]

Programme de Recherche sur l'Amiante de l'Universite de Sherbrooke, Departement de biologieA et de chimieB, Faculte des sciences, Universite de Sherbrooke, Sherbrooke, Quebec, Canada J1K 2R1

The purpose of this study was to extend further the hypothesis that the grafting of foreign compounds on specific functional groups at the surface of mineral fibers can alter their biological reactivity. Some naturally occurring fibrous silicates such as chrysotile asbestos and attapulgite clay share the characteristic of possessing numerous structural hydroxyl groups. While for chrysotile, the hydroxyl groups are found on the external surface and the extremities of the fibers, for attapulgite fibers, these functional groups occur mainly inside exposed channels of the highly crystalline structure. The basic character of these hydroxyl groups confers to these mineral fibers a strong affinity toward many acidic structures or compounds, such as the highly reactive phosphorus oxychloride ($POCl_3$) vapors.

The phosphorylation of chrysotile and attapulgite fibers with $POCl_3$ causes the following physico-chemical modifications: 1) an addition of 4 to 5 percent of phosphorus by weight; 2) a decrease in their specific surface area, respectively of ~ 40 and ~ 75 percent for chrysotile and attapulgite; 3) the chrysotile fibers have their net surface charge switched from a positive to a negative value (+39 to –26 mV), while for the attapulgite fibers, the negative surface charge is slightly increased (–23 to –30 mV). Based on physico-chemical data such as infrared spectroscopy and thermogravimetric analysis, it is postulated that the phosphorylation process produces: 1) a polyphosphorous coating at the surface of the chrysotile fibers; 2) an occlusion of the channels or pores of the crystalline structure of the attapulgite fibers by phosphorous compounds.

Following the $POCl_3$ treatment, the highly respirable chrysotile and attapulgite fibers (L = ~ 1 um; D = ~ 0.1 um) were found to be aggregated, especially for the chrysotile sample. Therefore, for the biological assays, all the mineral fiber samples were dispersed in a Tween 80-saline solution with a Dounce homogenizer (hydraulic shearing effect). When the *in vitro* toxicity of the $POCl_3$-treated silicate fibers were compared to the native fibers, it was found that the modified fibers were less hemolytic to rat erythrocytes (respectively, a decrease of ~94 and ~80 percent for chrysotile and attapulgite). Moreover, when the phosphorylated fibers were tested on rat pulmonary alveolar macrophages, the $POCl_3$ treatment reduced considerably the cytotoxicity in both short-term (18 hours) and long-term (4 days) assays. Our conclusion is that these data provide further evidences that the surface chemistry can be a determinant factor to consider when one evaluates the biological reactivity of mineral fibers, more so if these fibers are rich in exposed hydroxyl groups.

Introduction

Pulmonary alveolar macrophages (PAM) play a pivotal role in the host defenses against inhaled particulates.[1] Following the ingestion of foreign materials by phagocytosis, the particles-laden PAM are removed mainly by mucocilliary transport.[2,3] PAM are very rich in lysosomal hydrolases; these enzymes are not only an essential mechanism for the killing of microbial invaders but are also secreted from the cells.[4] As the result of an oversecretion and/or cell death, these hydrolytic enzymes can cause tissue damage; consequently, they play a major role in the development of inflammation and certain lung diseases.[3,5]

It is generally recognized that mineral fibers can cause lung injury.[6-8] *In vitro*, the cytotoxic response of PAM exposed to toxic dusts such as chrysotile (CH) asbestos and attapulgite (AT) clay is characterized by the concomitant extracellular releases of marker enzymes.[7,9] The cytoplasmic lactate dehydrogenase (LDH) and one of the many lysosomal enzymes such as ß-galactosidase (ß-GAL), other viability indexes such as decreases in cellular Adenosine Triphosphate (ATP) and metabolic activities (e.g., lactic acid production), or the failure by PAM to exclude a vital dye, are often determined concurrently to assess the cellular damages caused by cytotoxic particles.[10,11]

The biological activity (both *in vivo* and *in vitro*) of respirable fibers has been regarded for quite some time to depend mainly upon their size distributions (length and diameter).[6-9] However, recent data suggest that these biological effects could also be linked in part to the chemical nature of the fibers. Physico-chemical treatments like acid-leaching, heat or mechanical milling have been shown to alter significantly the biological effects of CH fibers.[12-16] Other chemical treatments such as metal-micelle, organosilane and phosphorus depositions were also successful in reducing the biological activity of CH fibers.[17-20] So, as stressed recently, the total exclusion of the chemical surface characteristics as a significant contribution to the biological reactivity of fibers needs to be reassessed.[21]

Both AT and CH fibers are rich in hydroxyl (O-H) groups of basic character capable of reacting with acidic materials.

TABLE I

Basic Description of the Silicates Tested

Silicate (Mineral Class)	Fibrous Nature	Chemical Composition	Density ($g.cm^{-3}$)	Hydroxyl Groups Presence	Hydroxyl Groups Location
Chrysotile (Serpentine)	Yes	$(OH)_4Mg_3Si_2O_5$	2.5	Yes	Mainly on the surface (brucite layer)
Attapulgite (Clay)	Yes	$(OH_2)_4(OH)_2Mg_5Si_8O_{20} . 4 H_2O$*	2.4+	Yes	In open channels or pores running parallel to the surface

* Ideal cell composition.(28) For variations, see reference (24).

+ The value reported is for the product Attagel^R (Englehard Co.).

The objective of this study was therefore to evaluate the importance of those (O-H) groups relative to the biological reactivity of hydrous silicates. For that purpose, two *in vitro* assays were selected: the hemolysis test and PAM cytotoxicity assays.[11] These data have been presented recently in an abstract form.[22]

Material and Methods

Fibers

The very short CH asbestos fibers were isolated from the Canadian commercial grade 4T30 by sedimentation in demineralized water.[11,23] As for the AT fibers, we used the commercial product Attagel^R (type 40; Engelhard Minerals and Chemicals Corporation, Georgia, U.S.A.). This clay product has a crystalline structure similar to AT fibers; however, it has a higher content in carbonates.[24]

Phosphorylation Process

The $POCl_3$ gas treatment has been described before.[20] For this study, the procedure was essentially as follows: 24 hours before the phosphorylation treatment, known amounts of each fibers were dried at 100°C. Under a nitrogen atmosphere, the fibers were then treated with POCl3 vapors in a reaction vessel held at room temperature. Following the phosphorylation, the treated fibers were heated at 300°C for two hours.(24)

Physicochemical Characterization

Zeta potentials (surface charge), specific surface areas, phosphorus determinations and size distributions of the fibers have been determined.[11,24]

Hemolysis

The capacity by mineral fibers to induce the release of hemoglobin from a red blood cell (RBC) suspension was measured according to already published methods.[11]

Cells and Culture Conditions

The procedures to obtain enriched PAM and to carry out the short-term *in vitro* cultures have been previously described.[11] Briefly, the protocols are as follows:

Short-term Cytotoxicity Assays

PAM were isolated from Long-Evans rats by bronchoalveolar lavages. After lysis of contaminating RBC, 4 x 10^5 free-cells were suspended in a modified Minimum Essential culture medium (MEM) and seeded in multiwell culture dishes. After a two-hour incubation period at 37°C allowing the formation of *fresh PAM monolayers,* the attached cells were washed and fresh medium was added. The PAM cultures were then challenged for 18 hours with 50 or 250 ug of native or chemically modified CH and AT fibers.

For *one day-old PAM monolayers,* after the establishment of fresh cell monolayers, the cells were further incubated at 37°C for 24 hours. Then, the cell cultures were washed before being challenged with the mineral fibers for 18 hours. As with the fresh cell cultures, the PAM monolayers and the incubation media were collected and assayed for the cytotoxic responses.

Long-term Cytotoxicity Assay

For the long-term cultures, *fresh PAM monolayers* were prepared as described above. The cells were then challenged for 24 hours with a single dose of 50 ug of each mineral fibers, native or chemically modified. The following day, and every 24 hours up to 96 hours, the incubation media and the cells were collected and assayed. Fresh medium was added daily to the cell monolayers which had to incubate for the remaining periods of time.

Cytotoxicity Indexes

The LDH and ß-GAL enzyme activities were respectively measured by following the rate of transformation of NAD^+ to NADH and by end-point measurement of the hydrolysis of p-nitrophenyl-ß-D-galactoside; the ATP cell contents were measured by bioluminescence.[11] The metabolite lactate was determined by a rate analysis based on the LDH reaction.[25]

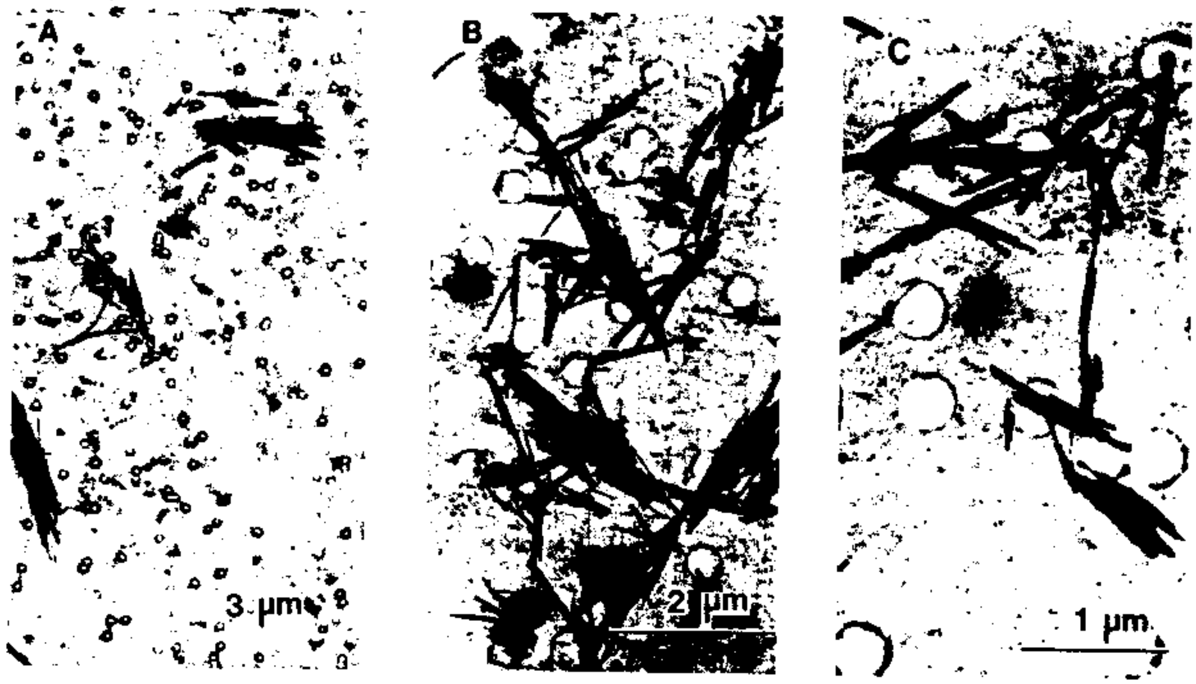


FIGURE 1. Transmission electron micrograph of the Attagel[R] (attapulgite) clay sample. (A) X10,000; (B) X11,600; (C) X20,700.

Statistical Analyses

First, the data were evaluated with a one-way analysis of variance.[26] Afterward, when the F-values were statistically significant, the treated cell monolayers were compared to the control by performing a Dunnett's multiple comparison test which allows the comparison of several treated groups to a single control group.[27] For a given time of incubation or dose of fibers, the fiber-exposed monolayers were tested against each other by performing a Student-t test (paired data, one or two sided).[26] The level of significance was set at $p \leq 0.05$ and, for each parameter evaluated per given incubation procedure, no statistical difference was ever observed between the control groups.

Results

Physicochemical Characterization of the Fibers

A general description of the silicates under study is presented in Table I. The fibrous nature of the CH and AT samples was confirmed by transmission electron microscopy (Figures 1 and 2). The mean length for the CH and AT fibers are respectively 0.9 and 0.8 um; both mineral fibers have a diameter averaging ~ 0.1 um.[11] Table II illustrates the physico-chemical modifications induced by the $POCl_3$ treatment.[24] Both types of fiber show substantial reactivity with $POCl_3$. Because of its brucite outer layer of basic character, a CH fiber has a positive surface charge atypical of silicate minerals. The phosphorylation of CH cause a switch in the zeta potential from a positive to a negative value (Table II). Although rich in (O-H) groups, AT fibers present an expected negative surface charge; so, despite its weak acidic surface, the net negative charge of the clay mineral is increased by ~ 30 percent after $POCl_3$. The specific surface area of the CH fibers was decreased by ~ 40 percent after the chemical treatment, while for AT fibers, the reduction observed was ~ 75 percent (Table II).

The phosphorylation process caused some aggregation of the mineral fibers, especially for the CH sample (data not shown). One potentially beneficial effect of the $POCl_3$ treatment was that, during the handling of these modified fibers, it was noted that the fibers were less likely to become airborne. Accidental inhalation of the $POCl_3$-treated fibers was therefore practically avoided. Although preliminary data with the long-term cytotoxicity assay showed that the $POCl_3$-treated fibers were less toxic, it was felt that the direct comparison with the untreated fibers was somewhat inappropriate without some form of physical dispersion of the aggregates.

We have been using for years the Dounce homogenizer (an all-glass tissue homogenizer) to resuspend fiber samples for our biological assays.[29] Usually, with most samples, this procedure has the advantage of being limited to a slight hydraulic shearing effect, much less disruptive than an ultrasonic bath for example.[16] However, due to the tight aggregation state of the $POCl_3$-treated fibers, the Dounce procedure had to be rendered more forceful hence potentially more damageable to the fibers.[15] Nonetheless, we were somewhat successful in achieving a good dispersion of the phosphorylated fibers suitable for the *in vitro* assays.

Biological Assays

The membranolytic effects of the native and chemically modified silicate fibers are shown in Table III. As demonstrated before, the native CH and AT fibers are highly hemolytic to rat erythrocytes.[11] Comparatively, the $POCl_3$-treated CH and AT fibers show considerably less membranolytic activities; respectively, reduction in hemolysis of 94 and 80 percent were seen with the phosphorylated fibers.

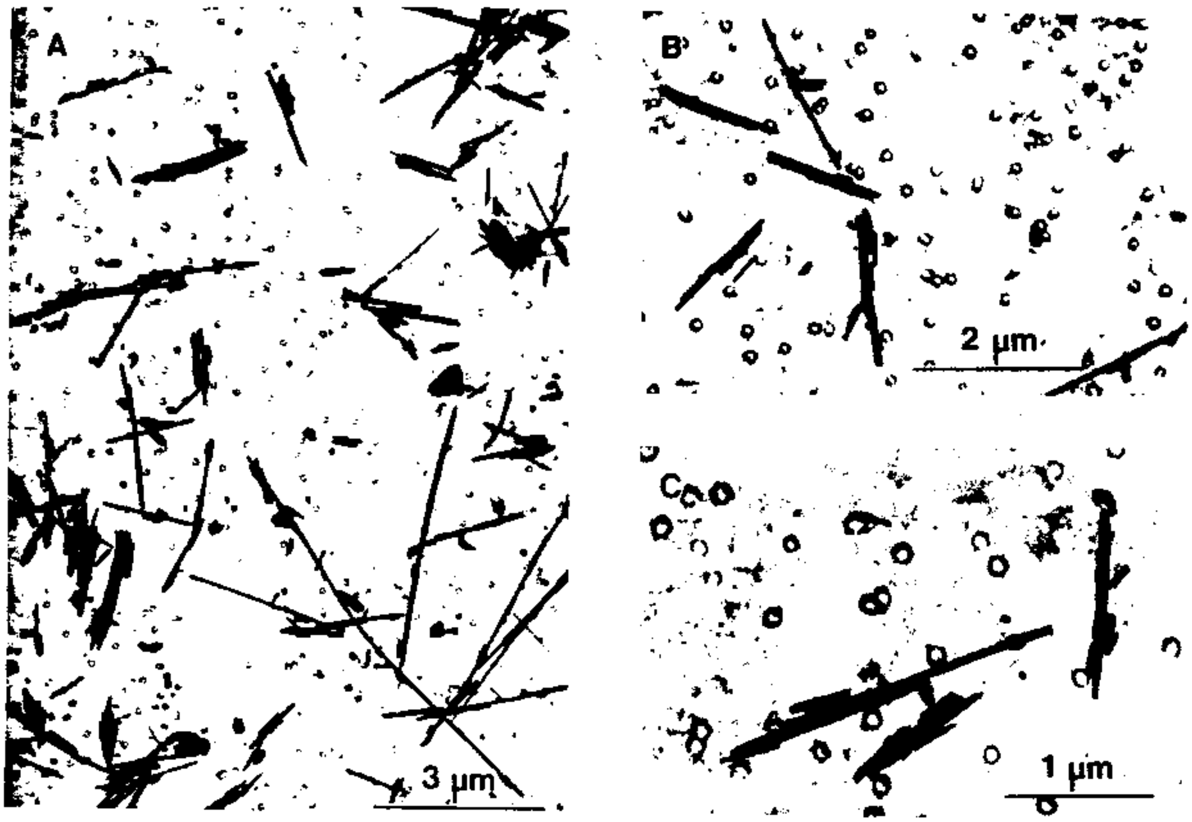


FIGURE 2. Transmission electron micrograph of the chrysotile asbestos sample. (A) X8,000; (B) X11,600; (C) X20,700.

Since it is recognized that the use of multiple assay systems and parameters provides a better assessment of the biological effects of industrial dusts, the PAM cytotoxicity assay was selected to complement the hemolysis data.[9] Moreover, in order to achieve a better evaluation of the respective potency of each fiber type, three variants of the cytotoxicity assay were carried out: 1) a short-term assay (18 hours) with *fresh cell monolayers*; 2) the same short-term assay (18 hours) but with *one day-old cell monolayers* instead; and 3) a long-term assay (96 hours) using *fresh cell monolayers* as the starting material.

Short-term assays

The results obtained with fresh PAM monolayers exposed for 18 hours to the mineral fibers are illustrated in Figures 3 and 4. First, when one looks at the reactivity of the two native silicate fibers, one can observe that the AT and CH fibers are highly cytotoxic. At both 50 and 250 ug, they caused significant extracellular releases of the marker enzymes when compared to non-exposed PAM (Figure 3). As previously reported, it is interesting to point out that the clay mineral induced significantly higher LDH releases than the

TABLE II

Effects of the Phosphorylation Process on Physico-chemical Properties of the Silicates*

Silicate	Phosphorous (% by weight)	Surface Charge (mV) –POCl3	+POCl3	Decrease in Specific Surface Area
Chrysotile	3.6	Positive (+39)	Negative (–26)	–40% (38 to 24 m2 . g-1)
Attapulgite (Attagel[R])	4.8	Negative (–23)	Negative (–30)	–75% (160 to 40 m2 . g-1)

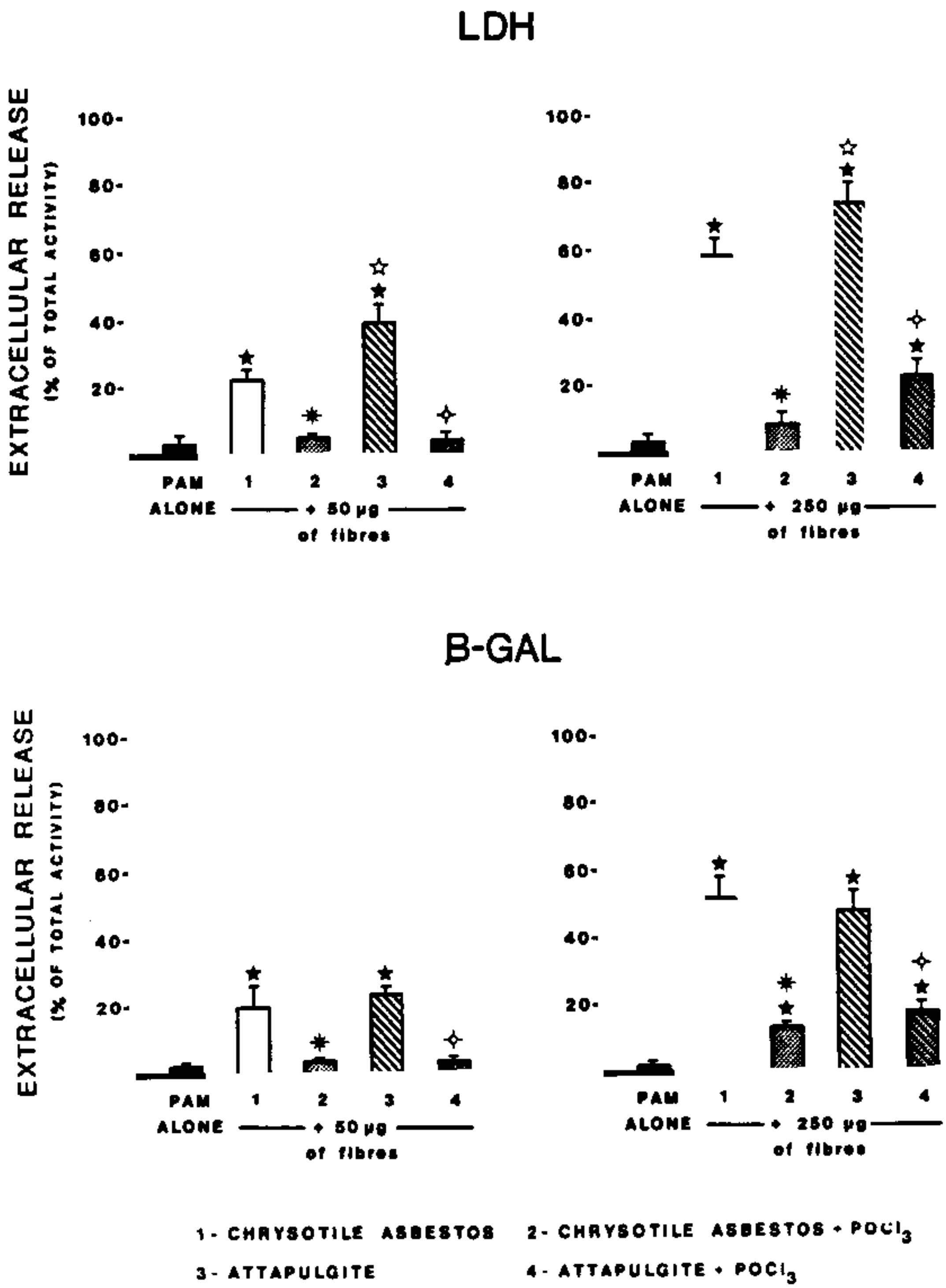


FIGURE 3. Rat pulmonary macrophage response (fresh monolayer). Percentages of the total LDH and ß-GAL enzymatic activities released in the extracellular medium from fresh cell monolayers exposed to 50 and 250 ug of mineral fibers. Each histogram represents the mean of 5 experiments +/- S.E.

★ $p \leq 0.05$ Each mineral fiber vs control (Dunnett's test, one sided).
☆ $p \leq 0.05$ Attapulgite vs chrysotile (t-test, paired data, two sided).
$p \leq 0.05$ POCl3-treated chrysotile vs chrysotile (t-test, paired data, one sided).
$p \leq 0.05$ POCl3-treated attapulgite vs attapulgite (t-test, paired data, one sided).

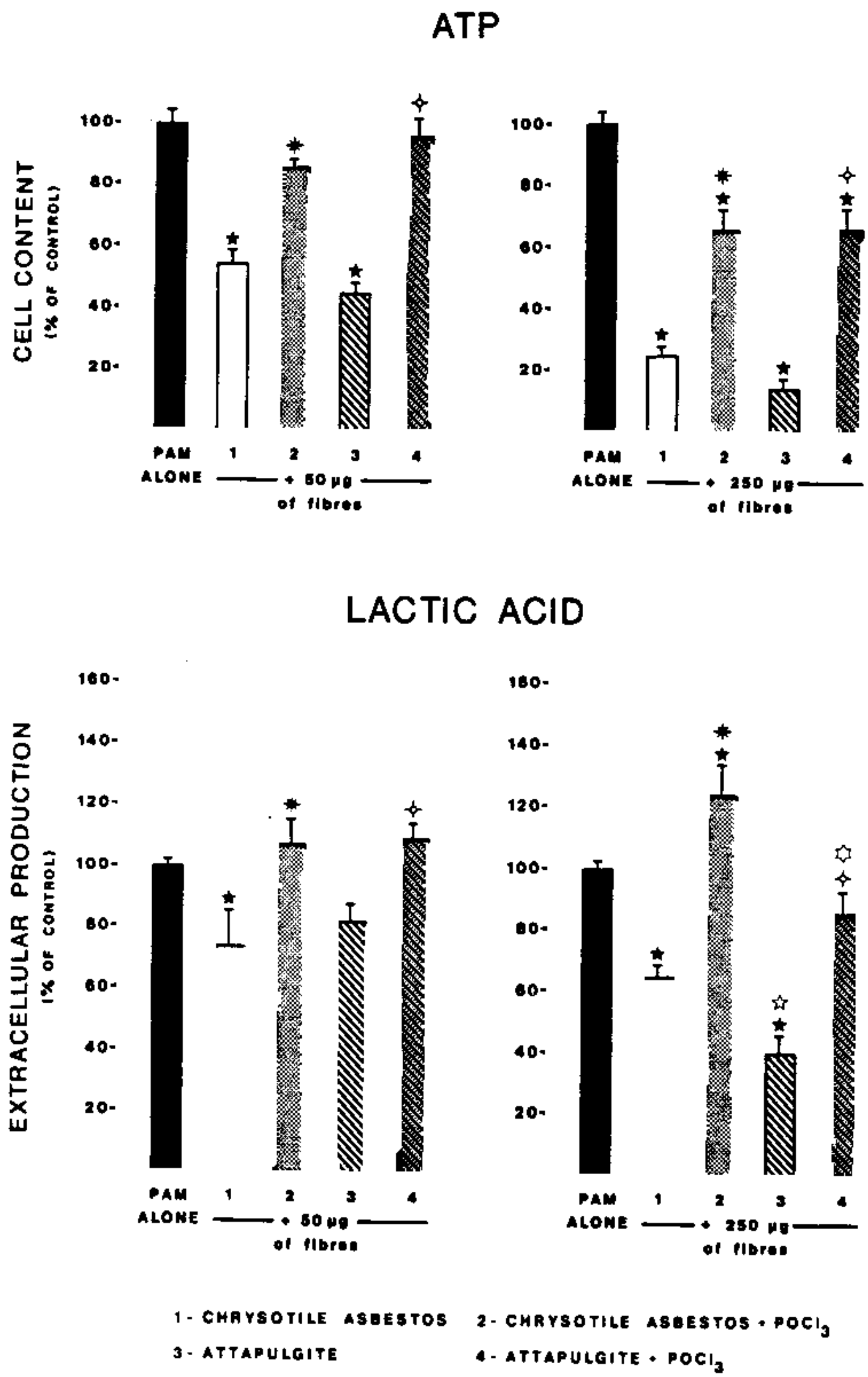


FIGURE 4. Rat pulmonary macrophage response (fresh monolayer). Cellular ATP levels and production of lactic acid from fresh cell monolayers exposed to 50 and 250 ug of mineral fibers. The results are expressed as a percentage relative to control cells incubated without stimulus. Each histogram represents the mean of 5 experiments +/- S.E.

★ $p \leq 0.05$ Each mineral fiber vs control (Dunnett's test, one sided for ATP; two sided for lactate).
☆ $p \leq 0.05$ Attapulgite vs chrysoltile (t-test, paired data, two sided).
$p \leq 0.05$ POCl3-treated chrysotile vs chrysotile (t-test, paired data, one sided).
$p \leq 0.05$ POCl3-treated attapulgite vs attapulgite (t-test, paired data, one sided).
$p \leq 0.05$ POCl3-treated attapulgite vs POCl3-treated chrysotile (t-test, paired data, two sided).

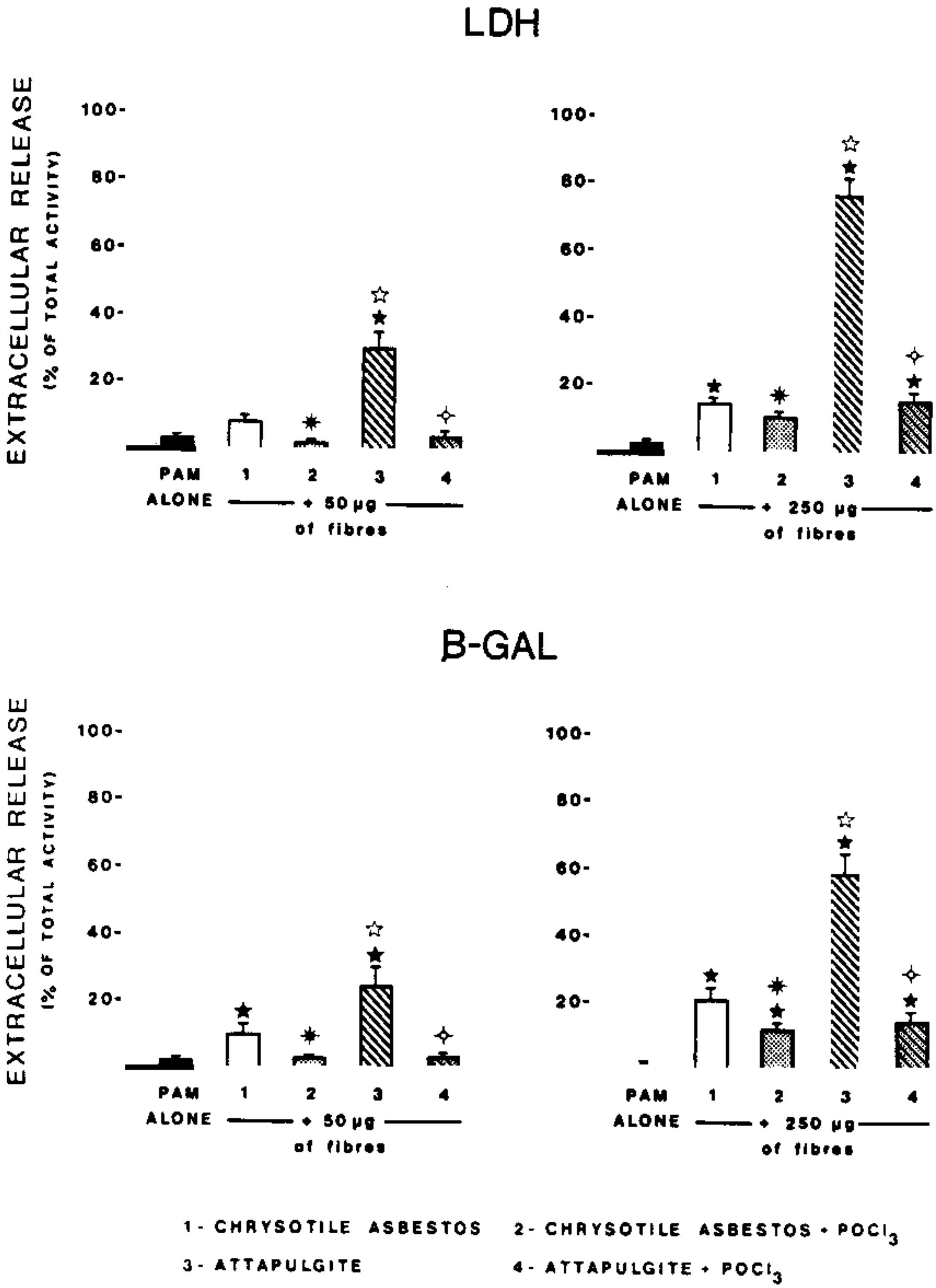


FIGURE 5. Rat pulmonary macrophage response (monolayer cultured for 24 hours). Percentages of the total LDH and ß-GAL enzymatic activites released in the extracellular medium from one day-old cell monolayers exposed to 50 and 250 ug of mineral fibers. Each histogram represents the mean of 5 experiments +/- S.E.

★ $p \leq 0.05$ Each mineral fiber vs control (Dunnett's test, one sided).
☆ $p \leq 0.05$ Attapulgite vs chrysotile (t-test, paired data, two sided).
✱ $p \leq 0.05$ POCl3-treated chrysotile vs chrysotile (t-test, paired data, one sided).
✧ $p \leq 0.05$ POCl3-treated attapulgite vs attapulgite (t-test, paired data, one sided).

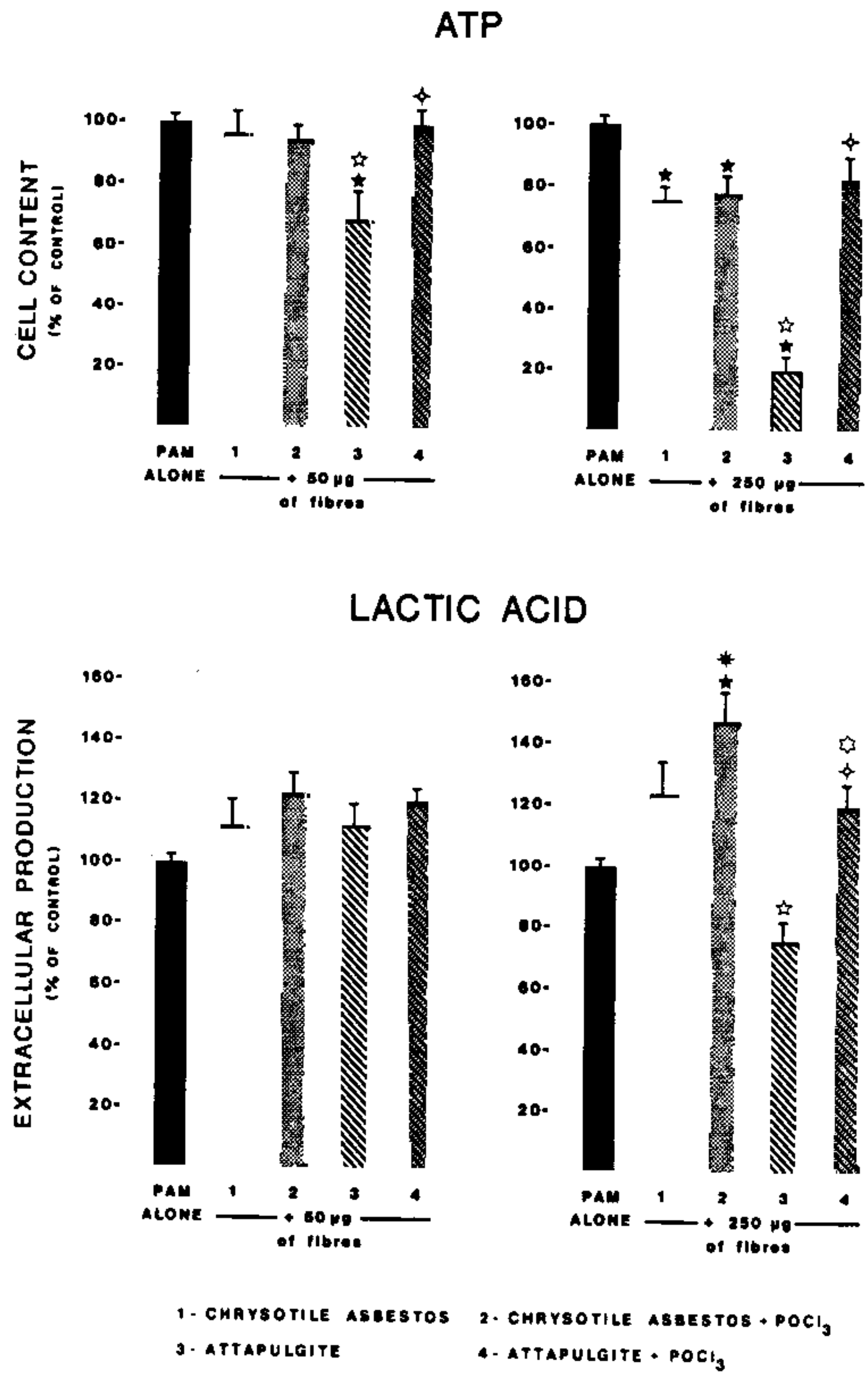


FIGURE 6. Rat pulmonary macrophage response (monolayer cultured for 24 hours). Cellular ATP levels and production of lactic acid from one day-old cell monolayers exposed to 50 and 250 ug of mineral fibers. The results are expressed as a percentage relative to control cells incubated without stimulus. Each histogram represents the mean of 5 experiments +/- S.E.

★ $p \leq 0.05$ Each mineral fiber vs control (Dunnett's test, one sided for ATP; two sided for lactate).
☆ $p \leq 0.05$ Attapulgite vs chrysotile (t-test, paired data, two sided).
✷ $p \leq 0.05$ POCl3-treated chrysotile vs chrysotile (t-test, paired data, one sided).
✧ $p \leq 0.05$ POCl3-treated attapulgite vs attapulgite (t-test, paired data, one sided).
✡ $p \leq 0.05$ POCl3-treated attapulgite vs POCl3-treated chrysotile (t-test, paired data, two sided.)

TABLE III

Membranolytic Effects of Chrysotile and Attapulgite Fibers Before and After the Phosphorylation Process

Fiber Sample	Percentage of Hemolysis at 1000 ug/ml[a]
Chrysotile	89.9 +/- 1.2
Attapulgite	78.8 +/- 3.1[b]
POCl3-treated chrysotile	5.5 +/- 1.3[c,d]
POCl3-treated attapulgite	16.1 +/- 1.6[c]

aData represent the mean value +/- S.E. (n = 8).

bp $\leq$ 0.05. Untreated AT vs untreated CH.

cp $\leq$ 0.05. Each phosphorylated fiber when compared to its respective native fiber.

dp $\leq$ 0.05. Phosphorylated CH vs phosphorylated AT.

asbestos sample.[11] No differences were observed between the AT and CH fibers as far as their respective capacity to induce an extracellular release of the lysosomal marker ß-GAL (Figure 3, lower panel). Comparatively, the $POCl_3$-treated fibers caused signifcant enzyme releases only at the 250 ug dosage; for the phosphorylated CH, only a selective release of ß-GAL was observed. Moreover, one can note that the intensity of the cytotoxic responses of the two chemically modified fibers at 250 ug are such that they are even less than what was observed with 50 ug of untreated CH or AT fibers. In order to validate the different cytotoxic profiles obtained with the marker enzymes (LDH and ß-GAL), cellular ATP levels and lactic acid productions were measured (Figure 4). Generally speaking, one can observe that these viability indexes reveal a better survival for PAM exposed to the chemically modified silicate fibers, as well as a higher biological reactivity for the AT fibers when the two native fibers are compared.

The responses of one day-old cell monolayers to the silicate fibers are illustrated in Figures 5 and 6. The main difference observed with this type of short-term cytotoxicity assay, when compared to the previous one (Figures 3 and 4), is that the older cell monolayers appear much less affected by native CH fibers. The native AT fibers remained as cytotoxic to PAM. Again, in this assay, both $POCl_3$-treated fibers showed significant reductions in toxicity. However, the decrease in biological activity was more evident for the phosphorylated AT sample because of the differences in the cytotoxic response between the untreated CH and AT fibers mentioned above. As shown in Figure 6, the difference in reactivity observed with older cell cultures, when compared to freshly established monolayers (Figure 4), may be linked with some kind of metabolic activation. While the ATP level remains generally a good index of cell viability, the production of lactic acid is significantly reduced only when the other parameters are indicative of a strong cytotoxic effect (very low cellular ATP and high LDH and ß-GAL releases). One can even observe that the production of lactic acid can be significantly stimulated, as it is with older PAM exposed to 250 ug of phosphorylated CH fibers (Figure 6, lower panels).

Long-term Assays

The long-term effects of the mineral fibers on PAM are illustrated in Figures 7 to 9. In this assay, fresh PAM monolayers were initially exposed for 24 hours to 50 ug of silicate fibers, then monitored up to 72 hours after the addition of fresh culture medium at the end of the initial 24-hour exposure period. This low dose of fiber was selected considering the strong toxicity observed in the short-term assays with the native CH and AT fibers. As observed in the two previous assays (Figures 3 to 6), the native AT fibers presented the strongest cytotoxic response. With the clay mineral, cellular levels of LDH (Figure 7), ß-GAL (Figure 8) and ATP (Figure 9, left panel) were depleted with time beyond viable recovery. Also, 96 hours after the initial challenge with the AT fibers, lactate production was reduced by ~ 60 percent (Figure 9, right panel). For PAM exposed to the native CH fibers, after the initial contact (24 hours), one can observe some kind of recovery by these cells when compared to control PAM. This recovery is reflected by the induction of cellular LDH levels (Figure 7, right panel), the leveling off in the depletion in ATP (Figure 9, left panel) and the slight stimulation in lactic acid production (Figure 9, right panel). Still, albeith less than for the native AT fibers, substantial levels of lysosomal enzyme were released in the extracellular medium by PAM exposed to native CH fibers (Figure 8).

The lower biological reactivity of the two $POCl_3$-treated mineral fibers was confirmed in this assay. As seen respectively in Figures 7 and 8 (left panels), the LDH and ß-GAL releases were hardly higher than those of the control cells, even after 96 hours of incubation. Although the chemically modified fibers show slight increases when one look at the cumulative enzyme releases (Figures 7 and 8, middle panels), these effects appear rather negligeable in comparison to the magnitude of what is observed with the native CH and AT fibers. Lactic acid productions (Figure 9, right panel) and LDH cellular levels (Figure 7, right panel) again appear stimulated with PAM who ingested the phosphorylated silicate fibers. The overall picture of low biological activity for the $POCl_3$-treated CH fibers is somewhat clouded by the significant decreases in ATP levels (Figure 9, left panel). Nonetheless, one can observe that the drop in cellular ATP is lower and much slower than the one seen with PAM exposed to untreated CH fibers. All in all, the $POCl_3$-treated AT fibers presented the lowest biological reactivity, being almost undistinguishable from the control PAM cultures.

Discussion

Two important points are revealed by these data. First, it is shown that two highly respirable short silicate fibers, namely AT and CH, are intrinsically cytotoxic.[11] Secondly, it is shown that the grafting of phosphorous compounds, thereby masking the (O-H) groups at the surface of those two native fibers, can drastically reduce their cytotoxic properties. Based on the hemolysis test and the three cytotoxicity assays, the decreasing order of biological reac-

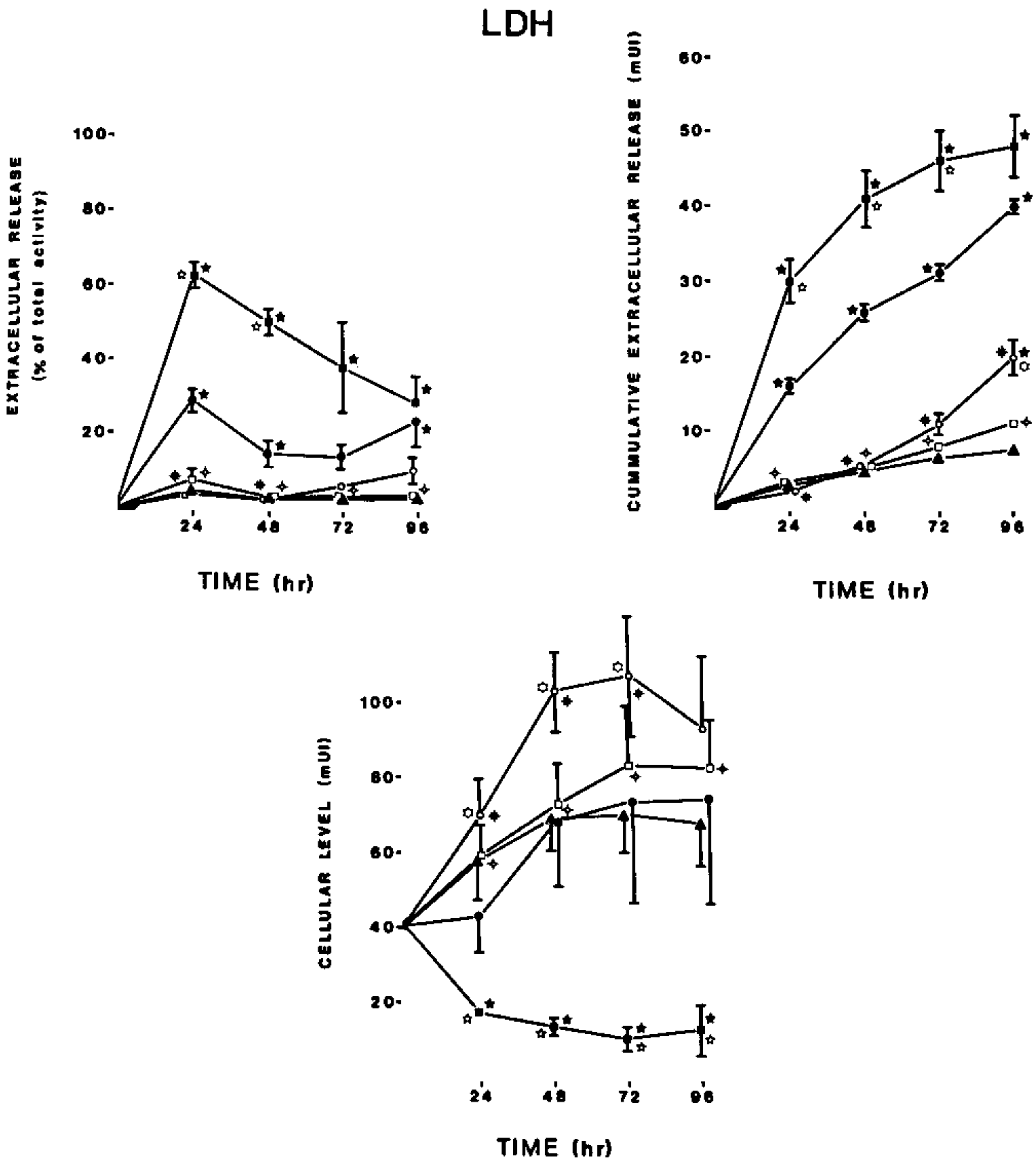


FIGURE 7. Long-term LDH profiles of fresh cell monolayers exposed to 50 ug of mineral fibers: control PAM (▲); chrysotile (●); POCl3-treated chrysotile (○); attapulgite (■); POCl3-treated attapulgite (□). Each data point represents the mean of 5 experiments +/- S.E.

★ $p \leq 0.05$ Each mineral fiber vs control (Dunnett's test, one sided).
☆ $p \leq 0.05$ Attapulgite vs chrysotile (t-test, paired data, two sided).
✱ $p \leq 0.05$ POCl3-treated chrysotile vs chrysotile (t-test, paired data, one sided).
✧ $p \leq 0.05$ POCl3-treated attapulgite vs attapulgite (t-test, paired data, one sided).
✡ $p \leq 0.05$ POCl3-treated attapulgite vs POCl3-treated chrysotile (t-test, paired data, two sided.)

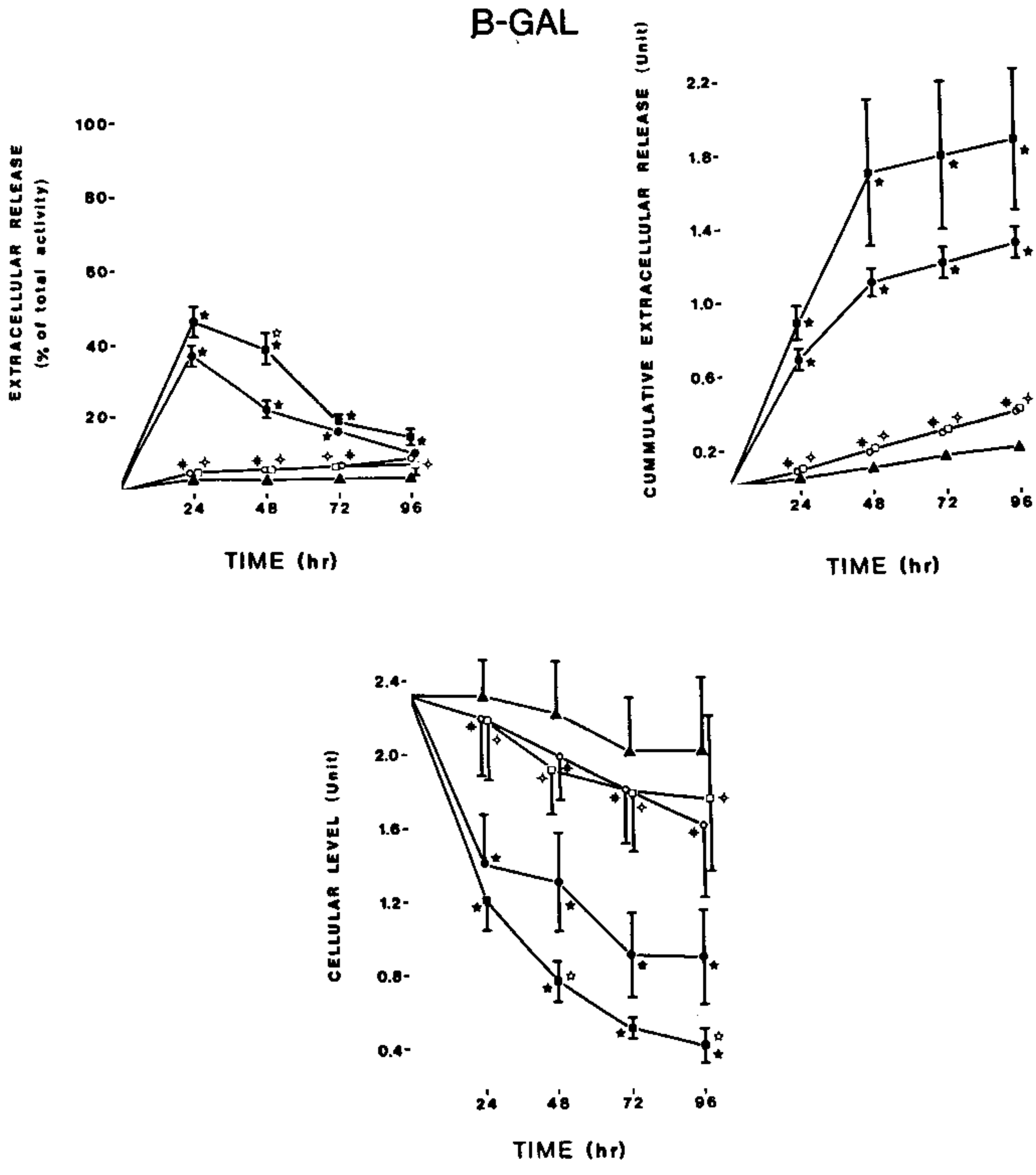


FIGURE 8. Long term ß-GAL profiles of fresh cell monolayers exposed to 50 ug of mineral fibers: control PAM (▲): chrysotile (●); POCl3-treated chrysotile (○); attapulgite (■); POCl3-treated attapulgite (□). Each data point represents the mean of 5 experiments +/- S.E.

$p \leq 0.05$ Each mineral fiber vs control (Dunnett's test, one sided).
$p \leq 0.05$ Attapulgite vs chrysotile (t-test, paired data, two sided).
$p \leq 0.05$ POCl3-treated chrysotile vs chrysotile (t-test, paired data, one sided).
$p \leq 0.05$ POCl3-treated attapulgite vs attapulgite (t-test, paired data, one sided).
$p \leq 0.05$ POCl3-treated attapulgite vs POCl3-treated chrysotile (t-test, paired data, two sided.)

tivity observed was: AT > > CH > > > > $POCl_3$-treated CH ≥ $POCl_3$-treated AT.

Physico-chemical analyses have shown that the POCl3 gas treatment induced the formation of a polyphosphorous coating at the surface of the CH fibers and an occlusion of the channels or pores of the crystalline structure of the AT fibers by phosphorous compounds.[24] In the past, metals like magnesium have been implicated in asbestos toxicity.[30-33] However, metal depositions or coating on asbestos fibers generally lessen the adverse effects of the native fibers on cell systems.[17,18,34,35] Moreover, our data as well as the available literature on the toxicity of heat-treated (dehydroxylated) CH fibers tend to point toward the (O-H) groups as the culprit chemical specie.[13,14,29] Similarly, a dehydroxylation of AT fibers by heat has also been shown to decrease the hemolytic potential of this clay mineral.[35,36] In fact, the lysis of RBC by AT and CH appear to be "primarily related to the minerals' surface physicochemical properties rather than their particle shape, involving hydrogen bonding between the fibers' surfaces and the RBC membrane."[35] The same phenomenon is most probably occurring with PAM in cytotoxicity assays.[29]

The $POCl_3$-treated silicates fibers induced very little secretion of lysosomal enzymes from PAM, as compared to the native CH and AT fibers. This would suggest that the chemically modified fibers should be less likely to cause lung damage.[3,5] Indeed, extracellular lysosomal enzyme releases by activation or damage to PAM have been linked to lung disorders such as inflammation, edema and fibrosis.[37-40] Although the $POCl_3$-treated CH fibers did not show an absolute reduction of their biological reactivity in the long-term cytotoxicity assay, as seen apparently with the phosphorylated AT fibers, it is nonetheless obvious that PAM exposed to modified CH fibers show a better survival than PAM exposed to native CH fibers. *In vivo*, PAM are known to appear quickly at the deposition sites of inhaled asbestos fibers.[41] Consequently, even if it was through a delayed cytotoxic effect instead of by complete innocuousness, the pulmonary clearance of both $POCl_3$-treated fibers should be by far more efficient than for the native silicate fibers.[42]

Native AT and CH fibers are known for their highly sorptive properties.[28,43,44] From the literature, growing evidences are accumulating on the ability of certain cytotoxic particles to adsorb and "carry" genotoxic agents (e.g., benzo[a]pyrene, B[a]P) and its link with carcinogenesis (for a review, see 21). While other chemical treatments such as acid-leaching and organosilane deposition have been shown to reduce only partially the binding of B[a]P to CH asbestos fibers, it has been demonstrated that $POCl_3$-treated CH

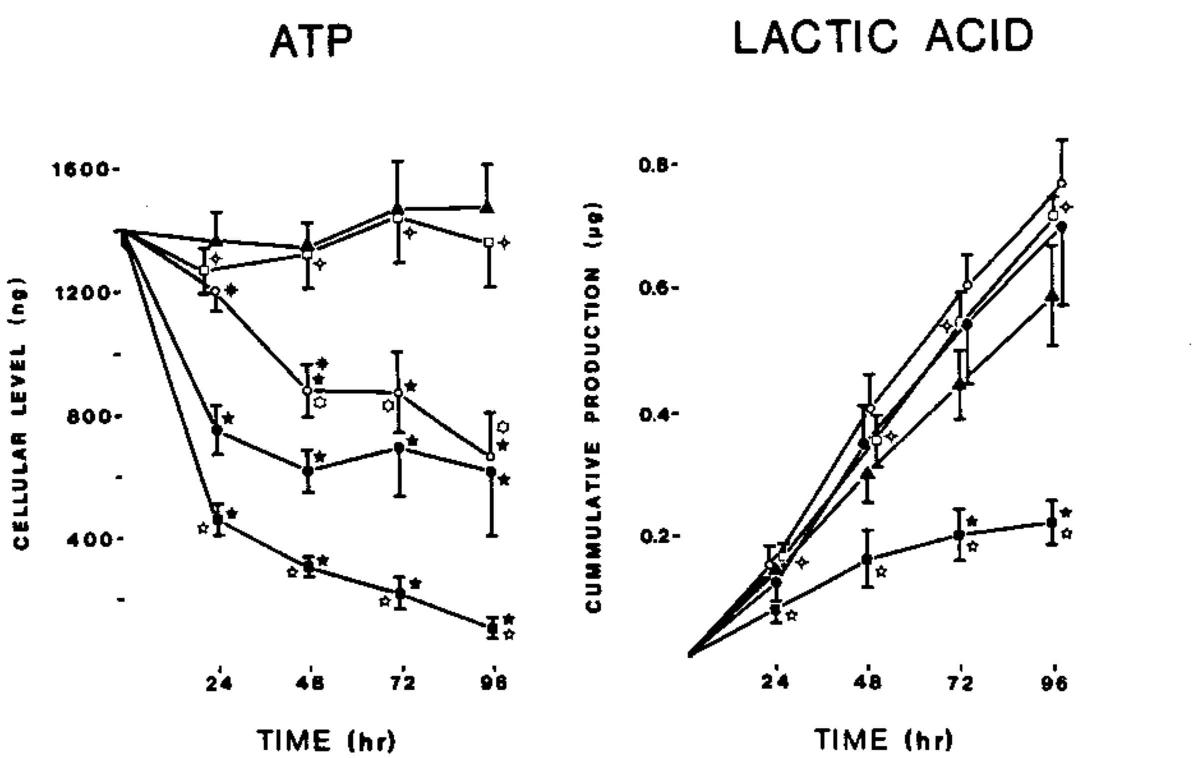


FIGURE 9. Daily cellular ATP levels and cumulative production of lactic acid of fresh cell monolayers exposed to 50 ug of mineral fibers: control PAM (▲); chrysotile (●); POCl3-treated chrysotile (○); attapulgite (■); POCl3-treated attapulgite (□). Each data point represents the mean of 5 experiments +/- S.E.

★ $p < 0.05$ Each mineral fiber vs control (Dunnett's test, one sided).
☆ $p < 0.05$ Attapulgite vs chrysotile (t-test, paired data, two sided).
✱ $p < 0.05$ POCl3-treated chrysotile vs chrysotile (t-test, paired data, one sided).
-◇- $p < 0.05$ POCl3-treated attapulgite vs attapulgite (t-test, paired data, one sided).
☆ $p < 0.05$ POCl3-treated attapulgite vs POCl3-treated chrysotile (t-test, paired data, two sided.)

fibers completely lose their adsorption potential for many polyaromatic hydrocarbons including B[a]P.[19,45] This finding is of tremendous importance since it is clearly established that the incidence of pulmonary cancers is multiplied (synergetic effect) in asbestos-exposed workers who smoke.[46] Without presuming on the importance of "solid-state" carcinogenesis mechanisms, preliminary data have also shown that rats treated with short $POCl_3$-treated CH fibers similar to those used in this study presented a decreased incidence of peritoneal mesothelioma, as well as an increased latency period for the appearance of the tumors.[47] Interestingly, this *in vivo* passivation effect observed with the $POCl_3$ treatment does not appear unique. Effectively, a chemical treatment such as acid-leaching, known to reduce the *in vitro* cytotoxicity of mineral fibers, has been shown to reduce their potential for inducing mesothelioma.[12,48]

In conclusion, our data provide further evidences that the surface chemistry can be a determinant factor to consider when one evaluates the biological reactivity of mineral fibers, more so if these fibers are rich in exposed (O-H) groups. One cannot however completely dismiss the involvement of the so-called "fibre-effect" in the mechanism of action of fibers. Size is very important insofar as the clearance of inhaled particles is concerned.[7,9] This latter aspect may turn out to be the predominant mechanism of action for long fibers. Consequently, it is imperative to compare native and chemically modified fibers of specific and restricted lengths and diameters. Only then will we be able to evaluate the relative importance of the chemical nature and the dimensional characteristics of a fiber to its intrinsic toxicity.

Acknowledgments

We wish to thank Ms. Martine Senneville, Ms. Irene Levesque, Mr. Bruno Gagne and Mr. Alain Lemieux for their able technical assistance, and Ms. Linda Dawson for typing this manuscript. This work was supported by L'Institut de l'Amiante/Division de la Recherche, Universite de Sherbrooke (Grant #A19).

References

1. **Green, G.M., G.J. Jakab, R.B. Low and G.S. Davis:** Defense Mechanisms of the Respiratory Membrane. *Am. Rev. Resp. Dis. 115*:479-514 (1977).

2. **Schiller, E.:** *Inhaled Particles and Vapours*, pp. 342-344. C.N. Davies, Ed. Pergamon Press, London (1961).

3. **Brain, J.D.:** Macrophage Damage in Relation to the Pathogenesis of Lung Disease. *Environ. Health Perspect. 35*:21-30 (1980).

4. **Nathan, C.F., H.W. Murray and Z.A. Cohen:** The Macrophage As an Effector Cell. *New Engl. J. Med. 303*:622-626 (1980).

5. **Goldstein, E.:** Hydrolytic Enzymes of Alveolar Macrophages. *Rev. Infect. Dis. 5*:1078-1092 (1983).

6. **Stanton, M.F. and M.W. Layard:** Carcinogenicity of Natural and Man-Made Fibers. *Adv. Clin. Oncol. 1*:181-187 (1978).

7. *Biological Effects of Mineral Fibres*, Vol. 1, pp. 1-494. J.C. Wagner, Ed. Scientific Publications No. 30, International Agency for Research on Cancer, Lyon (1980).

8. *Biological Effects of Mineral Fibres*, Vol. 2, pp. 497-1007. J.C. Wagner, Ed. Scientific Publications No. 30, International Agency for Research on Cancer, Lyon (1980).

9. *The* In Vitro *Effects of Mineral Dusts*, pp. 1-373. R.C. Brown, I.P. Gormley, M. Chamberlain and R. Davies, Eds. Academic Press, Toronto (1980).

10. **Pailes, W.H., D.J. Judy, H. Resnick and V. Castranova:** Relative Effects of Asbestos and Wollastonite on Alveolar Macrophages. *J. Tox. Environ. Health 14*:497-510 (1984).

11. **Nadeau, D., L. Fouquette-Couture, D. Paradis et al:** Cytotoxity of Respirable Dusts from Industrial Minerals: Comparison of Two Naturally Occurring and Two Man-made Silicates. *Drug Chem. Toxicol. 10* (#1-2) (in press).

12. **Jaurand, M.C., J. Bignon, P. Sebastien and J. Goni:** Leaching of Chrysotile Asbestos in Human Lungs. Correlation with *In Vitro* Studies Using Rabbit Alveolar Macrophages. *Environ. Res. 14*:245-254 (1977).

13. **Sakabe, H., K. Koshi and H. Hagashi:** *Inhaled Particles,* Vol. 1, p. 423. W.H. Walton, Ed. Grusham Press, England (1971).

14. **Le Bouffant, L., S. Bruyere, H. Daniel et al:** Influence d'un Traitement Thermique des Fibres de Chrysotile sur Leur Comportement Dans le Poumon. *Pollution Atmospherique (Janv.-Mars)*:44-49 (1983).

15. **Langer, A.M., M.S. Wolff, A.N. Rohl and I.J. Selikoff:** Variations of Properties of Chrysotile Asbestos Subjected to Milling. *J. Toxicol. Environ. Health 4*:173-188 (1978).

16. **Spurny, K.R., W. Stober, H. Opiela and G. Weiss:** On the Problem of Milling and Ultrasonic Treatment of Asbestos and Glass Fibers in Biological and Analytical Applications. *Am. Ind. Hyg. Assoc. J. 41*:198-203 (1980).

17. **Pezzoli, P.A.:** Asbestos Treatment with Metal Molybdates. United States Patent, No. 4,171,405 (1979).

18. **Flowers, E.S.:** Novel Metal-Micelle Asbestos and Treatment of Asbestos and Other Silicate Minerals to Reduce their Harmful Properties. United States Patent, No. 4,401,636 (1982).

19. **Morrison, D.G., T.L. McLemore, E.C. Lawrence et al:** *In Vitro* Cytotoxicity of Chrysotile Asbestos to Human Pulmonary Alveolar Macrophages is Decreased by Organosilane Coating and Surfactant. *Cell Biol. Toxicol. 2*:293-309 (1986).

20. **Lalancette, J.-M. and J. Dunnigan:** Phosphated Asbestos Fibers. United States Patent, No. 4,356,057 (1982).

21. **Dunnigan, J.:** Biological Effects of Fibers: Stanton's

Hypothesis Revisited. *Environ. Health Perspect.* *57*:333-337 (1984).

22. **Nadeau, D., L. Fouquette-Couture and J. Khorami:** Surface Chemistry and Mineral Fiber Toxicity: Evidences for an Interrelation. *Proc. Can. Fed. Biol. Soc. 29*:141 (1986).

23. **Jolicoeur, C., P. Roberge and J.L. Fortier**: Separation of Short Fibers from Bulk Chrysotile Asbestos Fiber Materials: Analysis and Physico-Chemical Characterization. *Can. J. Chem. 59*:1140-1148 (1981).

24. **Khorami, J. and D. Nadeau**: Physicochemical Characterization of Asbestos and Attapulgite Mineral Fibers Before and After Treatment with Phosphorous Oxychloride. *Thermochimica Acta. 108*:279-287 (1986).

25. **Paradis, D. and D. Nadeau**: Quantitative Determination of Lactic Acid in Cell Culture Media and Biological Fluids: Optimization by Automatic Rate Analysis. *J. Tis. Cult. Methods* 7:175-180 (1982).

26. **Tallarida, R.J. and R.B. Murray:** *Manual of Pharmacologic Calculations with Computer Programs.* Springer-Verlag, New York (1981).

27. **Dunnett, C.W.**: A Multiple Comparison Procedure for Comparing Several Treatments with a Control. *J. Am. Stat. Assoc. 50*:1096-1121 (1955).

28. **Haden, W.L., Jr. and I.A. Schwint:** Attapulgite. Its Properties and Applications. *Ind. Eng. Chem. 59*:58-69 (1967).

29. **Dunnigan, J., D. Nadeau, D. Paradis et al:** *Proc. Fourth Int. Conf. on Asbestos,* Vol. II, pp. 747-772. Istituto di Arte Mineraria del Politechnico and Associazione Mineraria Subalpina, Torino (1980).

30. **Macnab, G. and J.S. Harington:** Haemolytic Activity of Asbestos and Other Mineral Dusts. *Nature (Lond.) 214*:522-523 (1967).

31. **Allison, A.C.:** *Biological Effects of Asbestos: Proceedings of a Working Conference,* pp. 89-93. P. Bogovski, Ed. International Agency for Research on Cancer, Lyon (1973).

32. **Morgan, A., P. Davies, J.C. Wagner et al:** The Biological Effects of Magnesium-Leached Chrysotile Asbestos. *Brit. J. Exp. Pathol. 58*:465-473 (1977).

33. **Weitzman, S.A. and P. Graceffa**: Asbestos Catalyses Hydroxyl and Superoxide Radical Generation from Hydrogen Peroxide. *Arch. Biochem. Biophys. 228*:373-376 (1984).

34. **Hahon, N., V. Vallyathan, J.A. Booth and M.J. Sepulveda:** *In Vitro* Biologic Responses to Native and Surface-Modified Asbestos. *Environ. Res. 39*:345-355 (1986).

35. **Oscarson, D.W., G.E. Van Scoyoc and J.L. Ahlrichs:** Lysis of Erythrocytes by Silicate Minerals. *Clay and Clay Minerals 34*:74-80 (1986).

36. **Hayashi, H., K. Koshi and H. Sakabe:** *Proc. Int. Clay Conf. Tokyo,* Vol. 1, pp. 903-913. L. Heller, Ed. Israel University Press, Jerusalem (1969).

37. **Heppleston, A.G.:** The Fibrogenic Action of Silica. *Brit. Med. Bull. 25*:282-287 (1969).

38. **Danvenberg, A.M.:** Macrophages in Inflammation and Infection. *Physiol. Med. 293*:489-493 (1975).

39. **Davies, P. and A.C. Allison:** *Lysosomes in Biology and Pathology,* pp. 61-98. J.T. Dingle and R.T. Dean, Eds. Elsevier-North Holland, Amsterdam (1976).

40. **Schorlemmer, H.U., P. Davies, W. Hylton et al:** The Selective Release of Lysosomal Acid Hydrolases from Mouse Peritoneal Macrophages by Stimuli of Chronic Inflammation. *Brit. J. Exp. Pathol. 58*:315-326 (1977).

41. **Brody, A.R., D.B. Warheit, L.Y. Chang et al:** *Technology Impact: Potential Directions for Laboratory Medicine,* Vol. 429, pp. 108-120. D.B.P. Goodman, Ed. The New York Academy of Sciences, New York (1984).

42. **Privalova, L.I., B.A. Katsvelson, A.B. Osipenko et al:** Response of a Phagocyte Cell System to Products of Macrophage Breakdown as a Probable Mechanism of Alveolar Phagocytosis Adaptation to Deposition of Particles of Different Cytotoxicity. *Environ. Health Perspect. 35*:205-218 (1980).

43. **Frank, K.:** *Asbestos*, pp. 89-91. Becker and Haag, Hamburg (1952).

44. **Hodgson, A.A.:** *Fibrous Silicates, The Royal Institute of Chemistry*, Lecture Series No. 4, pp. 26-28, 41-44, The European Printing Company, London (1965).

45. **Menard, H., L. Noel, J. Khorami et al:** The Adsorption of Polyaromatic Hydrocarbons on Natural and Chemically Modified Asbestos Fibers. *Environ. Res. 40*:84-91 (1986).

46. **Selikoff, I.J., E.C. Hammond and J. Churg:** Asbestos Exposure, Smoking and Neoplasia. *J. Am. Med. Assoc. 204*:106-112 (1968).

47. **Minardi, F.:** *Int. Conf. Occup. Environ. Signif. Indust.* Carcino. Oct. 6-10, Bologna, Italy (1985).

48. **Monchamp, G., J. Bignon, M.C. Jaurand et al:** Mesothelioma in Rats Following Inoculation with Acid-Leached Chrysotile Asbestos and Other Mineral Fibers. *Carcinogenesis 2*:229-236 (1981).

A Hypothesis on the Possible Contribution of Coal Cleats to CWP

THOMAS P. MELOY
Benedum Professor, Particle Anaylsis Center, West Virginia University

The presence of respirable quartz-bearing mineral particles has been well documented in many coal mines, and the Mine Safety and Health Administration regulations address the quartz content of mine dusts. Unfortunately, the correlation between the quantity of respirable quartz-bearing mineral particles and the pathogenicity of the dust is not strong. Work is currently underway by the National Institute for Occupational Safety and Health/U.S. Bureau of Mines and work is being included in the Respirable Dust Center Program by Dr. Seehra to determine the surface availability of quartz in mixed composition mine dusts. However, this paper propose a possible source of surface quartz or a special region in the coal that may contribute to the pathogenicity of selected particles in the respirable dust.

Assumed in this model is the hypothesis that either the cleat surface is coated with quartz or some cytotoxic substance that in the body is capable of destroying macrophage and thus inducing a fibrotic response,[1] that during the fragmentation a reasonable proportion of the respirable size coal particles contain some of the original cleat surface and that these particles have the same order of *in vivo* cytotoxicity as do the quartz particles. It may be that these cleat surfaced respirable size particles are only contributory to the overall pathogenicity of the coal dust, nevertheless, there are enough of these particles to te considered as a potential source of the cytotoxic dust particles.

This paper demonstrates that if the cleat surfaces are mineralized with quartz or have a pathogenic coating, then in many mines there will be enough respirable coal dust particles containing some cleat surface to cause a fibrotic reaction. To understand why some of the dust particles contain as part of their surface some of the cleat surface, consider what happens when a beer bottle is broken. While there are a large number of beer bottle fragments, many of the fragments, particularly the larger fragment sizes, will have as a fraction of their surface part of the original beer bottle surface. The mcdel and mathematics of this problem have been worked out by Meloy.[2-4]

In the homogeneous IAC model,[2,5] a fragment or particle resulting from comminution is equally likely to occur anywhere in the material being broken. Therefore the probability of a particle of size x having part of the cleat surface in it, p(x), is proportional to x. Thus:

$$p(x) = kx \qquad (1)$$

where:

k is a constant.

To quantify k, one must know the surface area of the cleats per cubic meter, which is the number of cleats per meter, n, times the surface area of the cleat, times 2 – the cleat has two surfaces. Thus a coal with 100 cleats per meter, has 200 square meters of cleat surface per cubic meter.

For a particle of size x to contain part of the cleat surface, it must be within a distance of plus or minus half the particles diameter, x/2, from a cleat surface.[2] The probability of a fragment of size x being in this region is the ratio of the volume of plus or minus half the fragment diameter times the cleat surface area, 2nx, divided by the total volume of the block, one meter cubed. Thus:

$$p(x) = 2nx/1 \qquad (2)$$

Hence:

$$k = 2nx.$$

Before proceeding further with the quantification, two concepts must be understood. First, when a fragment containing part of the cleat surface is formed, actually two fragments are formed, one on either side of the cleat surface. This is known as the two step process. Considering now the two step breakage problem: in the IAC model, when a fragment forms that contains the cleat surface, the fragmentation proceeds thru the cleat surface and completes the fragmentation on the other side of the cleat surface. However, since the cleat is a double surface, the fragment is further divided at the cleat surface into two smaller particles – the two step fragmentation process.

Secondly, during this two step fragment formation, larger particles secondarily break into smaller particles. These particles have their own size distribution as derived by Meloy and Clark.[4] For the sake of simplicity, it will be assumed that the two particles are half the size of the original particle – two hemispheres of thickness x. Therefore, since the original size particle is 2x, and since it broke into 2 equally sized particles of thickness x, the probability of a respirable size particle containing some of the original cleat surface forming is, from equation 2:

$$p(x) = 8nx/1 \qquad (3)$$

To obtain the probability of a particle of size x not containing part of the cleat surface, one takes the volume where a non cleat particle must form, and ratios it to the total volume, 1 minus equation 1. Thus the probability that a particle of size x will not contain cleat surface, p(x)nc beccmes:

$$p(x) = (1-nx)/1 \qquad (4)$$

To find the ratio of fragments of size x containing cleat surface to those not containing cleat surface, one ratios the respective probabilities, equations 3 and 4. One obtains:

$$\text{ratio} = 8nx/(1-nx) \qquad (5)$$

where nx in the denominator is small compared to 1, and thus the ratio becomes 8nx.

If one assumes that n is equal to 800 cleats per meter — Preston County bright layer coals and the particle size is 5 microns, then 3.2 percent of the respirable size coal particles have some of the original cleat surface on their surface. Because quartz has twice the density of coal, this is equivalent to saying that 3.2 mg/m^3 of quartz are present in a respirable dust that contains 50 milligrams of coal dust or 6.4 mg/m^3 of quartz are present in a respirable silica mine dust. For 10 cleats per meter this is equivalent to 0.4 and 0.8 mg/m^3 respectively.

Discussion

As presented, the model contains two parts: the prediction that the cleat surface fragments will be cytotoxic and that there will be enough particles in the dust with some cleat surface to be a significant source of cytotoxicity. If one considers that the average coal fragment containing cleat surface is six sided, then in theory it would have only 1/6th the toxicity of a quartz particle. On the other hand, it only takes one corner or edge to make the particle toxic. This is and will probably remain an unresolved problem for quite some time.

Providing that there is no other major source of cytotoxic internal communicating surface in coal, this hypothesis predicts that for a given level proportional to the cleat surface in the coal. Naturally there may be other sources of pathogenic particles that mask the above predicted relationship.

The calculation of the percent of respirable size coal dust particles that are likely to be present, while a simplified calculation, is relatively conservative. Though the discussion has been limited to cleat surface, it applys equally well to any other internal coal surface that is both cytotoxic and is likely to appear on a respirable size dust particle. However, assuming cleat surface cytotoxicity, there are more than enough particles containing cleat surface, present in coal dusts to be a significant source of particles that are pathogenic to anyone inhaling a sufficient quantity.

In the literature there is very little information on either the total amount of connected internal surface, its surface composition, or how much of this surface is likely to be present in the dust. This is one area that should be investigated.

Conclusion

This theoretical paper presents the hypothesis that respirable size coal particles containing some of the cleat surface may be a significant source of the pathogenic particles in the dust. Specifically:

1. In coal seams that contain between 10 and 80 cleats per decimeter, the respirable coal dust contains the equivalent of .6 to 6 percent by weight of silica particles.
2. The pathogenicity of the coal is proportional to the cleat or communicating internal surface area of the coal.
3. A more definitive calculation as to the amount of respirable cleat surface dust particles present in dusts.
4. One should measure the cytotoxic behavior of coal particles containing a thin layer of silica.
5. Work needs to be done to determine the ccmposition of cleat surfaces, its cytotoxic behavior, how much cleat surface is present in coals and how much other communicating internal surface is present in coals.

Acknowledgment

This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

References

1. **Meloy, T.P.:** Liberation Theory — Eight Useful Theorems. *Int. J. Miner. Process.* *13*:113-124 (1984).
2. **Meloy, T.P., U. Preti and G. Ferrara:** Volume and Mass Locking Profiles Derived — Theoretical and Practical Conclusions. *Int. J. Miner. Process.* (to be published). (1986)
3. **Meloy, T.P. and N.N. Clark:** Gereralized Locking Profile of Angular Particles — Locked Particle Theory. *Part. Charact.*, pp. 63-67 (1086)
4. **Meloy, T.P. and N.N. Clark:** Locking Profile of Diamond Shaped Particles — of all Aspect Ratios. *Int. J. Miner. Process.* (to be published) (1987).
5. **Meloy, T.P.:** A Working Hypothesis on How Silica and Surfaces May Cause Silicosis and CWP. *Proceedings Repirable Dust in the Mineral Industries*, pp. 15-18. Univ. Park, Pa. (1987).

GENERIZATION & CHARACTERIZATION II

Reducing Employee Silica Dust Exposures – A Case Study

WILLIAM J. FRANCART[A], JOSEPH M. DENKA and W. CAROL ENSMINGER[B]
[A]Mine Safety and Health Administration, Pittsburgh Health Technology Center; [B]Mine Safety and Health Administration, Metal and Nonmetal Mine Safety and Health

Introduction

One function of the Mine Safety and Health Administration's (MSHA) Pittsburgh Health Technology Center is to provide assistance to MSHA enforcement efforts and industry for maintaining air contaminants within applicable standards. In fulfilling this objective, a number of silica sand operations have been investigated to determine employee silica dust exposures and respirable dust sources, and to evaluate existing dust control techniques. In plants where improvements can be made or deficiencies are found, recommendations for changes to dust control systems are presented to the company.

The purpose of this paper is to present results of investigations at two silica sand operations where initial and follow-up investigations have been conducted. The focus of the paper will be the identification of dust sources, the evaluation of dust collection systems, and reductions obtained by the companies in employee silica dust exposures following improvements to the process and support systems.

Controlling silica dust levels to a minimum is important since silica dust can severely damage the lungs. Respirable dust standards normally range from 0.15 to 0.60 mg/m^3 depending on silica content, but can be as low as 0.10 mg/m^3.

Prior to these investigations, the plants had difficulty maintaining compliance with the respirable silica dust standard. Improvements in dust control techniques have provided both plants with 100 percent compliance in follow-up studies.

Description of Operations

Two operations were surveyed to determine the extent of silica dust overexposures. Plant A processed a high grade sandstone (Orthoquartzite) by crushing, drying, screening and milling. The major uses of the sand which was bagged or bulk loaded into truck and rail cars were the production of glass and paint. Plant B also processed a high grade sandstone, which was bagged and bulk loaded as pool filter media, play sand and landscaping material. Both operations had been cited by MSHA for silica dust overexposures prior to the surveys.

At Plant A, material hauled from the quarry was crushed at a primary crusher and a secondary crusher to reduce the material to a size suitable for wet processing. Rod and chaser mills wet ground the material into a sand slurry which is dewatered on vacuum filters and dried by a fluid bed drier. The cleaned sand was then either sized for sale as whole grain sand, or further reduction was made in pebble mills to produce a ground silica product. Both products were then bulk loaded into trucks and rail cars.

At Plant B, material hauled from the quarry was also crushed and sized. Whole grain sand was bagged and palletized manually in 100 pound paper bags, and by an automated bagger into 50 pound plastic bags. Landscaping chips were also bagged with the automated bagger. On occasion, sand was bulk loaded into trucks.

Respirable Dust Sampling Procedures

Respirable dust samples were collected using approved respirable dust samplers calibrated and operated at 1.7 Lpm. Samples were collected on Type FWS-B (PVC) membrane filters with a 5.0 micron pore size. The filters were pre- and post-weighed on an analytic balance to the nearest thousandth of a milligram. Samples with sufficient weight gain were analyzed by the Denver Safety and Health Technology Center for quartz content using the X-ray diffraction method. The Time Weighted Average (TWA) and Threshold Limit Value (TLV) for each sample were calculated using the following formulas

$$TWA = \text{dust wt (mg)}/1.7\ \text{Lpm} \times \text{time (min)} \times 0.001\ m^3/L$$

$$TLV = 10\ mg/m^3/[\%\ SiO_2 + 2]$$

The TWA is the average full shift respirable dust exposure determined from gravimetric sampling data, while the TLV is the allowable respirable dust exposure based upon the quartz content of the respirable dust.(1)

Personal respirable dust samples were collected on a variety of occupations depending on work locations and previous Metal and Nonmetal Mine Safety and Health (MNMS&H) inspector sampling results. These samples were collected to determine employee exposures.

Area respirable dust samples were collected at a variety of locations depending on visible dust emissions and employee proximity to those areas. These samples were collected to assist in determining silica dust generation sources and the contribution to personal employee exposures.

In addition to the gravimetric sampling, GCA instantaneous dust concentration measurements were taken in all areas where the employees worked while wearing the personal samplers. The instrument used for these measurements was the RAM-1 (Real-Time Aerosol Monitor) made by the GCA[3] Corporation/Environmental Instruments. The concentrations are given in mg/m^3. GCA readings are helpful in identifying respirable dust generating sources and indicating areas where dust control measures are inadequate, and do not indicate full shift respirable dust concentrations.(2)

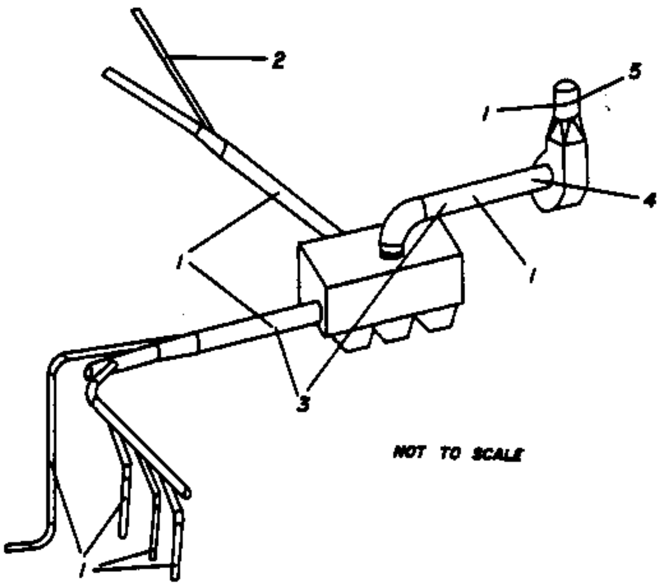


FIGURE 1. Location of measurements for testing ventilation systems. Key: 1. Static and velocity pressures — all branches; 2. Velocity using thermoanemometer — low velocity; 3. Static pressure drop across collector, 4. Personal dust sampling results for Mill Operator Occupation, 5. Personal dust sampling results for Dryer Operator Occupation, 6. Personal dust sampling results for Bagger Operator Occupation.

Ventilation Systems Testing Procesures

During the investigations each dust collection system installed at the plants was tested to evaluate its ventilating and dust control performance. Each ventilation system utilized a fan to induce airflow into collection hoods at various dust generating locations. The air then passed through a network of ducts to a wet or dry dust collector. At these collectors, dust-laden air was treated with water (wet scrubber), or circulated through dry filters (baghouse), so that the fine particles were removed before the cleaned air was discharged to the atmosphere.

Each ventilation system was evaluated by taking measurements at the intake and exhaust of the fan (when possible), inlet and outlet of the dust collecting device, and at strategic points throughout the network of ducts connecting the collector with the various collection hoods or pickups. These measurements included: size of the duct, temperature within the duct, barometric pressure, and air pressures using a Pitot-static tube. From these measurements, the static pressure, air quantity, and an average transport velocity were calculated for each location. In ducts with velocity pressures too low for a Pitot-static tube traverse, a velometer was used to obtain an average transport velocity. These measurements were taken in accordance with the American Conference of Governmental Industrial Hygienist (ACGIH) recommended practices as shown in Figure 1.[3]

Results of the Initial Surveys

Results of the initial survey at Plant A showed 17 of the 26 TWA concentrations exceeded the associated TLV. Of eight occupations sampled, four emplc_ees' concentrations were in excess of the TLV on each of three sampling shifts: two bulk railroad car loaders, and two ground silica product baggers. A third bulk railroad car loader exceeded the TLV on two of the three shifts.

The highest personal respirable dust concentrations were collected on ground silica product bagging personnel. Spillage from the bagging spouts after bag removal seemed to make a significant contribution to the dust concentrations, as did placement of the bags on the pallet behind the bagger operators.

Personal samples for the crusher helper, utility and float drier personnel were all within the calculated TLVs. TLV values for all personal samples ranged from 0.14 to 1.42 mg/m^3, with a median TLV of 0.20 mg/m^3.

Twenty of the 29 valid area samples collected exceeded the associated TLV. TLVs for the area samples ranged from 0.13 to 1.69 mg/m^3, with a median TLV of 0.18 mg/m^3. While area samples do not represent personal respirable exposures, they are helpful in identifying respirable dust sources.

GCA readings were used to determine dust generation sources throughout the plants. In one area of Plant A, GCA concentrations ranged from 0.5 to 15.0 mg/m^3, as shown in the dust concentrations profile in Figure 2. One major source of the dust in this area was determined to be the exhaust of a dust collector fan, where the connecting flange to the ductwork was in need of repair. This was reported to the company at a closeout meeting and was repaired.

GCA readings near the primary crusher discharge indicated the presence of a respirable dust source which was confirmed by gravimetric sampling results. Insufficient employee exposure data was available for evaluating conditions in the crusher area and making recommendations for improving respirable dust controls. Although area samples collected in the area exceed the TLVs, exposure times in these locations may not have cuased overexposures.

Another major dust source was spillage and leakage from material handling systems including chutes, conveyors, elevators and air sizing equipment. Any visible leaks were reported to the company at the closeout meeting.

Housekeeping in the plant was generally fair, however, brooms were used instead of vacuuming or wet-washing which also contributed to personal exposures of employees performing this task.

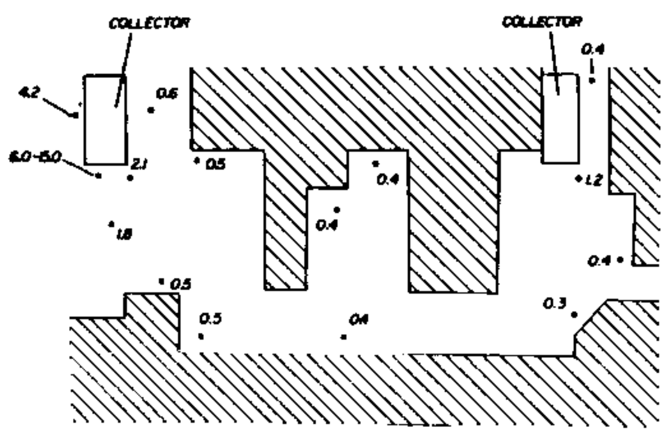


FIGURE 2. Using GCA instantaneous respirable dust readings to determine dust sources.

TABLE I

Comparison of Personal Respirable Dust Samples

Occupation	1984 Survey TWA	(% TLV)	TLV	1986 Survey TWA	(% TLV)	TLV
Plant A						
Rail Car Loaders	0.70	(350)	0.20	0.20	(42)	0.48
Fluid Bed Dryer operator	0.25	(336)	0.70	0.25	(24)	1.05
Crusher Operator	0.33	(30)	1.10	0.12	(55)	0.22
Ground Silica Baggers	0.51	(243)	0.21	Operation Discontinued		
Total number of samples collected	26					12
Number of samples exceeding TLV	17					0
Plant B						
Bagger Operator	0.48	(120)	0.40	0.12	(40)	0.30
Total samples collected	2					2
Exceeding TLV	2					0

Note: During the investigations an Employee Respirator Program of integrity was in effect at each plant which required individual employees to wear approved respirators in all areas designated as silica dust hazards.

GCA readings collected while rail cars were loaded indicated that controls needed to be instituted. In loading rail cars, the loader would position himself upwind of the loading port whenever possible. While GCA readings show this to be effective, the employee had to travel into the downwind and adjacent areas in the performance of his duties. GCA concentrations in those locations ranged from 0.6 to 40.0+ mg/m^3. An exposure time of only 12 minutes in a concentration of 12 mg/m^3 will cause a silica dust overexposure (0.30 TLV).

Sixteen of the dust collection systems installed at Plant A were tested to evaluate the ventilating and dust control performance of each system. Many of these were originally designed with less stringent dust control standards in effect, and to provide ventilation for limited processes within the plant. Over the years as stricter standards evolved more emphasis was placed on plant-wide dust control, these systems were then expanded to ventilate larger areas. That is, each system was expanded to handle more collection hoods and ducting to provide ventilation for more equipment throughout the plant. However, these changes had resulted in several problems which became evident during the survey.

Transport velocities through many of the ventilating ducts were below the levels recommended for silica dust by the ACGIH (3500 – 4000 fpm).[4] The ventilation systems as operated, were not capable of exhausting a sufficient quantity of air to maintain a proper velocity in each duct. As material settled out of the airstream and accumulated within

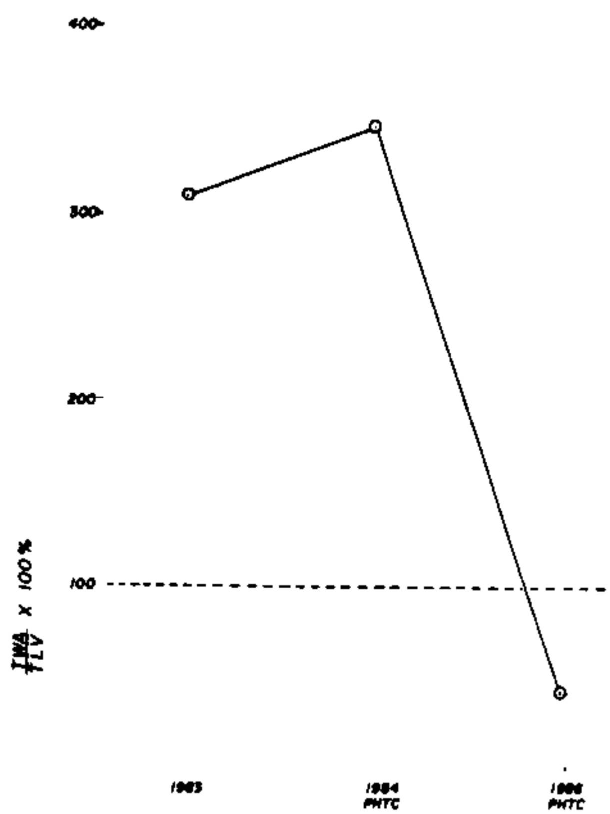


FIGURE 3. Personal dust sampling results for Bulk Rail Loader Occupation.

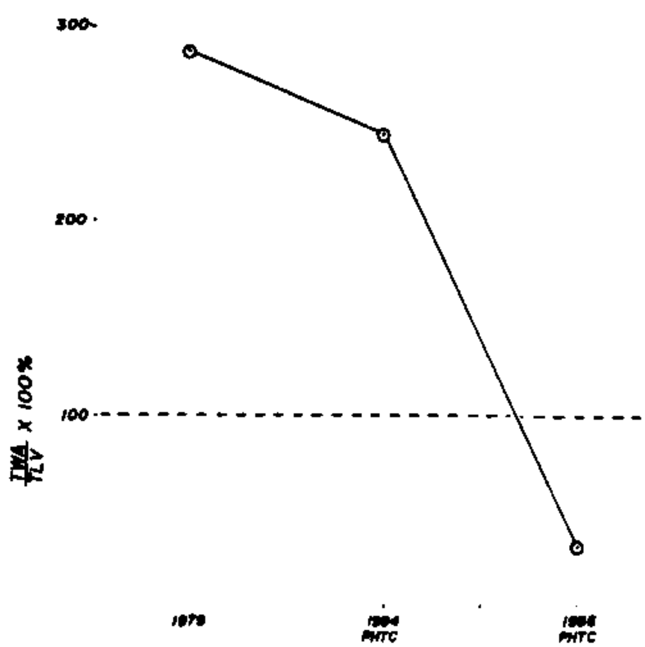


FIGURE 4. Personal dust sampling results for Mill Operator Occupation.

the ducts, partial and complete obstructions in the ducts compounded the situation.

Generally, the maintenance of the ventilation duct work throughout the plant was adequate. However, because of the extent of the ventilation networds some areas were overlooked and disrepair allowed leakage into the systems.

One other problem observed in the plant involved the manner in which modifications had been made to existing dust collection networks. The new ducts that were installed did not always utilize basic engineering principles of airflow, which may have been detrimental to the overall efficiency of the particular dust collection system. In some instances imbalances within the system were due to these make shift additions.

Finally, the above mentioned deficiencies in the ventilation systems could have been detected earlier and corrected if periodic ventilation testing hadbeen scheduled and performed by plant personnel.

Results of the initial survey at Plant B were somewhat different in that only one occupation was overexposed and noncompliance with the standard was not consistent. The occupation, a bagger operator, would be in compliance during one hygiene survey, and overexposed during the next. Dust sources affecting this occupation included dust leaking from filled plastic bags and dust generated by cleaning with brooms. These sources were identified using instantaneous GCA readings.

Respirable dust levels were normally very close to calculated TLVs, which ranged from 0.12 to 0.52 mg/m^3. The bagger was usually no greater than 30 percent over the TLV when overexposed.

A complete ventilation system evaluation was not conducted at this plant due to the extensiveness of the system. One exhaust hood is utilized to remove dust generated while filling bags. The quantity through the hood was within recommended values, although the transport velocity in the ducts were slightly less than recommended.

TABLE II

Comparison of Area Respirable Dust Samples

Location	1984 Survey TWA	1984 Survey TLV	1986 Survey TWA	1986 Survey TLV
Plant A				
Primary crusher discharge	0.32	0.20	0.53	0.18
Secondary crusher discharge	0.48	0.16	0.56	0.19
Mill building	0.47	0.16	0.23	0.27
Total number of samples collected	27		34	
Number of samples exceeding TLV	19		24	
Plant B				
Automated Bagger - Pulletizing Area	(No samples collected)		0.09	0.30
Bagging Area	do.		0.05	0.30
Total samples collected	do.		15	
Samples exceeding TLV	do.		0	

Note: During the investigations an Employee Respirator Program of integrity was in effect at each plant which required individual employees to wear approved respirators in all areas designated as silica dust hazards.

Recommendations

As a result of the initial surveys, recommendations were presented to the companies for reducing respirable silica dust exposures. For Plant A, the following are some of the recommendations which were made. (Because the bagging operations were to be eliminated, no recommendations were made for that occupation.)

1. Installation of dust control measures for the bulk railcar loading facility planned by the company should be expedited. An exhaust ventilation system such as a ventilated loading spout will be most effective in reducing personal respirable silica dust exposures.
2. Maintain material handling systems to eliminate spillage and leakage.
3. Improve housekeeping throughout the plant to reduce exposures. Use of a vacuum system is most effective in cleaning spillage and settled dusts.
4. Obstructed ventilation ducts should be cleaned, and systems rebalanced to maintain minimum transport velocities above 3500 fpm.
5. Dust collection systems should be maintained and repaired to assure proper ventilation.
6. Velocity pressures in each ventilation branch should be measured periodically to assure proper operation, and to identify problems in the respective ventilation systems.
7. The policty of recording static pressure drops across the collector should be continued as a method to identify problems in the systems.

At Plant B, the major recommendation was to remove brooms from the plant, and to clean spillage and settled dust with a vacuum system.

Follow-up Studies

At Plant A, many improvements were made following the initial study. Conveying systems were rerouted to allow the company to use water to wash down floors, etc., as a housekeeping method. Leaks in production systems were repaired, and improvements were made in some exhaust ventilation systems. Many occupations were assigned for booths to perform duties for much of the shift, including the railcar loader and mill operators. A ventilated loading spout was installed to reduce dust generated at the bulk loading area. In addition, the bagging of ground silica products was discontinued and mill production was proportionally reduced according to market demands.

At Plant B, the company instituted a policy of cleaning only with a vacuum, and insisted that no dry sweeping would be done. In addition, a dampening of the sand was performed bofore it was bagged into plastic bags which reduced dust emitted from the bags.

Table I compares personal respirable dust exposures for Plants A and B from both the initial and follow-up surveys. Average TWA concentrations and TLVs are reported to simplify analysis. For personal exposures, both plants have achieved 100 percent compliance for the occupations in question. Table II compares area respirable dust concentration for Plant A, from the two surveys. Data was not collected at Plant B in this manner, however, GCA instantaneous readings were recorded and are reported in Table III, along with data from Plant A.

TABLE III

Comparison of GCA Instantaneous Dust Readings

Location	1984 Survey	1986 Survey
Plant A		
Bulk rail loading - on car	0.1 - 40.0 +	0.1 - 9.0
Mill building - floor 1	0.1 - 1.5	0.1 - 0.2
Mill building - floor 2	0.3 - 15.0	0.1 - 12.0
Primary		
Crusher discharge	OA - 2.5	0.3 - 13.5
Secondary		
Crusher discharge	0.3 - 1.6	0.2 - 1.2
Plant B		
Pulletizing Station	1.6 - 2.5	0.1 - 0.5
Bagging Hood	0.6 - 1.0	0.1 - 0.2

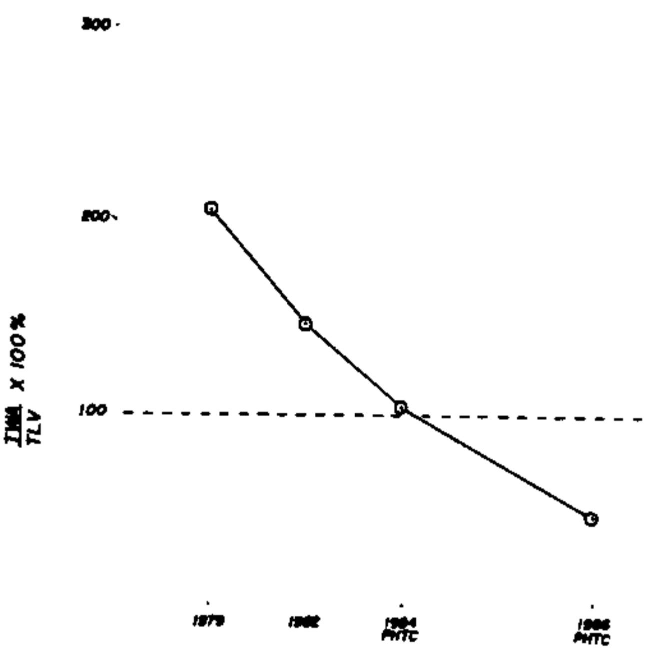


FIGURE 5. Personal dust sampling results for Dryer Operator Occupation.

Data on the three tables show definite reductions in respirable silica dust concentrations in most areas of the plants. However, the results also show that there is still room for improvement at Plant A in the Primary and Secondary crusher areas. Although these areas have dust concentrations which exceed eight-hour average limits, they do not contribute to personal overexposures.

Both of the silica sand operations have made significant improvements in reducing personal respirable silica dust exposures. Figures 3 through 6 show the historical trends for various occupations for the two plants. Figure 3 is the data for Bulk Rail Loaders for Plant A. The dust levels have been reduced from over 300 percent to less than 50 percent of the TLV. Similar results have been achieved for the mill operator (Figure 4, 280 percent to 35 percent) and Dryer Operator (Figure 5, 205 percent to 48 percent). These reductions are due to instituting good housekeeping practices, improved ventilation system operations and isolating employees in control booths. Figure 6 shows historical data for the bagger operator at Plant B. Reduction at this plant is due to the dampening of the product prior to bagging and improved housekeeping practices.

During the investigations at Plant A, 14 of 20 dust collection systems were surveyed to evaluate the ventilating performance of each system. Details for each dust collector surveyed during the initial investigation (December 1984) and the re-survey (July 1986) are shown in Table IV.

The maintenance and modifications performed on dust collection systems at this plant after the initial investigation were concentrated in the problem areas that had been detected at that time. These improvements included refurbishing the inner mechanisms of some of the collectors, cleaning out obstructed ducts, patching holes in ducts, and replacing temporary patches with new pipe or permanent-type patches. Also, attempts were made to lessen the load on overextended collectors and rebalance collectors after modifications were made to keep the transport velocities in the ducts at prescribed levels. In most of the systems modified by Plant A personnel, there was a marked improvement in reduced leakage, increased transport velocities and reduced respirable dust levels in areas serviced by each collector. However, in the systems that remained unchanged in the 19 months between investigations, there was a reduction in system performance, as indicated by reduced fan capacities, increased leakage and lower transport velocities. This shows that continued maintenance and monitoring of systems is important in providing adequate ventilation and dust control.

General Recommendations

As a result of the studies at these two plants and other studies conducted by the Pittsburgh Health Technology Center (PHTC), the following recommendations for reducing and maintaining personal respirable dust exposures below applicable limits are:

1. Monitor existing ventilation systems to assure proper operation. This includes monitoring the static pressure drop across the dust collector, and velocity pressures within each branch of the system.
2. Visually inspect, maintain and repair ventilation systems and product conveyor to minimize leakage and spillage.
3. Maintain good housekeeping practices, including wet sweeping or washing down and vacuuming. Dry sweeping should be eliminated entirely.
4. Educate employees on the hazards associated with silica dust and how they can personally reduce their exposures.

Ultimately, dust control and reduced employee exposures will be achieved by having employees follow good work practices and policies set by the company. Increased

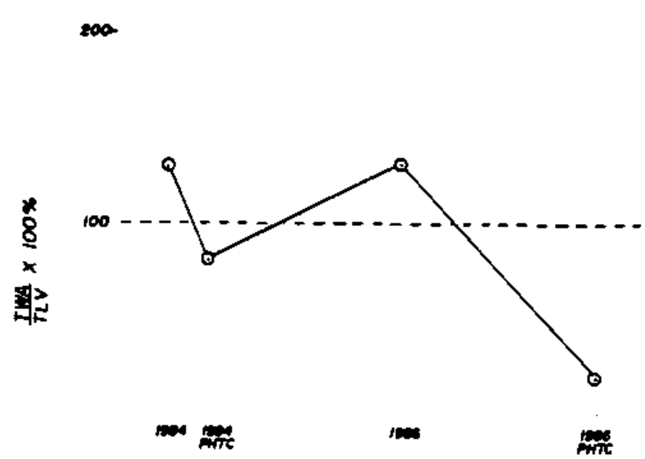


FIGURE 6. Personal dust sampling results for Bagger Operator Occupation.

TABLE IV

Comparison of Ventilation System Parameters

Collector No./Type	December 1984 Qa	P^b	V^c	July 1986 Q^a	P^b	V^c
1 Scrubber	13000	4.4	1860 - 5390	14900	4.7	2000 - 5390
2 Scrubber	10400	5.8	2160 - 4650	11500	5.8	1910 - 4460
4 Baghouse	5000	5.5	1240 - 3360	4300	3.7	1790 - 5220
5 Baghouse	4800	4.8	1900 - 4780	4500	6.3	1650 - 4320
6 Baghouse	6300	2.7	1120 - 6820	5700	6.0	1270 - 4840
7 Baghouse	2400	0.5	2180 - 4590	2300	0.6	650 - 3980
8 Baghouse	2700	0.6	770 - 5460	2600	0.6	850 - 5450
9 Scrubber	16900	4.5	1640 - 9370	16500	3.6	3500 - 8400
10 Baghouse	7400	3.5	4570 - 4790	8400	5.7	3600 - 5200
11 Scrubber	49200	5.7	2350 - 4620	44100	4.6	1790 - 3280
12 Scrubber	5800	2.8	4740 - 4920	6400	4.5	4100 - 4300
15 Scrubber	2100	5.7	1910 - 4990	2300	5.8	2500 - 6100
16 Scrubber	4900	3.7	2460 - 3220	4800	3.1	2000 - 3100
20 Baghouse	–	–	–	4500	< 1.1	5390 - 5800

[a]Q Measured Quantity, cfm

[b] P Static Pressure Drop Across Collector, inches H2O

[c]V Range of Transport Velocities, fpm

awareness and education is a key to a successful Dust Control Program.

Employee Respirator Program

During the investigations an Employee Respirator Program of integrity was in effect at each plant which required individual employees to wear approved respirators in all areas designated as silica dust hazards. While personal protection was required it was not considered to be a permanent substitute for adequate engineering controls.

References

1. **American Conference of Goveramental Industrial Hygenists:** *Threshold Limit Values for Chemical Substances in Workroom Air Adopted by ACGIH for 1973*, pp. 32-33. Cincinnati, OH (1973).

2. **Rubow, K.L. and V.A. Marple:** *Instrument Evaluation Chamber: Calibration of Commercial Photometers*, Chap. 55, pp. 777-795. Ann Arbor Science, Ann Arbor, MI (1983).

3. **American Conference of Governmental Industrial Hygienist:** *Industrial Ventilation*, 18th Ed., Sec. 9, p. 23. Ann Arbor, MI (1984).

4. *Ibid.*, Sec. 4, p. 7.

Investigation of Quartz Dust Sources and Control Mechanisms on Surface Coal Mine Operations

ROBERT A. ZIMMER[A], STAN R. LUECKA and STEPHEN J. PAGE[B]
[A]PEI Associates, Inc.; [B]U.S. Bureau of Mines

A significant problem in surface mining is complying with reduced dust standards resulting from high quartz concentrations. In areas where potentially harmful concentrations of silica-bearing dust exist, reduced dust standards are applied to limit the amount of silica to which the workers are exposed. According to the Mine Safety and Health Administration (MSHA) data, the overburden drilling occupations are those with the greatest exposure to quartz.

Worker exposure to silica may be reduced by decreasing the amount of dust produced by the drill. This can be accomplished with either dry collection or wet suppression systems. Both of these systems were evaluated in the field and the results of this testing are the subject of this paper. This work was performed under a Bureau of Mines contract by PEI Associates, Inc.

Both dry and wet systems were evaluated at nine mine locations. The testing protocol involved measuring concentrations attributable to the drill at immediate downwind locations. Both RAM-1 and gravimetric samplers were used for the testing. The test results showed that both control systems are capable of achieving greater than 95 percent control when operated properly. Quartz concentrations of the respirable particulate captured on the downwind filters varied from below detectable limits to 13.6 percent. The use of control equipment on the drills did not result in any consistent change in the percent quartz in the collected particulate.

A special study of dry and wet systems was conducted to determine the proper operating parameters for each type of system. Shroud height was tested for dry systems and water flow rate was tested for wet systems. In the case of dry systems it was found that a nearly inverse relationship exists between shroud height and control efficiency. The dry system performed most efficiently when the shroud was positioned as close to the ground as possible. In the case of wet systems, the control efficiency versus water flow rate curve showed a steep increase in efficiency in the range of 0.4 to 0.6 gallons per minute (gpm). The highest control efficiency (96 percent) was at a water flow rate of 1.2 gpm. However, flow rates this high can cause operational problems which include drill bit plugging.

In general, the results of the study demonstrated the efficacy of control equipment for overburden drills. Used in combination, dust control equipment, pressurized cabs, and personal protective equipment should be adequate to eliminate the need for reduced dust standards at surface coal mines.

Introduction

A significant problem in surface mining is complying with reduced dust standards (less than 2.0 mg/m^3) resulting from a quartz content in excess of five percent. The harmful effects of inhaling silica bearing dust are directly related to the amount of silica in the dust. Therefore, the threshold limit value for an eight hour workman's exposure must take into consideration the amount of silica in the dust. The present federal occupational standard is 0.1 mg/m^3 of respirable quanty. When potentially harmful concentrations of silica dust exist, reduced dust standards apply to limit the silica emissions from drilling operations. According to the Mine Safety and Health Administration (MSHA) data, the overburden drilling occupations are those with the greatest exposure to quartz.

Prior to the present study, no known research had been performed which quantified and ranked the sources of quartz dust from drilling operations and how they affect the respirable dust exposure of drilling occupations. The objective of this study was to evaluate the sources of airborne quartz dust during the removal of overburden at surface coal mines.[1] This was accomplished by measuring respirable dust concentrations around various drills during the drilling process. The percentage of quartz in this dust and in the drill cuttings was also determined. Additionally, improved dust control technology was investigated for wet and dry systems. As a subset of this investigation, operational parameters were tested in the field to optimize the use of wet and dry systems.

Overview of Dust Control System Technology

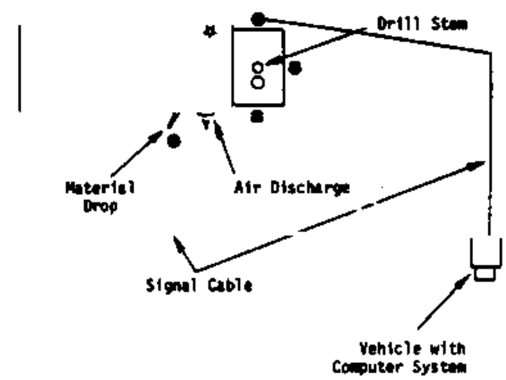
The control of dust from earth drilling equipment is accomplished by one of two methods. These control methods are commonly referred to as dry and wet systems.

Dry Systems

The use of a dry system involves enclosing the area where the drill stem enters the ground by hanging a rubber or cloth curtain or "shroud" from the underside of the drill deck. This enclosure is ducted to a filtering device, the clean side of which is equipped with a fan. The fan creates a negative pressure inside the entire system thus capturing dust as it exits the hole during drilling. The dust is removed in the filtering device and clean air is exhausted through the fan.

Wet Systems

Wet drilling systems consist of a water tank mounted on the drill from which water is pumped into the downhole air line. The water droplets in the bail air conglomerate dust particles as they travel up the annular space of the drilled hole thus controlling dust as the air bails the cuttings from the hole. The tank on the drill typically holds several hundred gallons. The pumps used in wet systems are usually hydraulic or electric piston-type pumps. Common water flow rates are 2.0 gpm or less depending upon the size and type of drill as well as the condition of the material being drilled. Flow rate is controlled manually by the drill operator by means of a valve located in the cab. Some drills are also equipped with a flow meter to give the operator visual indication of the flow rate.



○ RAM-1 and four personal monitor pumps and filters mounted on the drill table

● RAM-1 and four personal monitor pumps and filters mounted at ground level to three feet above ground level

* RAM-1 and four personal monitor pumps and filters mounted at air discharge

Recording windspeed/wind direction

* RAM-1 with Metrologger and four personal monitor pumps and filters located in cab

FIGURE 1. Sampling configuration for drills.

Field Sampling

Test locations

Sampling was conducted at nine separate surface coal mines. The mines were located in Pennsylvania, Arizona, Colorado, New Mexico, Wyoming, and Montana. The annual production varied from 13,000 to 9,000,000 tons per year (1983 production).

Drilling Equipment Tested

Ages of the drills tested varied from new to over ten years. Conditions of the drills also varied from like-new to marginally operational. However, the condition of the drill was not necessarily proportional to age. Some of the older drills were kept in excellent operating condition, with very clean cab interiors. All units tested were portable blast hole drills mounted on trucks or tracks and were equipped with either wet or dry control systems. All but one were equipped with enclosed cabs, although only a few operators were conscientious about maintaining the integrity of the cab. Drill bit diameters varied from six to 12 1/4 in.

Field Sampling Protocol

The objectives of the field testing were to measure respirable concentrations of dust around the drills and to quantify the percent quartz in the dust. To collect the data to satisfy these objectives, two different types of monitors were used. The first type was a GCA RAM-1 instrument. (Reference to specific manufacturers is for information only and does not imply endorsement by the Bureau of Mines.) The second consisted of colocated gravimetric samplers. The RAM-1 monitor is a portable sampler for measuring respirable particulate. Its measurements are based on detection of near-forward scattered electromagnetic radiation by particles passing through an optical chamber. The sample flow is passed through a cyclone precollector to remove particles with aerodynamic diameters larger than 3.5 um. Sampler flow rates were set to 2 l/min prior to use at each test location. The RAM-1 instruments were then used to measure respirable dust concentrations around the drills.

The RAM-1 monitors could not be used to determine the quartz content of the measured dust concentrations. Consequently, gravimetric samplers were deployed. Each sampler consisted of a personnel monitor (pump), 37 mm-5.0 um pore size filter, filter cassette, and a cyclone precollector identical to that on the RAM-1 monitors. The precollectors were used to provide only the respirable fraction of the airborne dust. Each sampler was set to a nominal flow rate of 2 l/min at each test site prior to use. Actual deployment of the samplers consisted of four colocated samplers to obtain a sufficient mass of particulate for analysis. Following use in the field, the four colocated filter cassettes were combined and analyzed for quartz using MSHA Method P7.

In addition to the particulate monitors, windspeed and wind direction instruments were deployed at each test site. Both the RAM-1 instrument and the meteorological sensor outputs were recorded using an on-site computer system. The signals were sent via cable to an Apple IIe computer where they were converted to digital signals. The computer took a reading from each instrument approximately every 2.5 seconds. These individual readings were then accumulated over a one minute period and averaged. The one minute averages were printed out on-site at five minute intervals and simultaneously recorded on magnetic disk for later analysis.

Sampler Deployment

Placement of the samplers around each drill was guided by the following principles:

1. Samplers were placed downwind of the points of dust generation (i.e., drill table, drill skirt, air discharge, and material discharge).
2. Samplers were placed in drill cabs only where there was sufficient room and where prior permission for such monitoring was obtained.
3. Concurrent measurements were made upwind and downwind with the same types of measurement devices to assure the compatibility of results (i.e., gravimetric data were not directly used with optical data).

The basic sampling configuration as shown in Figure 1, was modified as needed to accommodate different situations. For example, on wet drills no samplers were required for either the air discharge or material discharge points. At other times, the height above ground level was adjusted to compensate for varying terrain or different heights of dust generation. RAM-1 instruments and gravimetric monitors were colocated at each sampling point.

Test Procedures

Sampling of drill emissions at each mine occurred over a number of days. In general, at least one test without the control system in operation was performed each day. When using the gravimetric samplers, test length was controlled by the need to collect 0.5 mg of combined sample at each location for MSHA Method P7 analysis. Consequently, test periods ranged from 15 minutes to two hours in duration with the uncontrolled tests requiring the shorter times and the tests with a high degree of control the longer times. For the computerized (RAM-1) data collection, it was possible to resolve the data into shorter time increments. These data were then summarized in two ways: 1) by hole, and 2) by sampling time of the gravimetric samplers (multiple holes). In some cases both summaries involved only single holes; however, in the majority of tests multiple holes were sampled. Three types of data were collected: 1) RAM-1 data; 2) personnel pump/filter data; and 3) independent variable data. All data for each test not captured with the computer were recorded on one data form prepared specifically for this study.

Results

Particulate Emission Rates During Drilling Activity

During the testing it was found that average concentrations varied dramatically from test to test. It was necessary to normalize the results to some standard measurement in order to evaluate the efficacy of the existing dust controls. This normalization was necessary since not only the average concentration of dust produced changed but other variables such as sampling time, depth of hole drilled, windspeed, and plume area also changed from test to test. In order to normalize the results, the concept of emission rate was used. For each hole drilled, the quantity of respirable dust generated was reduced to the common units of grams/foot (g/ft) with the following equation:

$$E = [(T)(F)(C)(WS)(P)]/[(K)(FV)(I)(D)] \qquad (1)$$

where

E = emission rate, g/ft
T = sample time, min
F = sampler flow rate, l/min
C = average particulate concentration during sample period, mg/m^3
WS = windspeed, mi/h
P = plume area, ft^2
FV = sampler flow velocity, mi/h
I = sampler inlet size, ft^2
D = depth of hole drilled during sample period, ft
K = conversion constant to satisfy equality of units, (1,000 l/m^3)(1,000 mg/g)

The RAM-1 concentration values used in the equation were averages based on the time when drilling was occurring. Concentrations recorded during idle time and drill moving time were not included in the emission rate equation. It was not possible to perform the same calculations for the gravimetric samplers since no real time concentration data were available.

Once the dust emission data were normalized, it was possible to directly compare calculated emission rates between tests. Specifically, by comparing uncontrolled emission rates to controlled emission rates, control efficiencies of the various control equipment were calculated using the following equation:

$$CE = 1 - (ER_c/ER_u) \times 100 \qquad (2)$$

where

CE = control efficiency, %
ER_c = controlled emission rate, g/ft
ER_u = uncontrolled emission rate, g/ft

Summary of Test Results — Emission Rates

Table I presents an overall summary of the results of the testing at the nine mines. A wide range of emission rates (0.0007 to 30.0318 g/ft) was encountered throughout the testing. Both the dry collection and the wet suppression systems were found to be effective under most conditions. The most significant variable that affected the degree of control appeared to be operation of the dust control systems.

The results show a high degree of variability in control efficiencies at some mines. This variability is most often due to operating practices and the condition of the material being drilled (i.e., high moisture content). Rarely did a control system fail outright. Well operated dry collection system devices can achieve greater than 95 percent control efficiency. The primary reason for not achieving this level of control is the operational practice of not lowering the shroud to seal with the ground.

Wet systems are also capable of greater than 95 percent control. The principle problem in achieving high control levels is determining and maintaining the correct water flow to optimize dust control. The operational characteristics of the dry and wet systems were evaluated further in the field. These results are presented below.

Test Results — Quartz Content

In this study, two types of samples were analyzed for quartz content, filter samples and bulk samples. The filter samples taken with the personnel monitoring pumps were analyzed by MSHA Method P7. In using this method, the filters used for sample collection were weighed to determine the amount of material deposited on them. After weighing, the material on the filter was then scanned by infrared spectrometry to determine the presence of quartz. The amount of quartz in the sample was determined by measuring the height of the infrared quartz peak at 795 cm^{-1} and using calibration data from standard quartz samples.

TABLE I

Summary of Control Efficiency Results

Mine	Control Type	Mean Emission Rate g/ft	Mean Control Efficiency %
1	AmerPulse (Dry)	0.15	71
	None	0.53	—
2	Water	0.18	80
	Rotoclone (Dry)	0.074	90
	None	0.83	—
3	Tipton (Dry)	1.4	86
	None	10.2	—
4	Water	1.0	79
	None	3.9	—
5	Water	0.58	83
	W/0.9[a]	0.17	95
	W/1.2	0.12	97
	0.9/0.04[b]	0.24	93
	0.8/0.04	0.60	82
	None	3.4	—
6	W/0.1	1.7	70
	W/0.2	5.9	−3
	0.2/0.2	0.40	71
	0.1/0.1	1.3	3
	None	3.54	—
7	Tipton (Dry)	0.084	98
	None	5.3	—
8	AmerPulse (Dry)	0.044	48
	None	2.5	—
9	Tipton (Dry)	1.18	3
	None	6.6	—

[a]W/0.9 = water at 0.9 gal/min.

[b]0.9/0.04 water at 0.9 gal/min -- surfactant 0.04 percent.

Bulk samples were stored in their airtight containers until split with a sample splitter (riffle), dried, and analyzed by X-ray diffraction. During the X-ray diffraction analysis, sample spikes were performed on every tenth sample. Both standards and spikes consisted of NBS-traceable quartz standards. The X-ray diffraction apparatus was calibrated and operated in accordance with proper laboratory methods and the manufacturer's recommendations.

The amount of quartz was determined by relative quartz to fluorite peak height ratios as compared to a series of standard samples prepared using pure quartz and fluorite in the same ratio as the unknown samples. This was achieved by doping the unknown samples with the same quantity of fluorite as in the standard sample.

The quartz concentrations of the respirable particulate captured on the downwind filters varied from below the detection limit of the method to 13.63 percent. The average quartz concentration on the downwind filters was 5.05 percent. Concentrations on the filters did not change appreciably by filter location or by mine. Likewise, the use of dust control equipment on the drills did not result in any consistent change in the percent quartz in the captured particulate.

The quartz concentrations of the bulk samples varied from 20 to 86 percent. Average quartz concentration of the bulk samples was 47 percent. Mines 1, 7, 8, and 9 showed a somewhat lower quartz percentage. The percentages did not vary consistently between drill cutting and collector discharge samples. The difference between the filter and bulk sample concentrations is most likely due to the aerodynamic properties of the quartz particles.

Optimization of Dry Systems

Most rock drills are static with regard to hood geometry (the position of the emissions point in relationship to the hood). Collector volumes are invariant, and no control can be exerted on the dust properties or outside influences. The only parameter that can be varied is the hood open area.

Varying the hood open area will change the hood's capture efficiency, since as the open area is reduced, the face velocity will increase. There are no empirical data to predict the system capture efficiency versus the hood face velocity. Consequently, a field study was designed to examine this important relationship.[1]

Field Sampling

Testing was performed over a two week period at a mine previously tested in southeastern Montana. Two drills were evaluated, a BE45R and a BE60R. Each drill was tested with the front of the shroud set at different heights above the ground. It was not always possible to obtain a consistent height for the entire shroud because of the irregularity of the ground surface. Consequently, all height measurements were taken at the front of the shroud.

Results

Uncontrolled emission rates varied from 0.6549 to 10.6028 g/ft. Comparable control efficiencies varied from 41 to 99 percent over the 0 to 27 inch of shroud height range evaluated. All of the tests of the BE45R drill occurred in approximately the same area; however, several of the tests conducted appeared to be of a different strata. The data for the BE60R were taken while drilling scoria. Consequently, these data represent a totally different material and drill parameters than obtained at the BE45R.

Control efficiency vs shroud height are compared in Figure 2. The plotted data points represent the average control efficiency measured at each shroud height. With a shroud height of 6 to 9 inches or lower it is apparent that the control system works well; however, as the height increases the control efficiencies decrease. As discussed earlier, when the open area of the shroud increases, the face velocity must increase to maintain a given capture efficiency. Since the air flow of the collector is invariant, the control efficiency must decrease as the open area increases.

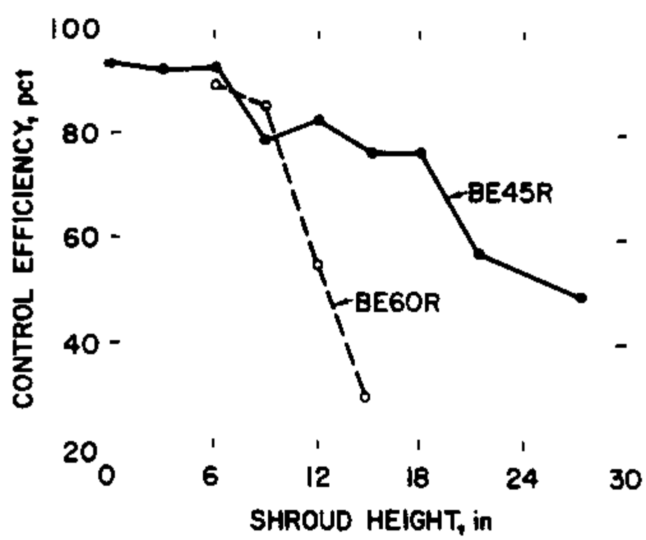


FIGURE 2. Control efficiency vs shroud height.

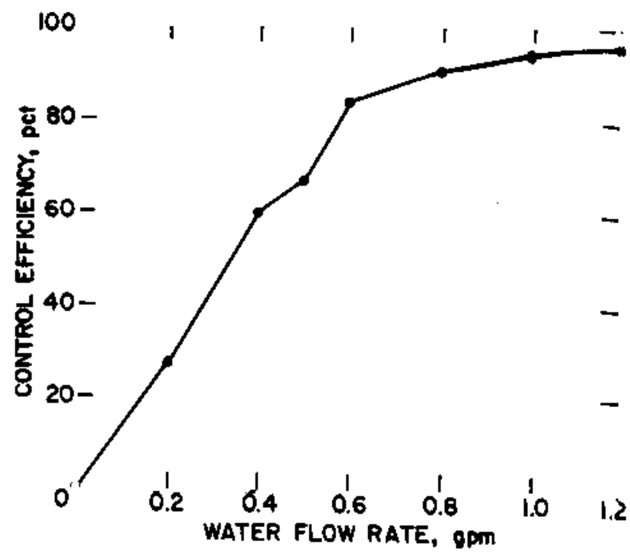


FIGURE 3. Control efficiency vs water flow rate.

Optimization of Wet Systems

Previous tests conducted in nine mines showed that wet suppression systems have the capability of controlling respirable dust. The one critical factor affecting the efficiency of the wet systems appeared to be the amount of water being pumped into the bail air. Since no data were available on optimal water flow rates for wet suppression systems, a field study was designed to examine the relationship of emission rate versus water flow rate.[1]

Field Sampling

Testing was performed over a two-week period at a mine previously tested in northwestern Colorado. Various water flow rates were tested for a number of holes. Each hole was drilled at a specific and constant water flow rate. A water flow meter equipped with a needle valve was mounted in the cab of the drill. Flows were controlled and recorded by one of the test team members from inside the cab. A recording flow meter was also mounted in the water line near the control system pump.

Results

The conditions during the first week of testing were favorable for evaluating the efficiencies of the various water flow rates because the two drills tested were operating in close proximity to one another and the holes were drilled in a very tight pattern. This geometry limited the changes in the geologic strata from hole to hole. Also, the strata being drilled were very dry throughout the depth of the hole. Conditions during the second week of testing were not as favorable because the holes were drilled through very wet overburden strata and there was little or no difference in emission rates discernable between the different water flow rates. Moreover, the drill operator had difficulty in maintaining a constant water flow due to problems with the bit plugging. For this reason, data from many of the test holes had to be discarded.

Uncontrolled emission rates measured during the first week of testing varied from 3.82 to 9.26 g/ft. Control efficiencies varied from 9.07 percent at a flow of 0.2 gpm to 96.3 percent at a flow of 1.2 gpm. Figure 3 shows a graphical representation of the average control efficiency for each flow rate.

Summary

The results of the study show that both dry collection and wet suppression systems can be effective in controlling respirable dust from overburden drills. The most important factor in the case of both systems is a conscientious effort on behalf of the operator to operate the equipment correctly. Dry systems operate most effectively when the shroud is in contact with the ground. Wet systems operate most effectively at water flow rates approaching 1.0 gpm; although flow rates in this range can cause operational problems.

References

1. Lueck, S.R. and R.A. Zimmer: Investigation Of Quartz Dust Sources and Control Mechanisms on Surface Coal Mine Operations: Results, Analysis, and Conclusions. Contract No. J0348032 (March 1986).

Assessment of Respirable Dust Control for Rotary Blasthole Drills at Surface Coal Mines

RAYMOND GADOMSKI and DEBORA L. CHIZ
Mine Safety and Health Administration, Pittsburgh Health Technology Center

Several studies were conducted to assess respirable coal mine dust levels and evaluate the environmental dust controls used in conjunction with rotary blasthole drills at surface coal mines. Because the quartz content of the material being drilled is often greater than five percent, operators must maintain respirable dust concentrations below a dust standard based on the quartz content of the dust. As a result specialized dust collection equipment is often required to maintain compliance with the applicable standard.

Dust was controlled on each of the drill units evaluated by use of two independent dust control systems. One system used a dust collector to capture and remove dust generated from the drill hole, while the other system, an environmentally controlled cab enclosure, was used to control the amount of respirable dust to which the drill operator was exposed. Dust samples were collected inside the cab enclosure and near the air inlet on the outside of the cab enclosure. While the efficiency of the drill steel dust collection system was not evaluated, the systems were being properly maintained and outside dust concentrations were below 2.0 mg/m^3. Study results indicate that with the additional control obtained from a properly maintained cab enclosure, respirable dust levels at the drill operator position inside the cab could be maintained at or below 0.4 mg/m^3.

Introduction

Among the health hazards associated with the mining industry is the occurrence of several lung diseases known as pneumoconiosis. The two most prominent forms of the disease include coal workers pneumoconiosis (CWP) caused by the inhalation and deposition of coal dust in the lungs, and silicosis, caused by inhalation and deposition of crystalline silica (quartz) in the lungs. Once the dust is deposited within the lungs a process occurs which inhibits the exchange of oxygen and carbon dioxide in the lungs. As this process progresses, disability or even death to the individual can occur.

Since there is no cure for pneumoconiosis the primary focus has been to control the exposure to which an individual is subjected.

Part 71 of Title 30, Code of Federal Regulations sets forth Mandatory Health Standards for Surface Coal Mines and Surface Work Areas of Underground Coal Mines. Part 71.100 sets a respirable dust standard of 2.0 mg/m^3 and Part 71.101 reduces that standard when quartz is present. When the respirable dust in the mine atmosphere of the active workings contains more than 5 percent quartz, the respirable dust standard is computed by dividing the percent quartz into the number 10. This procedure essentially provides for a 100 ug/m^3 standard for exposure to quartz.

As part of routine mine inspection procedures, respirable dust samples are collected on various surface mine occupations. After determining the respirable dust concentration of the sample at the local Mine Safety and Health Administration (MSHA) office, the samples are forwarded to a central laboratory for quartz analysis.

Figure 1 shows information for occupations on which data was obtained for surface mine operations. The number of samples analyzed on each occupation ranged from a low of 14 on the road grade operator occupations to a high of 222 on the bulldozer operator occupation. The solid bar depicts the percent of samples that contained greater than 50 ug/m^3 of quartz and the hatched bar depicts the percent that exceeded 100 ug/m3 of quartz. Thirty-one percent of all the samples (719) analyzed in this program contained more than 50 ug/m^3 of quartz (National Institute for Occupational Safety and Health [NIOSH's] recommended standard for quartz exposure), and approximately 18 percent contained more than 100 ug/m^3 (MSHA's current standard for quartz exposure). The data also shows that the occupations of bulldozer operator, highwall drill operator and highwall drill helper had the highest quartz exposure. Approximately 40 percent of the samples analyzed on these occupations had a quartz content that exceeded 100 ug/m^3

This information indicates the potential for excessive dust exposures containing high levels of quartz for selective surface mining occupations. As a result, the Dust Division

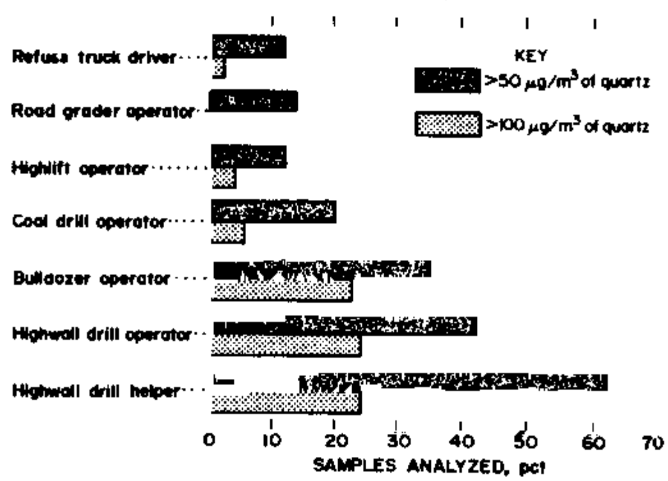


FIGURE 1. Information for surface mine occupations.

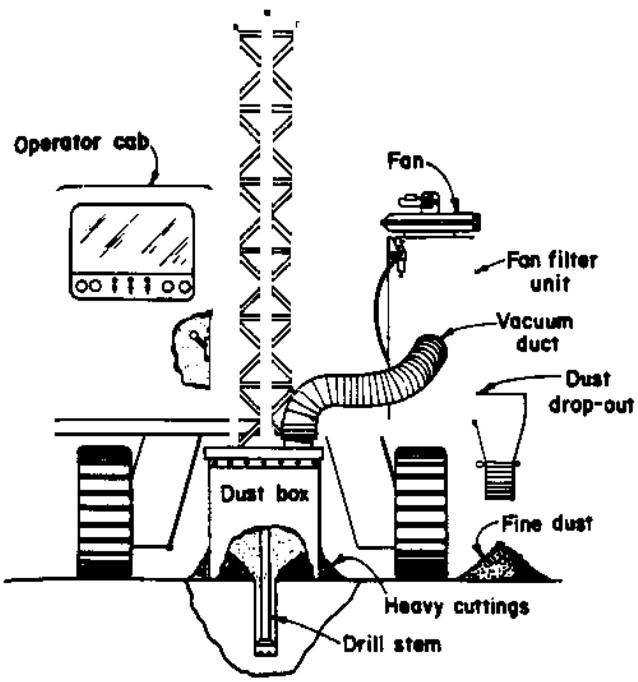


FIGURE 2. Typical dust collector system.

began a program to evaluate the technology that was currently available to control respirable dust exposures for these occupations.

Dust control measures for bulldozers generally are limited to cab enclosures. Dust Control measures for highwall drill operations include both cab enclosures and drill steel enclosures with collectors. Shown in Figure 2 is a typical dust collector system with basic components. Since highwall drills incorporate two dust collection systems, they were selected for evaluation. Through input from various MSHA District Offices, operations were selected for evaluation which used various state-of-the-art dust collection systems. The operations selected were on reduced respirable dust standards. Based on the quartz content of the dust, the standards ranged from 0.5 mg/m3 to 0.8 mg/m^3. The purpose of these studies was to evaluate the efficiency of the environmental dust controls used in conjunction with rotary blasthole drills at surface coal mines.

Description of Operations

The Highwall Drill Systems evaluated included a Driltech, Reedrill and a Bucyrus Erie Drill. (Reference to specific makes of equipment for identification purposes only and does not constitute endorsement by the Mine Safety and Health Administration.) Each of the three drills had an enclosed cab, equipped with an air conditioning/filtration unit and additionally, a dust collection system which surrounded the drill steel and exhausted the dust from around the blasthole. The cab enclosure and air conditioning/filtration systems along with the drill steel and blasthole dust collection systems were optional equipment designed for compatibility with the drills.

The dust collection systems for the drill steel and drillhole of the Driltech and Reedrill were a Kentucky Road Equipments' Electronic Dust Collector and a Metroplex "L" Series Dust Collector, respectively. These collectors draw dust through ducting from a bonnet-hood type apparatus centered around the hole, to an automatic self-cleaning dust collector. The dust collector contains filter elements which are cleaned by an electronically controlled backflushing operation. Dust from the backflushing operation is deposited into a dropout hopper. The dust in the dropout hopper is manually dumped from a remote location after each hole is drilled. Airflow through the collection system is maintained by a fan powered by a hydraulic motor.

The Bucyrus Erie Drill was equipped with an Amerpulse dust control system. The Amerpulse is a continuous cleaning pulse jet dust collector. A duct leads from the dust enclosure over the drillhole to the dust control unit. Dust laden air is drawn from the blasthole enclosure into the dust collection unit. Air is cleaned in two stages. The first stage is a skimmer which removes the larger particles, the second stage is a diffuser where the smaller particles are filtered. Particles removed in both the skimmer and diffuser area drop into the skimmer hopper. The dump gates on the hopper are air operated and the air cylinders are connected to the same air line as the hoist clutch for the drill steel. When the hoist clutch is activated to remove the drill from the hole, the cuttings are automatically dumped beside the machine.

The cab enclosure on the Driltech and Reedrill had combined air conditioning/filtration units. The cab enclosure on the Bucyrus Erie Drill had separate air conditioning and filtration systems. These systems were designed to condition and filter air entering the cab and at the same time maintain

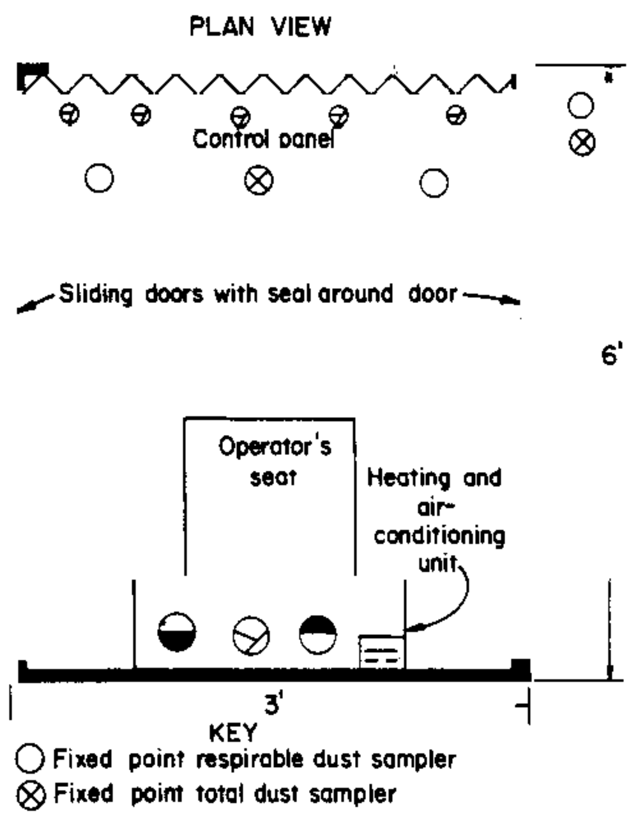


FIGURE 3. Relative locations of the respirable and total dust samplers.

TABLE I

Results of Gravimetric Sampling of Operators Cab of Various Drills Studies

Make/Model of Drill	Condition Sampled	Respirable Dust Concentration, mg/m³ (MRE Equivalent) Inside Cab[a]	Outside Cab
Driltech Model D40-K	Baseline	1.32	1.06
	Operator did not smoke	0.56	1.94
	Installation of new filters	0.20	1.69
Reedrill Model SK-35	Baseline	0.30[b]	1.79
	Installation of new filters	0.29	0.79
Bucyrus Erie Model 45R	Baseline	0.322[b]	0.67
	Installation of new filters	0.31	0.57

[a]Average of two respirable dust measurements.

[b]Average of concentration obtained on two sampling shifts.

the cab under a positive pressure to prevent dust entering the cab through openings in the cab.

Sampling Procedures

Respirable dust samples were collected with approved Mine Safety Applicances (MSA) coal mine dust personal sampler units. The dust samplers were calibrated and operated at a flowrate of 2.0 lpm. The MSA equipment with the 10 mm nylon cyclone removed, was used to take total airborne dust samples. Samples were pre- and post-weighed to 0.01 mg on an electronic analytical balance. Concentrations for the respirable samples were converted to Mining Research Establishment Instrument (MRE) equivalent concentrations by multiplying by the factor 1.38.(1) Respirable dust samples were analyzed for quartz content by infrared spectroscopy. Total dust samples were particle sized with a Model TA II Coulter Counter(2) using a 50 um aperture tube to classify particles, ranging in size from 0.79 to 25.41 um, into 16 size intervals.

To evaluate the performance of the dust collection systems on the various highwall drills, respirable dust samples were collected inside and outside the operators' cab. Samples collected inside the cab included two respirable dust samples and a total dust sample. One respirable sample and a total sample were collected at a fixed point approximately two feet from the operators controls. This location was typical of the position used when collecting samples for compliance purposes. The other respirable sample collected inside the cab was collected at a fixed point near the discharge of the air conditioning/filtration unit. Respirable and total dust samples were also collected at two locations outside the cab. One set of samples was collected near the drill steel. The other set of samples was collected near the inlet of the cab air conditioning unit. The relative locations of the samples are shown in Figure 3. All respirable dust samples were collected for eight hours of the ten-hour work shift.

A differential pressure measurement was taken using a Dwyer Magnehelic gauge to determine if a positive pressure existed inside the cab. Chemical smoke tubes were also utilized to determine if any air leaks were present in and around

TABLE II

Respirable Dust Concentration at Various Times After Cleaning of Dust Filtration Systems on Rotary Blasthole Drills

	Respirable Dust Concentration, mg/m³ Inside Cab	Outside Cab
Driltech Model D40-K		
Basline	1.32	1.94
After Installation of New Filters	0.20	1.69
After 30 working shifts	1.15	1.82
Reedrill Model SK-35		
Basline	0.30	1.79
After Installation of New Filters	0.29	0.79
After 5 working shifts	0.36	1.55
After 10 working shifts	0.35	0.50
After 25 working shifts	0.25	2.41

TABLE III

Comparison of Fixed Point Samples Collected Inside the Cab and Personal Samples Collected on the Drill Operator

	Respirable Dust Concentration, mg/m^3	
	Fixed Point	Operator Sample
Reedrill Model SK-35	0.24	0.27
	0.37	0.36
	0.29	0.30
	0.36	0.37
	0.35	0.46
	0.23	0.34

the door seals of the cab and the ducting running to the dust collector unit.

After each survey was completed, the dust samples were weighed and the respirable dust concentrations computed to the near 0.01 mg/m^3. These samples were then analyzed for quartz.

Results and Discussion

Table I shows the gravimetric sampling results of operators cabs of various drill studies. Samples were taken inside and outside the cab to establish a baseline so a comparison of the dust levels could be made before and after the installation of new filter. Initial dust levels inside the cab ranged from 0.30 mg/m^3 to 1.32 mg/m^3. Dust levels, after changing the filters, decreased in all the cabs, ranging from 0.20 mg/m^3 to 0.31 mg/m^3. The Reedrill and the Bucyrus-Erie dust concentrations inside the cab decreased by three percent. The Driltech concentration decreased by 84 percent.

In addition to filter maintenance, various work practices also contributed to maintaining the dust levels. Good housekeeping which includes keeping the cab free of debris and periodic wet mopping of the cab can also contribute to lower dust levels inside the cab.

For these three drills, keeping doors and windows of the cab closed tightly did not significantly effect the dust levels inside the cab. This, however, was due to the fact that the air filtration systems did maintain a slight positive pressure inside the cab. Prior to changing filters the positive pressure inside each cab was approximately 0.01 inches of water. After changing the filters the positive pressure inside the cabs ranged from 0.03 to 0.04 inches of water. This increased positive pressure also indicates that after cleaning the cab air filtration system more airflow is induced into the cab.

On two of the drills, efforts were made to determine the life expectancy of the filters. Sampling was conducted at various intervals following filter replacement. Results of these samples for the Driltech and Reedrill are given in Table II. In this case of the Driltech, samples were collected immediately before and after the installation of a new filter and then after 30 working shifts. Immediately after the filter change, there was an 85 percent decrease in concentration. However after 30 shifts, the concentration was seen to increase indicating a deterioration of the filter. In an attempt to determine more precisely when the system begins to deteriorate additional incremental sampling was conducted during the study of the Reedrill. As seen in Table II the deterioration of the filter was not as clearly defined as the study of the Driltech indicated.

In addition to evaluating dust levels inside and outside the cab, a comparison was made between the fixed point sample collected inside the cab and the personal sample worn by the operator. The fixed point sample location was typical of the location monitored for enforcement sampling and evaluation of the dust collection system. Table III shows the results of fixed point samples collected inside the cab and personal samples collected on the drill operator. A comparison of the fixed point samples and the personal samples collected on the operator shows that the samples collected on the operator were slightly higher than the fixed point sample. This difference can possibly be attributed to the fact that the operators' duties require work outside the cab approximately 15 percent of the time.

While a fixed point sample inside the cab approximates the operators' dust exposure, it may not be representative of a helpers' exposure if a helper is required to perform work outside the cab. As evident from sample results, dust levels outside the cab are significantly higher than dust levels inside the cab.

Table IV summarizes the quartz determinations made on respirable dust samples collected during these evaluations. The quartz values for the samples collected inside and outside the cab are shown. Although, the quantity of dust collected for some samples was less than normally utilized for quartz analysis, the data indicates that the quartz content of samples collected inside the cab were consistently less than those collected outside the cab. The data also indicate that the filtration systems were selectively removing quartz from the filtered air.

TABLE IV

Comparison of Quartz Levels Inside and Outside of Cabs of Rotary Blasthole Drills

	Percent Quartz	
	Inside Cab	Outside Cab
Reedrill Model SK-35		
Baseline	3	7
Baseline	6	11
After Installation of New Filters	7	13
After Installation of New Filters	13	15
After Installation of New Filters	3	6
After Installation of New Filters	9	16
Bucyrus Erie Model		
Baseline	13	29
Baseline	12	6
After Installation of New Filters	11	26

TABLE V

Particle Size Distribution

Particle Size (um)	Inside Cab % Mass	Inside Cab Cumulative %	Outside Cab % Mass	Outside Cab Cumulative %
1.00	5.01	5.01	1.01	1.01
1.26	5.91	10.93	1.30	2.31
1.59	7.11	18.05	1.78	4.10
2.00	9.12	27.17	2.57	6.67
2.52	9.36	36.54	3.22	9.90
3.18	9.73	46.27	3.84	13.74
4.01	10.84	57.12	5.19	18.94
5.05	8.05	65.17	6.01	24.96
6.36	10.19	75.37	7.46	32.42
8.01	11.78	87.15	8.27	40.70
10.09	8.56	95.72	8.36	49.06
12.71	4.27	100.00	11.01	60.08
16.01	0.	100.00	7.33	67.41
20.17	0.	100.00	9.77	93.48
25.41	0.	100.00	6.51	100.00

Particle size distribution of the samples inside and outside the cab, were analyzed on a Model TA II Coulter Counter and the results are shown on Table V. The data gives a fraction of the total number of particles in any size range. The mass median diameter of the dust inside and outside the cab is 3.5 um and 10.0 um with standard deviations of 2.1 and 2.9, respectively. This information indicates that in addition to selectively removing quartz, the filtration systems were also removing the larger particles from the air.

Conclusions and Recommendations

Based on the sampling results obtained from each study, and observations made throughout the studies, several conclusions and recommendations can be made.

1. For each study, compliance with a reduced dust standard was achieved.
2. The dust collection systems, air filtering systems and seals on the door enclosures of the drill cab combined with the operators' work practices can maintain dust levels in the cab below the reduced standards.
3. Air filtering systems should be checked and cleaned and/or filters replaced on a regular basis.
4. Fixed point dust concentrations inside the cab may not be indicative of the drill operator's helper exposure since his duties require him to perform work outside the cab.
5. The cab or work enclosure should be maintained under a positive pressure to prevent dust from entering from the outside environment. Periodic replacement of air filters will increase the positive pressure in the cab and permit maximum air delivery of the filtration system

In addition to these conclusions and recommendations, the following work practices observed should be followed to minimize environmental contamination.

1. Excessive quantities of dust should not be allowed to build up in an enclosed cab. The interior of the cab should be vacuumed or wet mopped on a regular basis.
2. Seals on the doors and windows of the cab should be

maintained. In addition to helping to maintain a positive pressure in the cab, good seals may result in lower noise levels within the cab.

3. Smoking can contribute significantly to the respirable dust determination of a confined area such as an enclosed cab. This practice should be discouraged to the extent possible.

4. Minimize, to the extent practicable, the opening of the doors of the cab.

5. Maintain a program that encompasses a check for leaks of the hose and duct system of the dust collector on the drill. Leaks in the ducting results in a lowering of the air flow design factor of the collector resulting in the unit operating at less than its maximum capability.

Acknowledgment

The authors wish to acknowledge the assistance of personnel within the various District and Subdistrict offices of MSHA and the companies involved during the various studies. Without their support, the results obtained would not be possible.

References

1. **Tomb, T.F. et al:** *Comparison of Respirable Dust Concentrations Measured with MRE and Modified Personal Gravimetric Sampling Equipment.* p. 23. U.S. Bureau of Mines RI 7772 (1973).

2. **Anderson, F.G., T.F. Tomb and M. Jacobson:** Analyzing Midget Impinger Samples with an Electric Counter. U.S. BuMines RI 7104 (1968).

Dust Sampling Roof Bolting Operations

ROBERT ONDREY, RICHARD STOLTZ, DAVID ATCHISON, and EVERETT GERBEC
Mine Safety and Health Administration, Pittsburgh Health Technology Center

The Dust Division, Pittsburgh Health Technology Center, has conducted environmental dust studies on various roof bolting operations. The Mine Safety and Health Administration (MSHA) has determined that it may be necessary to collect respirable dust samples on roof bolting operations to assure the health of the miner is being protected. When the quartz content of the dust is greater than five percent, the respirable dust standard is based on the amount of quartz in the dust. Analysis of dust samples collected by mine inspectors have shown that many roof bolting operations have quartz levels greater than five percent. The purpose of this study was to determine locations where dust samples could be collected to assess the roof bolter's occupational exposure to respirable dust. Gravimetric dust samples were collected in order to determine the most appropriate location to collect respirable dust samples to assess the environment of the roof bolter. All samples were collected full shift (8 hours) using approved coal mine respirable dust sampling equipment. Personal samples were collected on the roof bolter and helper as well as fixed point samples at various locations on the roof bolting machine. Analysis of the results of these samples indicate that fixed point dust samples collected on a roof bolting machine in general are not representative of the roof bolter's personal exposure. The results of this study show that if a personal sample cannot be collected on the roof bolter operator, the most appropriate alternative sampling location is near the roof bolter drill controls.

Introduction

In 1980 Federal Regulations for assessing employees' exposures to respirable dust were changed. Prior to 1980 all employees were sampled. After 1980 only the designated occupation on each section was sampled. "Designated occupation" means the occupation on a mechanized mining unit that has been determined by results of respirable dust samples to have the greatest respirable dust concentration.

There is evidence that the respirable dust standard for the designated occupation may not adequately protect some occupations on the mechanized mining unit (mechanized mining unit means a unit of mining equipment including hand loading equipment used for production of material) specifically, the roof bolter(s) and/or roof bolter helper. One situation where this may occur is when the roof bolter is working on the return air side of the continuous miner on a section using a single split of air. In this situation the roof bolter(s) will be exposed to the dust generated by the continuous miner in addition to the dust generated by the roof bolting machine.

Another situation is when there is quartz present in the roof bolter's working environment resulting in a respirable dust standard significantly lower than that required by the designated occupation. Section 70.101, Title 30, of the Code of Federal Regulations provides that respirable dust samples with a quartz content exceeding five percent will result in a lower respirable dust standard. This reduced respirable dust standard is computed by dividing the number 10 by the percent quartz. There have been roof bolters on a reduced respirable dust standard since the beginning of the respirable dust sampling program. However, the number of roof bolters going on a reduced respirable dust standard has greatly increased since 1981.

In 1981 the Mine Safety and Health Administration's (MSHAs) analytical procedure for determining the quartz percentage of a respirable dust sample was changed. This change enabled a quartz determination to be made on nearly all samples collected by enforcement personnel. Analysis of quartz data showed that approximately 50 percent of all roof bolter samples analyzed contained greater than five percent quartz, and that 63 percent of the time the quartz percentage of the roof bolter exceeded that of the designated occupation on the same Mechanized Mining Unit. At the present time approximately 1000 roof bolter occupations are on reduced respirable dust standard. Hence, the necessity for making the roof bolter a designated area. "Designated area" means the active areas of a mine identified by the operator in the plan required under ~75.316 (Ventilation System and Methane and Dust Control Plan) where bimonthly samples will be collected to measure the dust generation sources.(1)

Once an area has been designated the operator must take one valid respirable dust sample from the designated area on a normal production shift each bimonthly period. If the sample fails to meet the requirements of CFR 70.100 or 70.101 the operator must take five valid respirable dust samples from that designated area within 15 calendar days. The operator shall begin such sampling on the first day on which there is a production shift following the day of receipt of notification by MSHA.

After an area has been made a designated area, the question arises as to the selection of the sampling point within the designated area. The placement of the respirable dust sampling instrument within a designated area is critical in order to obtain a representative measurement of respirable dust within the designated area so that its measurement is indicative of the highest dust exposure to personnel who are required to work or travel in that area. As required by 30 CFR 70.208(e), the methane and dust control plan shall show the specific location where designated area samples will be collected. Some guidelines for the selection of this position are:

1. Generally, within 10 to 20 feet downwind of the dust generating source. (Hard to do on a roof bolter since the sampling location would be in the return behind the canvas.)

TABLE I

Single Arm Roof Bolters Concentration (mg/m^3) and Percent Quartz (%)

Mine 1

	Section A						Section B					
	Shift 1-1		Shift 2-2		Shift 3-3		Shift 1-4		Shift 2-5		Shift 3-6	
	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	% Qtz
Bolter	2.0	7	1.1	6	1.6	6	3.3	8	2.5	7	2.3	7
Helper	2.8	7	1.0	6	1.1	3	2.0	6	0.9	4	1.9	5
Bolter Controls	1.7	6	0.3	4	1.3	6	2.4	6	1.2	5	2.4	6
Dust Box Side	1.7	5	0.5	3	1.4	6	1.6	5	*	*	1.4	5
Immediate Intake	1.4	4	0.0	0	0.7	3	*	*	0.5	5	1.7	5
Immediate Return	1.3	4	0.3	4	0.8	2	*	*	*	*	*	*
Opposite Dust Box	*	*	*	*	*	*	1.9	5	0.9	6	0.5	3

	Mine 2				Mine 5					
	Section A				Section A		Section B		Section C	
	Shift 1-7		Shift 2-8		Shift 1-9		Shift 1-10		Shift 1-11	
	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz
Bolter	1.4	0	1.1	6	1.2	7	1.5	1	1.6	5
Helper	0.6	4	1.0	5	1.3	7	1.3	8	1.8	12
Bolter Controls	0.3	17	0.5	4	0.6	*	1.2	*	1.6	5
Dust Box Side	0.4	1	0.5	3	*	*	*	*	*	*
Immediate Intake	0.2	0	0.4	2	0.6	5	0.5	22	0.7	2
Immediate Return	0.4	1	0.5	4	0.8	6	*	*	*	*
Opposite Dust Box	*	*	*	*	*	*	*	*	*	*

* no sample collected or no analysis

2. At normal breathing level, but not less than one foot from the roof or rib.
3. More than two feet from any obstruction and placed where it will not be directly behind an obstruction which would affect the airflow around the sampling device.
4. Within 36 inches inby of the operator's control station or normal work station.

Because these guidelines do not exactly fit the roof bolter as a designated area; a study was undertaken to determine the best location for the roof bolter designated area sample. The purpose of this study was to determine locations where dust samples could be collected to assess the roof bolter's occupational exposure to respirable dust.

Sampling Strategy and Procedures

A variety of roof bolters representing typical mining applications were selected to be studied. Single and double arm bolters operating in both blowing and exhausting ventilation systems were sampled. Also, bolters were sampled using single and double air split face ventilation systems. However, all roof bolters selected to be studied were on a reduced respirable dust standard (less than 2.0 mg/m^3) due to a high quartz level in the environment.

There were two reasons for choosing roof bolting operations with a high environmental quartz content. First, one of the guidelines proposed was to make the roof bolter a designated area when the quartz percentage of the sample is greater than five percent. Secondly, a sufficient amount of quartz was necessary to obtain a profile of the quartz distribution in the vicinity of the roof bolting operation.

Approved Mine Safety Appliances (MSA) personal respirable coal mine dust sampling instruments were positioned in several locations on and in the immediate area of the roof bolter. The locations consisted of sampling the single arm roof bolter operator, helper and bolting controls or on both bolter operators and their bolting controls on a double arm roof bolter. For both single and double arm roof bolters a dust sampling instrument was located on the tram controls, dust box and, for one sampling shift, the automatic temporary roof support. The fixed-point samples located on the machine were collected to determine the best alternate location(s) for collecting the designated area sample in case the personal sample could not be collected on the operator. Also, it was desired to compare the different respirable dust concentrations from different sampling locations to determine the sources of dust on these operations.

A dust sample was collected on the immediate intake and return of the roof bolter. These samples were moved and relocated in each place the bolter moved to bolt. The immediate intake and return samples were collected in order to determine the amount of respirable dust the roof bolting operation generated. This was accomplished by subtracting the intake dust concentration from the return dust concentrations for each sampled shift.

All fixed-point sampling instruments were operated while on section. All personal sampling instruments were operated portal-to-portal (480 minutes) and at a flow rate of 2.0 liters per minute (lpm). The filter cassettes were pre- and post-weighed on an analytical balance to a hundredth of a milligram and dust concentrations were calculated. All respirable dust concentrations were then converted to MRE equivalent concentrations by multiplying by the constant factor of 1.38. In addition, all respirable dust samples were analyzed for quartz content using infrared spectroscopy.

During the shift, different system parameters pertaining to each roof bolting machine were noted or measured. The different parameters noted were: type of drill bit, type of dust collector, the number of bolts per working place and the number of working places bolted per shift. The parameters measured were the air velocity and quantity in the entry the bolting machine was operating and the vacuum pressure at the drill chuck. Also, a time study was done to determine the amount of time the roof bolting machine operated in each place bolted. The objective in noting these parameters was to see what effect, if any, they had on respirable dust levels measured in the vicinity of the roof bolter.

Sampling Results and Discussion

Single Arm Roof Bolters

Respirable dust sampling was conducted on a total of 13 sections at five different mines. Initially multiple shifts were sampled on each section. However, once it was determined that large shift to shift variation in data was not occuring the study ended with only one shift being sampled on each section at Mine No. 5. A total of 23 shifts were sampled. Eleven of these shifts were on sections employing single arm roof bolters and the remaining 12 shifts were on sections employing double arm roof bolters.

All gravimetric respirable dust sampling data for single arm roof bolters is shown on Table I. Examination of this data shows that respirable dust concentrations and/or quartz percentages measured at the dust box and opposite the dust box were lower than either personal concentrations measured on the bolter operator and bolter helper or the concentration measured at the bolter controls. Therefore, these were determined to be poor locations to collect an area sample and no further discussion will be made of data from those two locations.

Individual respirable dust concentrations of the bolter operator, bolter helper and bolter controls from Table I are graphically shown on Figure 1. Figure 1 shows the roof bolter operators respirable dust concentrations are greater than the respirable dust concentrations measured at the roof bolter controls. For the 11 shifts sampled on single arm bolters, average respirable dust concentrations for the bolter operator bolter helper and bolter controls are 1.7 mg/m^3, 1.4 mg/m^3, and 1.0 mg/m^3, respectively. Statistical analysis of the data shows that the difference between respirable dust concentration measured on the bolter operator and on the bolter controls is significant at a 95 percent confidence level. Therefore the most appropriate location to collect a roof bolter designated area sample is on the roof bolter operator.

The quartz data for the bolter operator, bolter helper and bolter controls for single arm roof bolters is shown in Figure 2. Eight of the 11 bolter operator samples had a quartz content greater than five percent. This would result in a reduced respirable dust standard for those eight sections. In all but one case the bolter operator had a higher quartz content than the sample collected at the bolter controls. This is

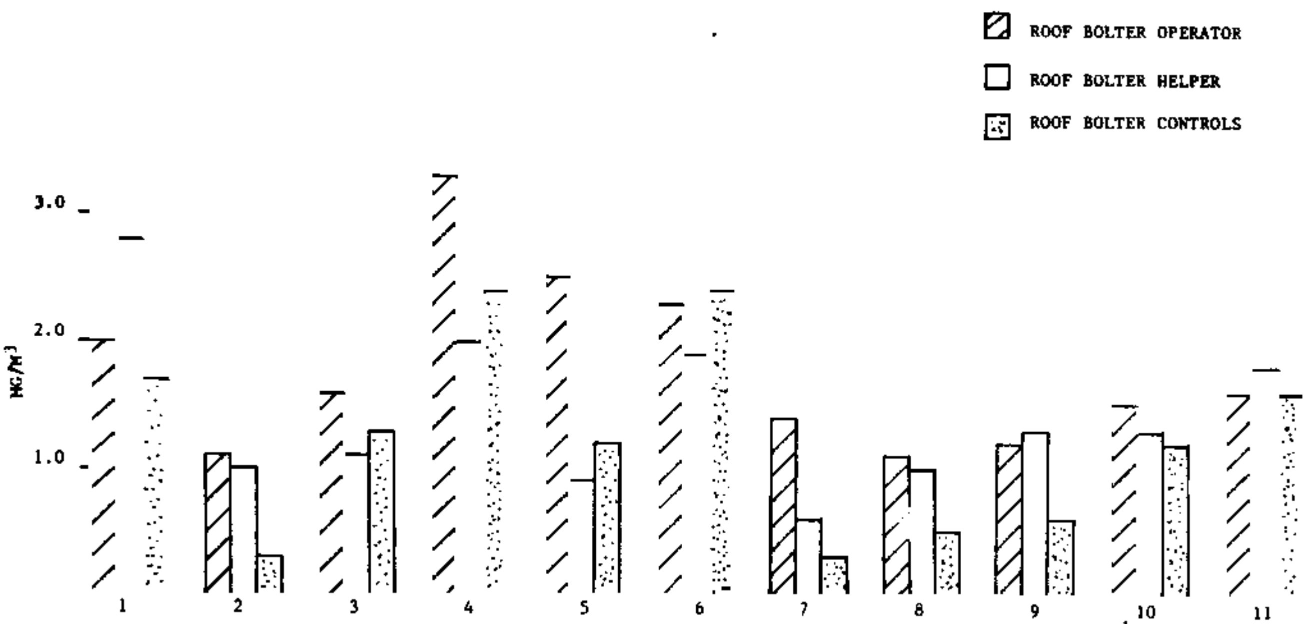


FIGURE 1. Single arm roof bolters.

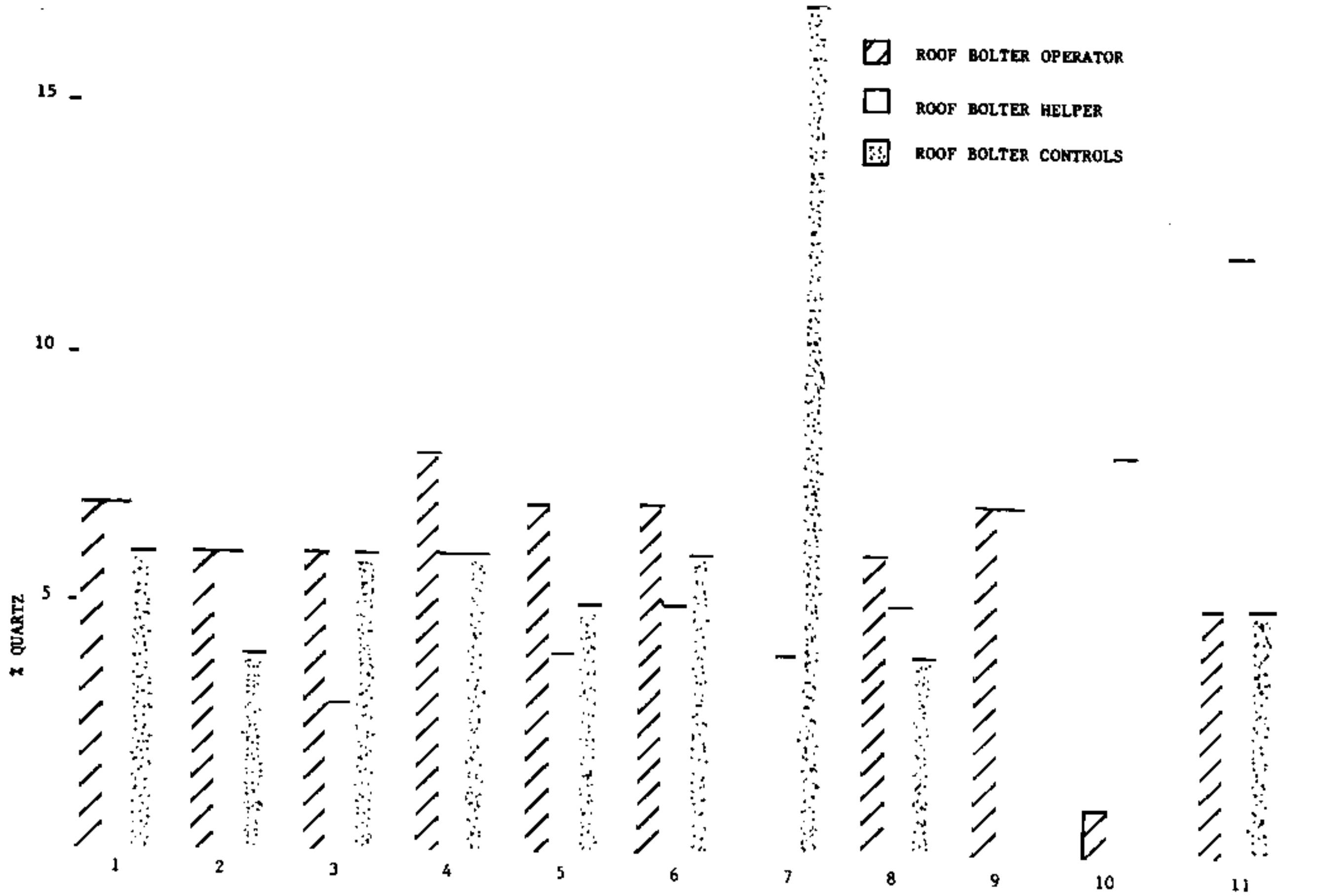


FIGURE 2. Single arm roof bolters percent quartz.

another reason for choosing to sample the roof bolter operator as the designated area.

Double Arm Roof Bolters

All of the gravimetric respirable dust sampling data for double arm roof bolters is shown on Table II. Examination of this data shows that respirable dust concentrations and/or quartz percentages measured at the dust box and tram controls were lower than personal concentrations measured on the right and left bolter operator. Therefore, these were determined to be poor locations to collect an area sample and no further discussion will be made of data from those two locations. Although the concentrations measured on the ATRS are more representative of the concentration measured on the left and right bolter operator; sampling at this location was stopped after only one shift due to the difficulty on collecting a sample at this location.

Statistical analysis of the double arm roof bolter data indicated the following: 1) there is no significant difference at the 95 percent confidence level between the right and left bolter operator's concentrations, 2) there is no significant difference at the 95 percent confidence level between the concentration measured at the right and left bolter controls, 3) there is no significant difference at the 95 percent confidence level between the concentrations measured at the right bolter operator and right bolter controls, 4) there is no significant difference at the 95 percent confidence level between the concentrations measured at the left bolter operator and the left bolter controls. Therefore, on double arm roof bolters any one of the above four sampling locations would be suitable for collecting a designated area sample. However, to make the designated area policy uniform, it is recommended that the bolter operator should be sampled.

Of the system parameters observed and measured during the survey, the only system parameter that had a noticeable effect on respirable dust exposures was the amount of time the roof bolter spent downwind of the continuous mining machine. As the amount of time the roof bolter spent downwind of the continuous mining machine increased, the respirable dust concentrations measured at the immediate intake and on the bolter operators increased. Subtracting the immediate intake concentration from the roof bolter operator's concentration would have resulted in all of the roof bolter operator concentrations being at or below 2.0 mg/m^3. The difference between the immediate intake and immediate return concentrations indicated the roof bolting operation was not generating a significant amount of dust (up to 0.3 mg/m^3).

Summary

The results of this study show that the most appropriate manner in which to sample the roof bolter DA is to collect a personal sample on the roof bolter operator. In situations

TABLE II

Double Arm Roof Bolters Concentration (mg/m^3) and Percent Quartz (%)

	Mine 2				Mine 3							
	Section B				Section A				Section B			
	Shift 1-1		Shift 2-2		Shift 1-3		Shift 2-4		Shift 1-5		Shift 2-6	
	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz
Right Bolter	1.0	7	0.6	9	1.1	8	0.9	7	3.9	9	1.6	13
Left Bolter	0.7	9	0.6	4	1.1	9	1.7	9	3.5	9	3.0	12
Right Bolter Controls	0.3	2	0.3	4	0.9	8	1.2	8	2.9	8	1.2	12
Left Bolter Controls	0.4	5	0.5	6	1.0	7	3.3	*	3.9	*	1.5	*
Tram Controls	0.2	4	0.5	6	*	*	*	*	2.6	8	0.8	9
Dust Box	*	*	*	*	0.8	8	0.7	10	*	*	*	*
Immediate Intake	0.1	2	0.2	0	0.7	7	1.1	7	2.7	8	0.7	8
Immediate Return	0.4	3	0.3	5	0.7	8	1.0	6	3.0	7	0.7	10
Right ATRS	*	*	*	*	*	*	*	*	*	*	*	*
Left ATRS	*	*	*	*	*	*	*	*	*	*	*	*

	Mine 3				Mine 4						Mine 5	
	Section C				Section A				Section B		Section D	
	Shift 1-7		Shift 2-8		Shift 1-9		Shift 2-10		Shift 1-11		Shift 1-12	
	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz	mg/m^3	%Qtz
Right Bolter	0.5	10	1.4	11	0.2	14	0.4	6	0.3	7	2.0	7
Left Bolter	0.4	11	1.5	4	0.2	24	0.1	18	0.5	5	2.9	8
Right Bolter Controls	0.1	9	1.3	*	0.2	27	0.1	14	0.3	7	2.4	7
Left Bolter Controls	0.1	*	0.7	10	0.2	33	0.2	29	0.2	3	3.0	8
Tram Controls	0.0	7	0.6	11	0.4	8	0.1	14	*	*	*	*
Dust Box	0.1	9	0.6	11	0.2	*	0.1	14	0.4	3	*	*
Immediate Intake	0.0	5	0.5	8	*	*	0.0	27	0.1	6	1.6	5
Immediate Return	*	*	*	*	*	*	*	*	0.3	5	*	*
Right ATRS	*	*	*	*	*	*	*	*	*	*	2.6	7
Left ATRS	*	*	*	*	*	*	*	*	*	*	2.7	*

* no sample collected or no quartz analysis.

where a personal sample cannot be collected on the roof bolter operator, the best alternate sampling location is near the roof bolter drill controls. The data also shows that location of the roof bolting machine with respect to the continuous mining machine noticeably affects the respirable dust exposure of the roof bolter operator.

References

1. Code of Federal Regulations, Title 30, Mineral Resources, Part 70, revised July 1, 1985, Office of Federal Register, National Archives and Records Service, General Services Administration, Washington, D. C.

CHARACTERIZATION II

Size Distribution of the Airborne Dust in Longwall Coal Faces

H.S. CHIANG, S.S. PENG and Y. LUO
Department of Mining Engineering, West Virginia University, Morgantown, West Virginia

Introduction

The way in which the particle sizes distribute in the airborne coal dust plays an important role in the transportation of the dust in the mine air and human respiratory systems. Though the particles of a size less than 10 microns could be inhaled, the real distractive portion of the dust is that the sizes range from 1 to 5 microns since only they can reach the lungs and be retained there. Those with an equivalent diameter larger than 5 microns will settle on the membranes of the branchial tubes[1] while those with diameter less than 1 micron can either be exhaled out of the lungs or the settled quantity is so insignificant that does very little harm to the lungs. In the transportation process, the finer dust will fly farther away from the sources than the coarser ones. Thus once the fine dust is generated and becomes airborne, it will spread out to a larger area.

In this paper, the coal samples collected from two longwall faces were analyzed statistically for size distribution. A mathematical model is proposed and the effects of different conditions on the dust size distribution were analyzed using the mathematical model.

Sampling and Statistical Analyses

Sampling Instrument and Procedure

The instrument used in the sampling were Mine Safety Appliance (MSA) personal sampling units equipped with 10-mm nylon cyclones, pre-weighed MSA PVC filters and constant-flow pumps.

Two longwall operating faces were selected for the dust sampling. The two faces were located in two coal mines extracting Pittsburgh seam. The double-ended ranging-drum shearer applying the unidirectional cutting sequence was employed. The two-leg shield supports were used for face support. The width of the two faces was about 215 meters.

In each of the two faces, four sampling stations were set up. The stations were located at the cross-cut immediately outby the headentry side, the 15th support (25 m), 65th support (107 m) and 111th support (182 m) from headentry T-junction, and numbered as #1, #2, #3, and #4 station, respectively (Figure 1). At each sampling station, a group of three sampling units was hung at proper position. At cross-cut (#1) station, the units were hung about one foot under the roofline in the center of the cut (Figure 2a), and at the stations in the face, the units were position near the hydraulic legs and one foot below the support canopy (Figure 2b).

One complete set of 12 samples was collected for each day. The sampling were performed for five consecutive days. All the samplings were conducted in the morning shifts. The time duration of the sampling for each day was about five hours. During that time, the shearer might complete 5 to 7 mining cycles.

Method of Laboratory Analyses

The samples were analyzed by Coulter Counter. In this method, the size range of the dust particles is divided into several sub-ranges with varying range widths, for example, 0.79–1.00, 1.00–1.26, 1.26–1.59, . . ., 16.01–20.17, 20.17–25.41 microns. The number of dust particles in each sub-range is counted and the total weight of those particles is determined.

Results of Laboratory Analyses

Since the dust concentration at any point in the longwall faces varies with time and its relative position with shearer's cutting and support advancing, the time-weighted average dust concentration (TWADC) is more representative of the dust exposure experienced by the face crew. TWADC is the sum of the products of the instantaneous dust concentrations and its time durations divided by the total sampling time or in integral form

$$\bar{N}(x) = \frac{1}{T}\int_0^T N(x,t)\ dt \qquad (1)$$

where:

TABLE I

Dust Sample Weight (mg) for Panel #1, Station #4

Size range (um)	Date 10/22/85	10/23/85	10/24/85	Average
0.79 - 1.00	0.021	0.038	0.020	0.0263
1.00 - 1.26	0.030	0.047	0.027	0.0347
1.26 - 1.59	0.045	0.065	0.042	0.0507
1.59 - 2.00	0.078	0.095	0.068	0.0803
2.00 - 2.52	0.104	0.115	0.093	0.1040
2.52 - 3.18	0.137	0.135	0.121	0.1310
3.18 - 4.01	0.127	0.112	0.112	0.1170
4.01 - 5.05	0.087	0.057	0.070	0.0713
5.05 - 6.36	0.042	0.030	0.034	0.0353
6.36 - 8.01	0.029	0.033	0.035	0.0323
8.01 - 10.09	0.017	0.017	0.010	0.0147
10.09 - 12.71	0.007	0.000	0.014	0.0070
12.71 - 16.01	0.014	0.000	0.000	0.0047
16.01 - 20.17	0.028	0.000	0.000	0.0093
20.17 - 25.41	0.000	0.006	0.000	0.0020
TOTAL	0.766	0.750	0.646	0.721

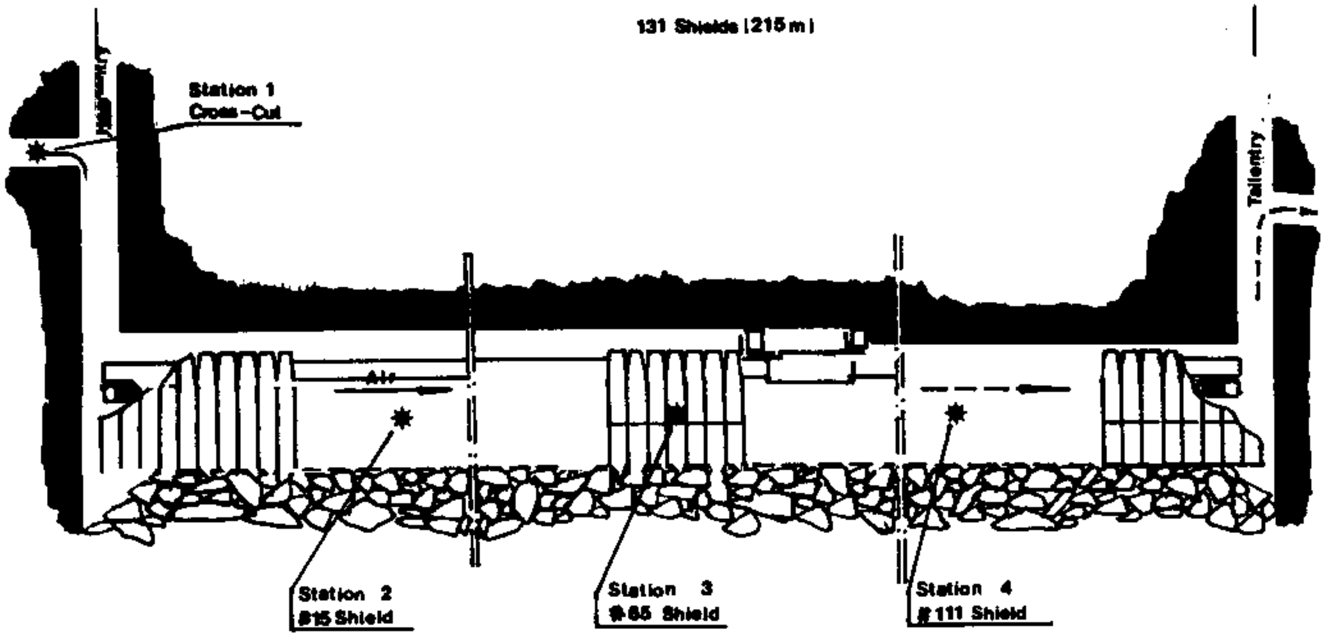


FIGURE 1. Face layout showing the location of the sampling stations.

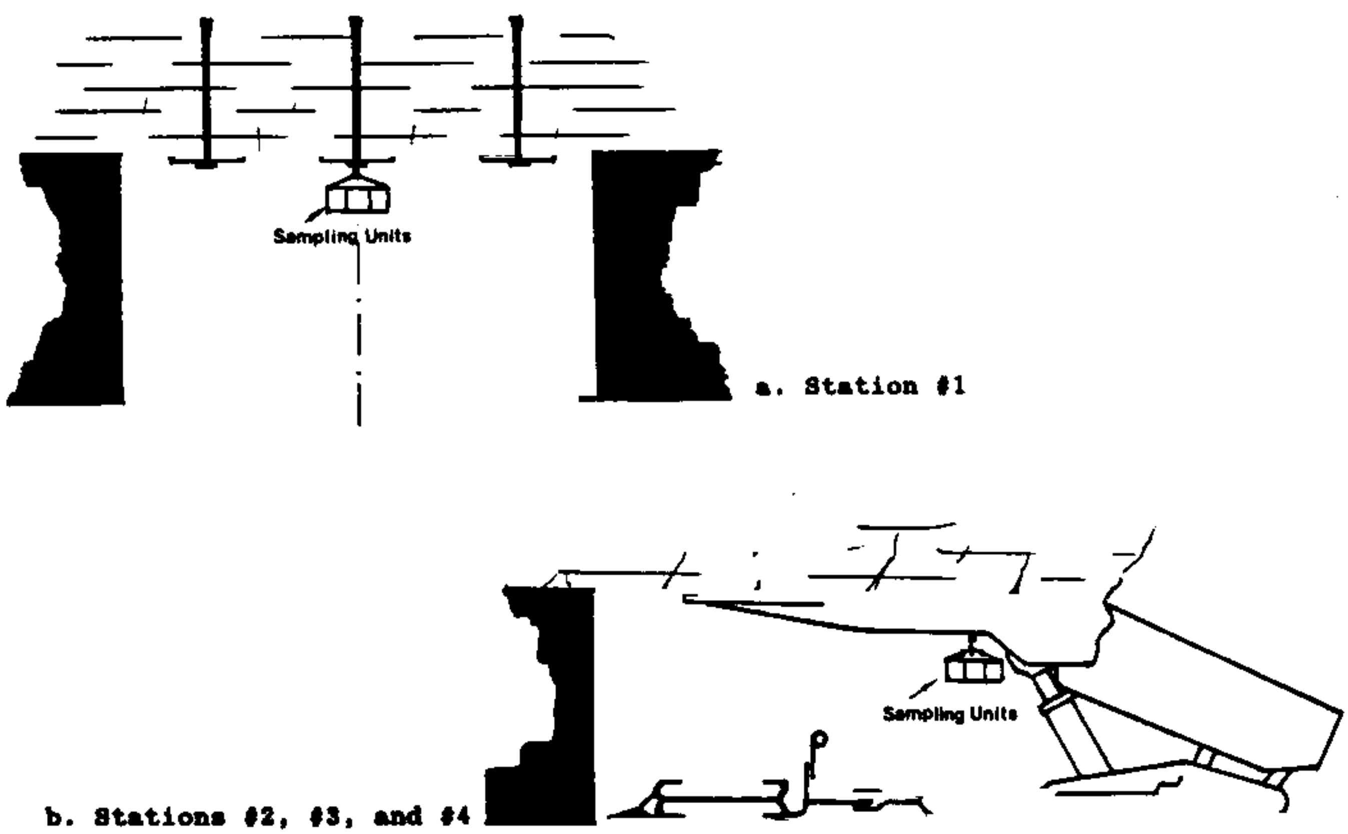


FIGURE 2. Installation methods of sampling units at various stations.

$\bar{N}(x)$ = TWADC at the sampling station x m from headenry T-junction in the face;
$N(x,t)$= instantaneous dust concentration at station x and at time t;
T = time duration of the sampling.

The results of the size analysis for the dust samples from Station #4, Panel #1 are shown in Tables I and II. Table I shows the dust weight by size range, and Table II shows the number of dust particles in each range. It is quite obvious that there are very few dust particles larger than 20 microns (equivalent diameter).

Statistical Analyses

In order to make the analyses of the dust size distribution more accurate and meaningful, the statistical analyses go through the following three steps:

Step I: Data Transformation

The raw data are transferred into cumulative percentile data by the following equations:

A. For cumulative dust weight in percent, Pw

$$P_w(D_i) = 100\ (\sum_{j=1}^{i} w_j)/W \qquad (\%) \qquad (2)$$

where:

D_i = upper size boundary of the ith size sub-range;
w_j = total weight of the dust particles with their size falling into jth size sub-range;
W = total weight of the prepared samples.

The transferred cumulative dust weight percentiles for Station #4, Panel #1 are plotted against the upper boundary of each range in Figure 3. This figure shows that at the sampling station, though the size composition of each individual sample deviates from each other to some extent, the degree of the deviation is very small and the general trend is similar.

TABLE I

Dust Sample Weight (mg) for Panel #1, Station #4

Size range (um)	10/22/85	10/23/85	10/24/85	Average
	Date			
0.79 - 1.00	1567.5	27845	1515.2	19557
1.00 - 1.26	11145	17372	10170	12896
1.26 - 1.59	8330	11912	7765	9339
1.59 - 2.00	7167	8605	6175	7316
2.00 - 2.52	4787	5275	4277	4780
2.52 - 3.18	3127	3085	2777	2996
3.18 - 4.01	1445	1280	1275	1333
4.01 - 5.05	488	325	397	407
5.05 - 6.36	12.0	87	97	101
6.36 - 8.01	42	47	50	46
8.01 - 10.09	12	12	07	10
10.09 - 12.71	07	00	05	04
12.71 - 16.01	02	00	00	01
16.01 - 20.17	08	00	00	03
20.17 - 25.41	00	02	00	01
TOTAL	52365	75857	48147	58790

B. For cumulative number of dust particles in percent, PN,

$$P_N(D_i) = 100\ (\sum_{j=1}^{i} n_j)/N \qquad (\%) \qquad (3)$$

where:

n_j = number of dust particles with their size falling into the jth size sub-range;
N = total number of the dust particles in the prepared sample.

The computed cumulative percentiles and the average values for Station #4, Panel #1 are plotted as Figure 4.

Step II: Regression

A. For cumulative dust weight, a function is proposed

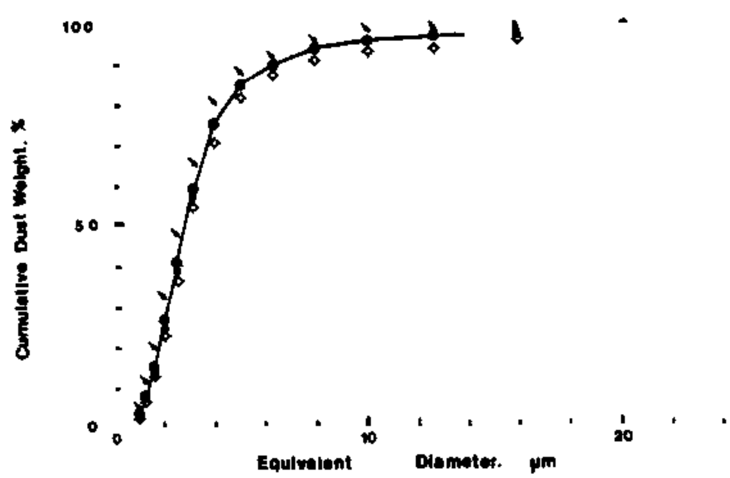


FIGURE 3. Cumulative dust weight for panel #1, station #4.

FIGURE 4. Cumulative number of particles for panel #1, station #4.

$$P_W = 100 - bDe^{-cD^d} \qquad (4)$$

to fit the cumulative weight percentiles. In the expression, P_W is the average cumulative dust weight percentile, b, c, d are coefficients and D the equivalent diameter of the dust particles in microns.

The predicted cumulative dust weight percentile vs dust size curves for the two investigated panels are plotted in Figures 5 and 6. The good agreement between the data points and the prediction curves is evident.

B. For cumulative number of dust particles

$$P_N = 100\ (1 - e^{-aD^2}) \qquad (5)$$

The following regression function was proposed for the cumulative number percentiles

where:

a = a coefficient

The prediction curves are plotted in Figures 7 and 8 for Panels #1 and #2, respectively.

Step III: Differentiation

By differentiating equations 4 and 5, the functions of size distribution in terms of dust weight and number of dust particles can be obtained, respectively as

$$P_W = \frac{dP}{dD} = be^{-cD^d}\ (cdD^d - 1) \qquad (6)$$

$$P_N = \frac{dP}{dD} = 200\ aD^{-aD^2} \qquad (7)$$

The predicted size distribution curves for the two panels are plotted in Figures 9 and 10. It should be noted that the effective size range for equations 6 and 7 is only from 1 to 20 microns.

Figure 9a shows that at Panel #1 the dust becomes finer as the distance from headentry T-junction toward the tailentry increases; in other words, the percentage content of the fine dust (i.e., 1 to 5 microns) increases as the airborne dust travels in the face. For example, if we apply equation 4

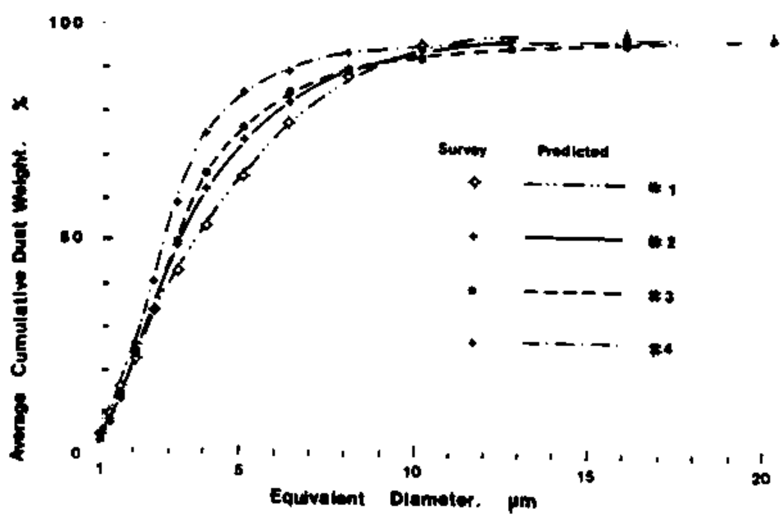


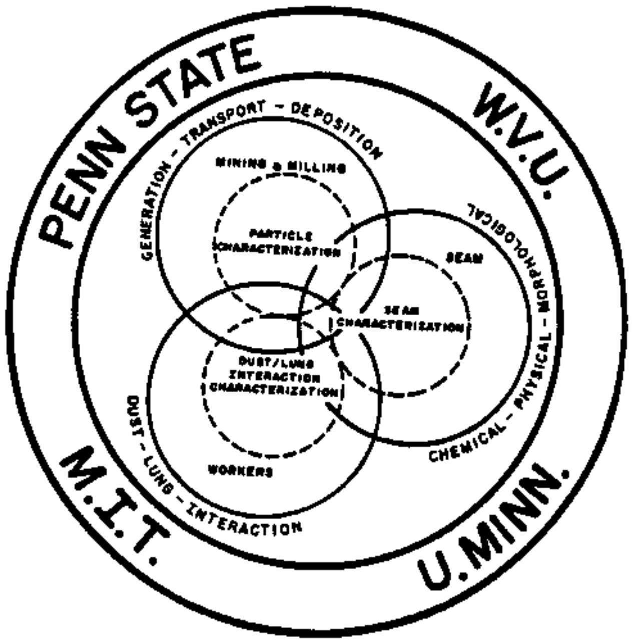
FIGURE 5. Average cumulative dust weight for panel #1.

RESEARCH PROGRAM AND STATUS REPORT 1984-1988

Edited by
ROBERT L. FRANTZ
and
RAJA V. RAMANI

GENERIC MINERAL TECHNOLOGY CENTER FOR RESPIRABLE DUST

RESEARCH PROGRAM AND STATUS REPORT 1984-1988



GENERIC MINERAL TECHNOLOGY CENTER FOR RESPIRABLE DUST

The Pennsylvania State University
West Virginia University
University of Minnesota
Massachusetts Institute of Technology
Michigan Technological University

Submitted To
Office of Mineral Institutes
U.S. Bureau of Mines
Washington, D.C.

November 1988

RESEARCH PROGRAM AND STATUS REPORT 1984-1988

THE GENERIC MINERAL TECHNOLOGY CENTER FOR RESPIRABLE DUST

Edited by
Robert L. Frantz
and
Raja V. Ramani

PENNSTATE

1855

WEST VIRGINIA UNIVERSITY

Volumes of the Respirable Dust Center

VOLUME 1	Status Report, 1984-1988
VOLUME 2	Report to the Committee on Mining and Mineral Resources Research,1987
VOLUME 3	Publications, l984
VOLUME 4	Publications, 1985
VOLUME 5	Publications, 1986
VOLUME 6	Publications, 1987
VOLUME 7	Respirable Dust Center Research Program Review
CONFERENCE PROCEEDINGS	Coal Mine Dust Conference West Virginia University Morgantown, West Virginia October l984
CONFERENCE PROCEEDINGS	Respirable Dust in the Mineral Industries: Health Effects, Characterization and Control The Pennsylvania State University University Park, Pennsylvania October l986

CONTENTS

	Foreword	page vii
	National Plan	x
	Advisory Council Members	xi
	List of Figures	xii
	List of Tables	xiii
1	**The Respirable Dust Center Research Program**	**1**
2	**Dusts, Tests, Samples and Analyses**	**13**
2.1	Suite of Characterized Dust Samples	15
2.2	Suite of Medical Tests	20
2.3	Sampling and Dust Generation Methods	22
2.4	Size, Chemical and Mineralogical Analyses	25
3	**Dust Center Project Abstracts**	**29**
3.1	**Interaction of Dust and Lung**	35
	Introduction	37
	Project Abstracts	40
3.2	**Particle Characterization Projects**	49
	Introduction	51
	Project Abstracts	53
3.3	**Mine Workers, Mining System, Seam Geology Dust Relationship Projects**	63
	Introduction	65
	Project Abstracts	67
3.4	**Dust Dilution, Transport and Deposition Projects**	73
	Introduction	75
	Project Abstracts	77
3.5	**Control of Dust Generation Projects**	83
	Introduction	85
	Project Abstracts	87
4	**Dust Center Project Reports**	**91**
4.1	**Interaction of Dust and Lung Projects**	93
	Mechanism of Lung Injury (PS4/USBM 4204) *Bartlett*	95
	Alveolar Macrophage and Polymorphonuclear Leukocytes (PS10/USBM 4209) *Demers*	105

Biochemical Alterations in Respiratory Tract Mucus
(PS11/USBM 4210) *Bhavanandan* page 116

Interaction of Dust and Nonhuman Primate Lungs
(PS12/USBM 4211) *White/Drozdowicz/Bowman* 126

Pulmonary Inhalation Toxicity of Respirable Dust
(WV5/USBM 5405) *Lantz/Stanley/Dalal* 134

Airway Reactivity in Coal Miners
(WV8/USBM 5407) *Abrons/Petsonk* 142

Effects of Dust on Release of Superoxide
(WV9/USBM 5408) *Cilento/Lantz* 149

Tracheal Acoustic Impedance of Air Passage
(WV14A/USBM 5413) *Sneckenberger* 158

Topographical Laser Holography for Detection of Black Lung
(WV14B/USBM 5413) *Stanley* 166

The Role of Platelet Activating Factor in Pneumoconioses
(WV17/USBM 5423) *VanDyke/Castronova* 174

4.2 **Particle Characterization Projects** **187**

Characterization of Dust Particles
(PS3/USBM 4203) *Hogg/Luckie* 189

Wetting Characteristics in Relation to Dust Abatement
(PS8/USBM 4207) *Chander/Aplan* 201

Analysis of Coal Dust Particles Using an SEM
(PS9/USBM 4208) *Hogg/Austin* 211

Adhesion, Aglomeration and Deposition of Dust
(PS15/USBM 4223) *Chander/Hogg* 220

Magnetic Resonance of Paramagnetic Ions and Free Radicals
(WV10/USBM 5409) *Dalal/Vallyathan* 227

Shape and Surface Characterization of Dust Particles
(WV12/USBM 5411) *Meloy/Vallyathan/Wallace* 233

Dust Testing in Mines and Metallurgical Operations
(MIT1/USBM 4202) *Ring* 257

Effect of Physical Properties of Dusts on Toxicity
(MIT2/USBM 2521) *Elliott/Bolsaitis* 248

Coal Mine Dust Characterization
(MN1/USBM 2701) *Marple/Rubow* 257

Determination of Silica Particle Concentration
(MN3/USBM 2703) *Marple/Rubow* 265

Determination of Active Silica Using PA Spectroscopy
(WV13/USBM 5412) *Seehra/Wallace* page 270

4.3 **Mine Workers, Mining System, Seam Geology Dust** **277**

Relationship Projects

Standard Procedures for Characterization of Dust Potential (PS5/USBM 4205) *Mutmansky/Bise/Frantz* 279

Improved Dust Sampling/Analytical Strategies for Mine Use (PS14/USBM 4222/5422/2722) *Mutmansky* 286

Longwall Dust (WV3/USBM) *Peng* 294

Correlations of Respirable Dust Characteristics (WV6/USBM 5406) *Stobbe/Grayson* 305

Analysis of Diesel Particulate by Raman Spectroscopy (MTU1/USBM 2601) *Johnson/Cornilsen* 313

Monitoring and Control of Diesel Particulate in a Mine (MTU2/USBM 2621) *Johnson/Cornilsen* 320

4.4 **Dust Dilution, Transport and Deposition Projects** **328**

Prediction of Ambient Dust Concentration in Mines (PS2/USBM 4202) *Ramani* 330

Computer Modeling of Longwall Face Ventilation (PS7/USBM 4206) *Ramani* 339

An Expert System for Planning Mine Ventilation Systems (PS13/USBM 4221) *Ramani* 347

Development of Mine Dust Distribution Models (WV11/USBM 5410) *Wang/Chiang* 357

Aerodynamic Diameter Analysis of Coal Dust (MN2/USBM 2702) *Marple/Rubow* 360

4.5 **Control of Dust Generation Projects** **370**

Fracture Mechanics Study of Crack Propagation in Coal (PS1/USBM 4201) *Bieniawski* 372

Mechanisms of Dust Generation and Entrainment (WV1/USBM 5401) *Khair* 389

Correlation of Dust Due to Regrinding at the Face (WV15/USBM 5421) *Khair* 399

5 Appendix **409**

Appendix 1: Respirable Dust Center Personnel 411
Appendix 2: Characteristics of Coals Used to Prepare Standard Dusts 417

FOREWORD

This report presents the research program and the status report 1984-1988 for the Generic Mineral Technology Center for Respirable Dust (Dust Center). This research has been supported by the Department of the Interior's Mineral Institute program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under grant number G1135142.

This report is a compilation of the status of the various research projects and activities of the Dust Center during the years 1984 to 1988. It was submitted by the Dust Center in January 1989. It is the first in a series of volumes describing the Dust Center research programs, the interactions with U.S. Bureau of Mines research (Volume 2), the publications emanating from the Dust Center over the period 1984-1987 (Volumes 3, 4, 5, and 6) and a Respirable Dust Center Research Program Review (Volume 7).

The primary goal of the Dust Center is to reduce the incidence and severity of respirable dust disease through advancement of the fundamental understanding of all aspects of respirable dust associated with mining and milling and the interaction of dust and lungs through:

- Research
- Graduate and Undergraduate Students
- Training Engineers and Scientists
- Technology Transfer
- Reference Center Library

A co-ordinated and integrated research effort to study the scientific, engineering and medical components of the respirable dust problem in the following five areas are underway:

- Dust Generation
- Dust Dispersion and Dilution
- Dust Characterization
- Interaction of Dust and Lungs
- Relationship of Seam Characteristics to Dust Generation and Mobility

The Dust Center's research program explores these concerns with the objective of refining existing strategies and developing new respirable dust control techniques that are consistent with the fundamental dust-lung interaction processes that lead to mine worker disability. The fundamental aspects of this work are applicable to the control of respirable dust problems in both hard rock mines and coal mines and to other dusts such as diesel- generated.

This Status Report details in a summary manner, the objective, scope and progress in the various research projects in the center. There has been significant accomplishments in the understanding of the scientific, medical and engineering aspects of the respirable dust problems.

The research performed in the Generic Mineral Technology for Respirable Dust has definitely established that varying coal dust characteristics do result in varying responses in a variety of experiments, and as such are being incorporated into medical investigations. Research findings developed by scientists in the Dust Center relate important variants, such as "stale" versus "fresh" dust and superoxide release. The findings are believed to be related to the potential for the reduction of the incidence and severity of black lung disease.

Three coal samples (Anthracite, Medium Volatile, High Volatile) having widely varying characteristics have been selected to provide the unique common thread of a suite of characterized dust samples--anthracite and bituminous coal, limestone rock dust, fireclay and silica--for investigations by Center researchers. Medical personnel are utilizing this suite of samples to perform a variety of medical experiments on small animal lung cells in such areas as lung damage (fibroblasts), immunology (chemical mediators) and mucus generation (cilia damage). A unique project to investigate the response of non-human primate pulmonary macrophages as compared to those of rats and guinea pigs is in progress. This unique concerted medical/primate animal effort is necessary to translate as rapidly as possible to human benefit the biochemical changes observed in small animal studies.

New equipment, instrumentation and test procedures for fracture toughness determination to assess the relative dust generation potential of various coals for engineering design has been developed. A variable response in the wetting rates and efficiency of surfactants related to the effectiveness of dust suppression utilizing water sprays in the mines has been determined for various coals.

Significant benefits have resulted from the synergism and rapid dissemination of research results embedded in the Dust Center's program of scientific, engineering and medical research.

The Dust Center co-directors express their sincere thanks to Dr. Richard A. Bajura, Dr. John Elliot, Dr. John Johnson, Dr. Virgil Marple and Dr. Z. T. Bieniawski for their co-operation in the administration of the center. It is recognized that the strength and accomplishments of the center are derived from the investigators and students who tirelessly perform to achieve the research and educational goals of the Center.

The support from the United States Congress for the Generic Mineral Technology Center for Respirable Dust is gratefully acknowledged. We also acknowledge and appreciate the support and inputs from USBM, NIOSH, MSHA, the Research Advisory Council, and the Committee on Mining and Mineral Resources Research which have significantly contributed to the activities of the Dust Center

January 1, 1989
University Park, Pennsylvania

Respectfully submitted,

Robert L. Frantz
Co-Director, Generic Mineral Technology
Center for Respirable Dust
Co-Editor

R. V. Ramani
Co-Director, Generic Mineral Technology
Center for Respirable Dust
Co-Editor

THE RESPIRABLE DUST CENTER
Excerpted From The

1988 UPDATE TO THE NATIONAL PLAN FOR RESEARCH IN MINING AND MINERAL RESEARCH

Report to:

December 15, 1987

The Secretary of the Interior
The President of the United States
The President of the Senate
The Speaker of the House of Representatives

Section 9(e) of Public Law 98-409 of August 29, 1984, (98 Stat. 1536 et seq.) mandates that the Committee on Mining and Mineral Resources Research submit an annual update to the National Plan for Research in Mining and Mineral Resources: "Improving Research and Education in Mineral Science and Technology through Government-(Federal, State and Local), Industry, and University Cooperation."
....

Respirable Dust (centered at Pennsylvania State U. and West Virginia U., with affiliates at U. of Minnesota and Massachusetts Institute of Technology): brings together experts concerned with particles causing potentially disabling or fatal diseases, including pneumoconiosis ("black lung"), silicosis, and asbestosis, the latter of deep concern not just to workers in the mineral sector of the economy but also to the general populace.
....

SIGNED:

Carl L. Randolph
Mining Industry

Win Aung
National Science Foundation

Don L. Warner
University Administrator

Walter R. Hibbard, Jr.
National Academy of Sciences

John H. DeYoung, Jr.
U.S. Geological Survey

Joseph N. Crowley
University Administrator

John C. Calhoun, Jr.
National Academy of Engineering

John D. Morgan
Bureau of Mines

Edward S. Frohling
Mining Industry

Orme Lewis, Jr.
Conservation Community
COCHAIR

James W. Ziglar
Asst. Secretary-Water & Science
U.S. Department of the Interior
COCHAIR

Generic Mineral Technology Center For Respirable Dust

RESEARCH ADVISORY COUNCIL MEMBERS

Dr. John A. Breslin
Senior Staff Physical Scientist
U.S. Bureau of Mines
2401 E Street, N.W.
Columbia Plaza
Washington, D.C. 20241
(202) 634-1220

Dr. John A. Campbell
Director, Engineering and Technology Support
Kerr-McGee Corporation
P.O. Box 25861
Oklahoma City, OK 73125
(405) 270-3778

Mr. Robert E. Glenn
Director, Division of Respiratory Disease Studies - NIOSH
944 Chestnut Ridge Road
Morgantown, WV 26505
(304) 459-5978

Dr. Jerome Kleinerman
Department of Pathology
Cleveland Met. General Hospital
3395 Scranton Road
Cleveland, OH 44109
(216) 459-5978

Dr. Ronald Munson
Director, Office of Mineral Institutes - MS 1020
U.S. Department of the Interior
2401 E Street, N.W.
Washington, D.C. 20241
(202) 634-1328

Mr. John Murphy
Research Director
Pittsburgh Research Center
U.S. Bureau of Mines
P.O. Box 18070
Pittsburgh, PA 15236
(412-675-6601

Dr. Kandiah Sivarajah
State Toxicologist
Room 825--Health and Welfare Building
Harrisburg, PA 17108
(717) 787-1708

Dr. Pramod Thakur
Research Group Leader
CONOCO, Inc.
R & D Division
Route #1, Box 119
Morgantown, WV 26505
(304) 983-2251

Dr. Lewis Wade
Research Director
Twin Cities Research Center
U.S. Bureau of Mines
5629 Minnehaha Avenue, S.
Minneapolis, MN 55417
(612-725-4610

Dr. James L. Weeks, C.I.H.
Deputy Administrator for Occupational Health
United Mine Workers of America
900 15th Street, N.W.
Washington, D.C. 20005
(202) 842-7300

PAST RESEARCH ADVISORY COUNCIL MEMBERS

Mr. Darrel Auch
Senior Vice President
Northern West Virginia Region
Consolidation Coal Company
P.O. Box 1314
Morgantown, WV 26507
(304) 296-3461

Dr. J. Harrison Daniel
Program Manager, Mining Research
Health and Safety
2401 E Street, N.W.
Washington, D.C. 20241
(202) 634-1253

Dr. Thomas Falkie
President
Berwind Natural Resources Company
Centre Square West
1500 Market Street
Philadelphia, PA 19102
(215) 563-2800

Dr. Fred Kissell
Research Supervisor
Pittsburgh Safety Research Center
U.S. Bureau of Mines
4800 Forbes Avenue
Pittsburgh, PA 15213
(412) 675-6679

Mr. C. Wesley McDonald
Senior Vice President (Mining)
Northern West Virginia Region
Consolidation Coal Company
P.O. Box 1314
Morgantown, WV 26505
(304) 296-3461

Dr. Donald Reid
Deputy Secretary for Public Health Programs
Department of Health
Health and Welfare Building
P.O. Box 90
Harrisburg, PA 17108
(717) 783-8804

LIST OF FIGURES

1 The Respirable Dust Center Research Program

Figure 1: The integration of scientific, engineering, and medical research findings into on-going projects. page 6

Figure 2: Standardized protocols for Respirable Dust Research in scientific, engineering, and medical areas. 8

Figure 3: Respirable Dust Center university locations. 9

Figure 4: Train engineers, scientists, medical personnel, graduate students and undergraduate students in the interdisciplinary aspects of respirable dust. 10

2 Dusts, Tests, Samples and Analysis

Figure 5: The holistic approach to standardized protocols and procedures. 16

Figure 6: Characterized dust samples. 19

Figure 7: Medical tests. 21

Figure 8: Sampling and dust generation methods. 23

Figure 9: Generalized layout of sampling locations. 24

Figure 10: Size, chemical, and mineralogical analyses. 27

3 Dust Center Projects: Introduction and Abstracts

Figure 11: Individual Dust Center projects in the Dust Lung Interaction Area. 39

Figure 12: Individual Dust Center projects in the Particle Characterization Area. 52

Figure 13: Individual Dust Center projects in the Mine Workers, Mining Systems, Seam Geology Dust Relationship Area. 66

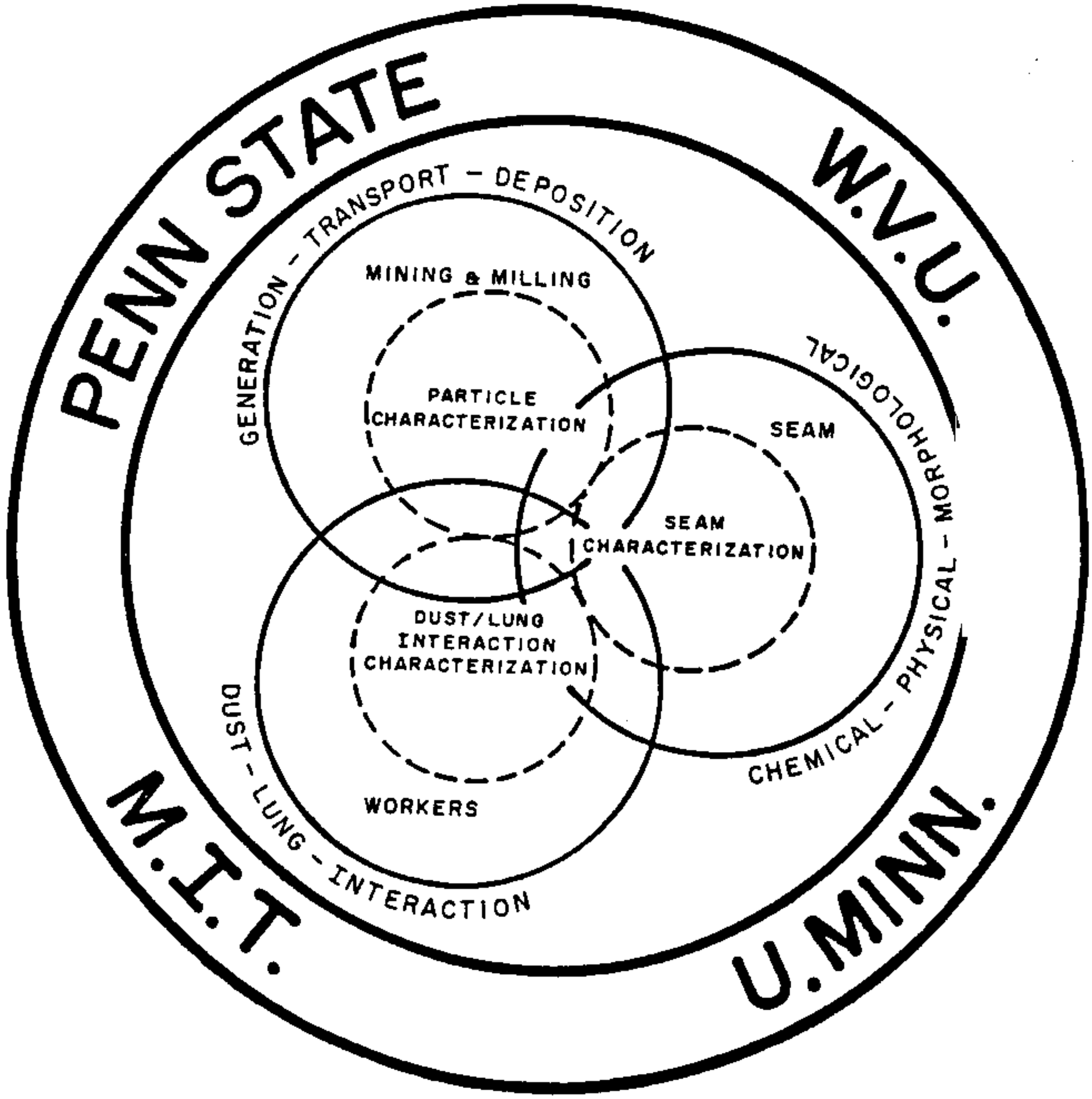
Figure 14: Individual Dust Center projects in the Respirable Dust Dilution, Transport, and Deposition Area. 76

Figure 15: Individual Dust Center projects in the Control of Dust and Particulate Matter Generation Area. 86

LIST OF TABLES

1 The Respirable Dust Center Research Program

Table 1:	Respirable Dust Center Personnel	page 4
Table 2:	Summary of Degrees Granted and Mineral Sector Employment	5
Table 3:	Summary of Dust Center Publications and Presentations	5



The Respirable Dust Center

1

The Respirable Dust Center Research Program

THE RESPIRABLE DUST CENTER RESEARCH PROGRAM

The U.S. Bureau of Mines established on August 15, 1983, The Generic Mineral Technology Center for Respirable Dust (Dust Center) within the Mining and Mineral Resource Research Institutes (MRIs) at The Pennsylvania State university and West Virginia University, and in association with participating MRIs at Massachusetts Institute of Technology and the University of Minnnesota. In 1986, Michigan Technological University (MTU) was awarded a grant through the Dust Center. The center's research program has been developed with recognition of the stated objective of the Federal Mine Safety and Health law, which is "... (to) permit each miner the opportunity to work underground during the period of his entire adult working life without incurring any disability from pneumoconiosis of any other occupation-related diseases..." The Dust Center's program is designed to foster an accelerated attack through fundamental research on problems confronting the control of respirable dust in mines. The interactions of the universities and the research program components in the characterization of coal seams, respirable dust particles and the workers lungs are depicted in the logo of the Dust Center.

The primary goal of the Dust Center is to reduce the incidence and severity of respirable dust disease through advancing fundamental understanding of all aspects of respirable dust associated with mining and milling, and the interaction of dust and lungs. The Dust Center's research program explores these concerns with the objective of refining existing strategies and developing new respirable dust control techniques that are consistent with the fundamental dust-lung interaction processes that lead to mine worker disability. The work concentrates on: (1) control of dust generation; (2) dilution, dispersion and collection of dust in mine airways; (3) characterization of dust particles; (4) interaction of dust and lungs; and (5) the relationship of the mine environment, geology, and seam characteristics to dust generation and mobility. The fundamental aspects of this work are applicable to the control of respirable dust problems in both hard rock mines and coal mines, and to other dusts such as those generated by diesel equipment. Achieving the Dust Center's goals also involves the training of engineers and scientists, graduate students, and undergraduate students through their respective institutions, and technology transfer to industry. The distribution of personnel in the various universities are presented in Table 1. A directory of Dust Center principal investigators is presented in Appendix 1. A summary of degrees granted and mineral sector employment is presented in Table 2. The subjects of theses developed under the various research projects are presented separately in Volume 7. The center research is fully compatible and complementary with the existing and ongoing U.S. Bureau of Mines activities (see Volume 2). Additionally, the expertise and facilities of the NIOSH--Division of Respirable Disease studies are available as a result of the existing relationship between NIOSH and West Virginia University. Figure 1, Respirable Dust Center Projects and Activities, presents the various projects in the five major areas of investigation and the scope of characterized dust samples, the suite of tests, the sampling and dust generation methods, and the size, chemical and mineralogical analysis performed in the center. Table 3 presents a summary distribution of the 95 publications and presentations that have emanated from the center. In addition there are more than thirty presentations made at each annual Dust Center review meeting. The titles, authors and location of presentation for publications supported by the Dust Center are presented in separate publication volumes for 1984 (Volume 3), 1985 (Volume 4), 1986 (Volume 5) and 1987 (Volume 6).

The research performed to date in the for Dust Center has definitely established, in a variety of scientific, engineering, and medical experiments, that varying coal dust characteristics do result in varying responses. This significant finding is believed

Table 1: Respirable Dust Center Personnel

University	Principal Investigators	Graduate Students	Research Associates and Research Technicians	Visiting Professors	Total
Penn State University	15	18	8		41
West Virginia University	21	27	8	1	57
University of Minnesota	4	9			13
M.I.T.	3	4			7
Michigan Tech University	3	2			5
NIOSH	6				6
TOTAL	52	60	16	1	129

Table 2: Summary of Degrees Granted and Mineral Sector Employment

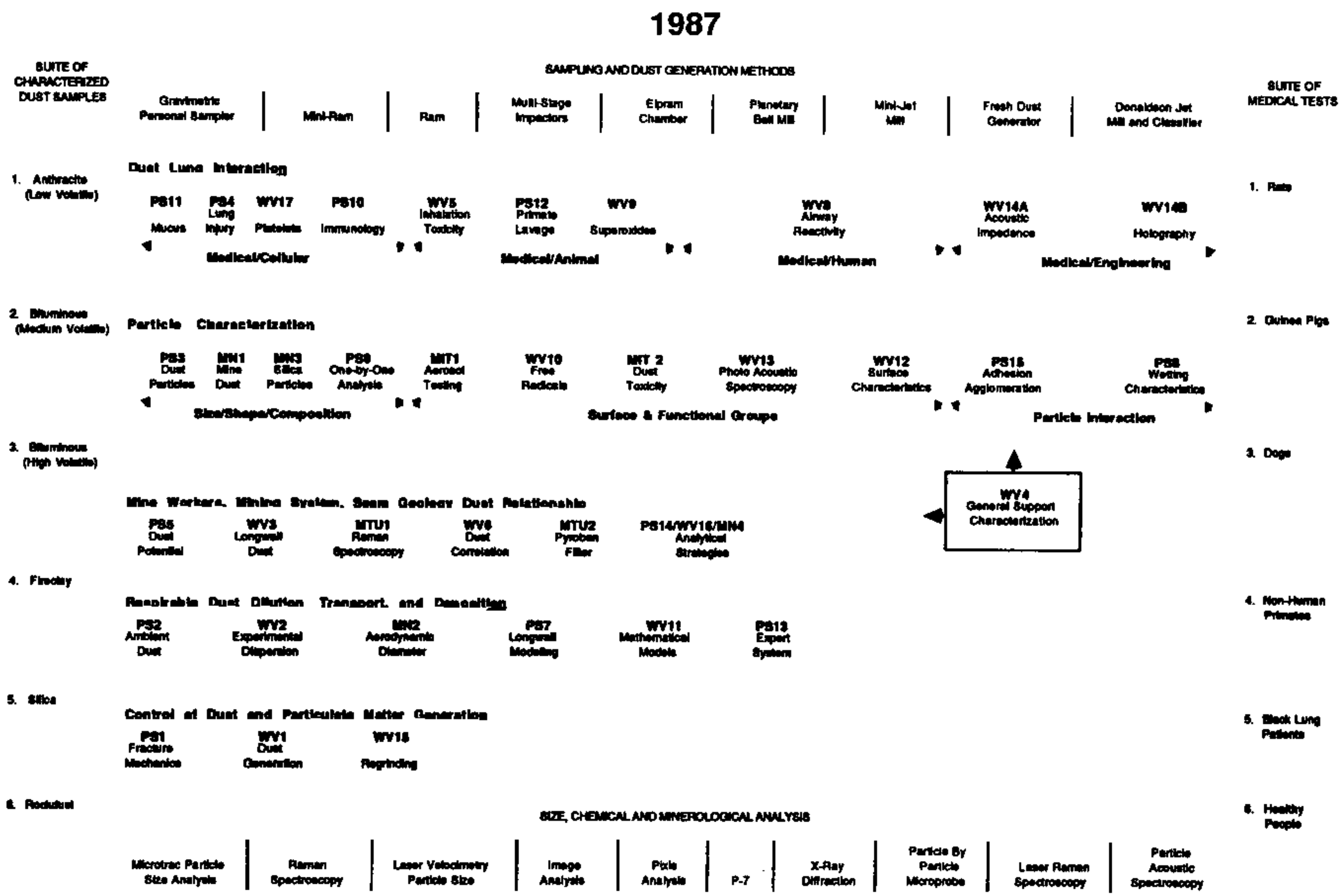
		Lead Institutions*	Affiliates+
1.	Doctorates	10	1
2.	Masters	21	2
3.	Graduates who got jobs in the mineral sector of the economy	14	1

* PSU/WVU
\+ MIT/U. MINN/MTU

Table 3: Summary of Dust Center Publications and Presentations

		Lead Institutions	Affiliates	Total
1.	In refereed professional journals	13	4	17
2.	In non-referred periodicals	58	6	64
3.	Presentations at technical meetings but not otherwise published	7	6	12
	TOTAL	78	17	95

Figure 1: The integration of scientific, engineering, and medical research findings into on-going projects.



to be related to the incidence and severity of Black Lung disease and has the potential to lead to their reduction. Through the comprehensive research program of the center, mechanisms and working conditions which influence the contraction of Black Lung disease have been identified. Further experiments are being performed by the Dust Center's expert team of nearly one hundred and thirty scientists, engineers, medical personnel and graduate students to investigate dust phenomena interrelationships; define more precisely the knowledge base concerning the characteristics of respirable dust; extend the findings to non-human primates initially and ultimately to human subjects. We are at the threshold of making accelerated progress in reducing the incidence and severity of Black Lung disease.

Three coal samples (anthracite, and med-volatile and high-volatile bituminous) having widely varying characteristics, plus silica, limestone rock dust, and fireclay dust have been selected to provide the unique common thread of a suite of characterized dust samples for investigation by center researchers. In their research to reduce the amount and severity of Black Lung, the center investigators are performing innovative investigations of fresh and stale dust particles, seam characterization, worker-mine system relationship and dust-lung interactions. For example, in the dust-lung research the suite of dust samples is being applied to a series of medical investigations involving cell injury, immunology, mucus generation and superoxide formation. Details of the characteristics of the coals and dusts used to prepare the standard dusts distributed to researchers in the center are presented in Appendix 2.

Characterized dust studies are also being performed in tests on live small animals and non-human primates. It is proposed to extend these studies to lavaged lung cells from healthy individuals, as well as Black Lung patients. Scientific characterization work will continue to build upon the findings documented to date on the varying responses to such factors as stale versus fresh dust, where the free radicals on the dust particle surface are different. There are accelerated efforts to integrate the achievements in multi-disciplinary dust characterization to develop and test analysis strategies for all respirable dust researchers.

Fundamental studies on dust generation, dust transport and deposition are following up on promising developments in quantifying generation, entrainment and capture for engineering design and control. Unusually rapid communication and utilization of project results together with effective cooperation between dust center institutions is significantly advancing knowledge of the fundamental characteristics of dust and dust-lung interaction. Investigations are also being extended into the area of dust particle generation in diesel haulage. Figure 2 depicts the application of standardized protocols in science, engineering, medical and technology adaptation for various respirable dust research programs areas.

Outstanding synergism and interaction between scientific, engineering, and medical researchers has characterized the Dust Center's work to-date. In a relatively short period of time the center has attracted and trained a significant number of graduate students in the area of respirable dust research. The location of the universities in the Dust Center in relationship to the USBM field facilities are presented in Figure 3.

The Dust Center's research has resulted in both an appreciation and the need for better methods of preparing and characterizing dusts for various research activities. This has resulted in the development of procedures for generating "standard" dust samples for various research projects in the center. Questions on "stale" vs. "fresh" dust has led to the development of sampling techniques where the dust is directly collected in a surfactant. Computer programs developed in the Center have been sent

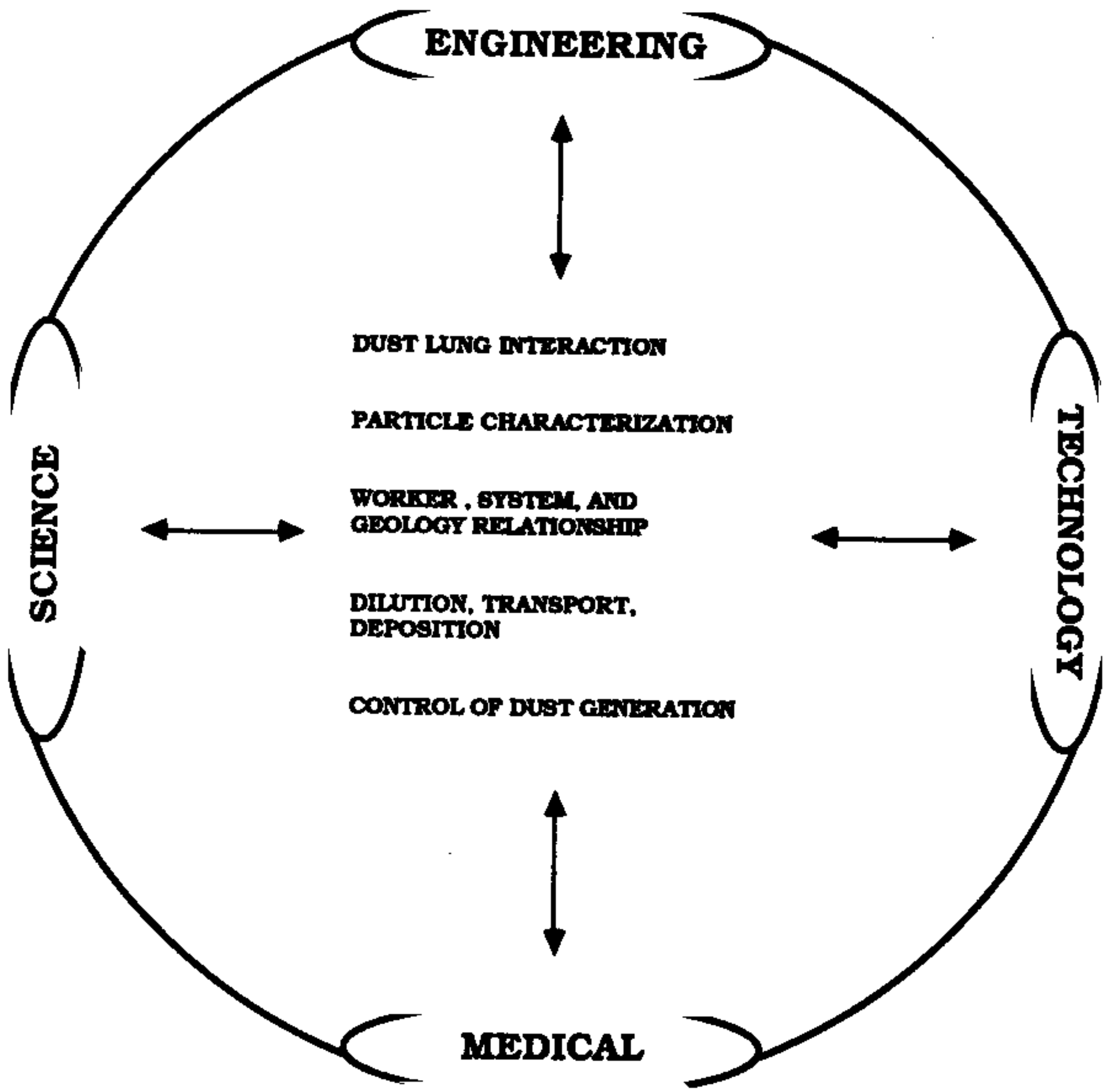
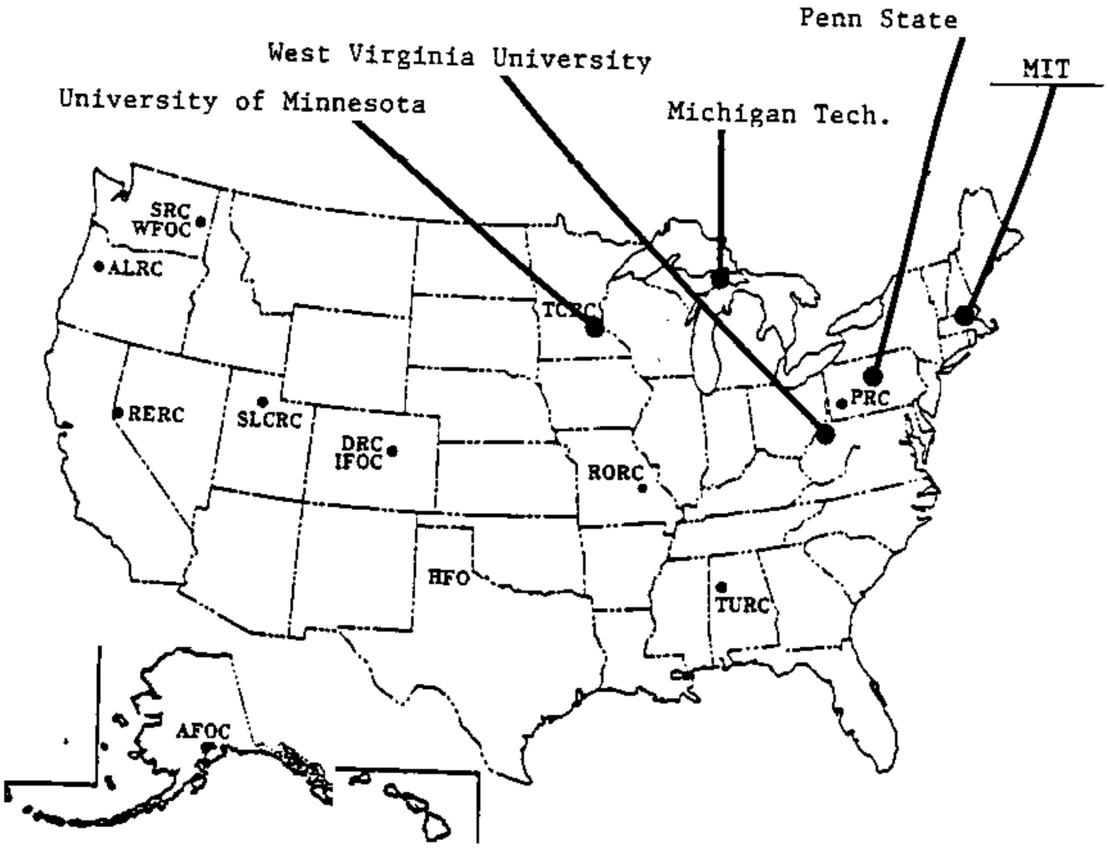


Figure 2: Standardized protocols for Respirable Dust Research in scientific, engineering, and medical areas.



Field Officials

Alaska Field Operations Center AFOC
201 E. 9th Avenue, Suite 101
Anchorage, AK 99501
(907) 261-2455
Chief: Donald P. Blasko

Albany Research Center ALRC
1450 Queen Avenue, S.W.
P.O. Box 70
Albany, OR 97321
(503) 967-5893
Research Director: George J. Dooley III

Denver Research Center DRC
Building 20, Denver Federal Center
Denver, CO 80225
(303) 236-0697
Research Director: Edward E. Hollop

Helium Field Operations HFO
100 South Fillmore Street
Amarillo, TX 79101
(806) 376-2602
General Manager: L. Dale Bippus

Reno Research Center RERC
605 Evans Avenue
Reno, NV 89520
(702) 784-5391
Research Director: Arthur F. Colombo

Rolla Research Center RORC
1300 Bishop Avenue
P.O. Box 280
Rolla, MO 65401
(314) 364-3169
Research Director: Danton L. Paulson

Salt Lake City Research Center SLCRC
719 Arapeen Drive
Salt Lake City, UT 84108
(801) 524-6100
Research Director: Stephen D. Hill

Spokane Research Center SRC
E. 315 Montgomery Avenue
Spokane, WA 99207
(509) 484-1610
Research Director: Douglas D. Bolstad

Tuscaloosa Research Center TURC
P.O. Box L
University, AL 35486
(205) 758-0491
Research Director: Martin H. Stanczyk

Intermountain Field Operations Center IFOC
Building 20, Denver Federal Center
Denver, CO 80225
(303) 236-0421
Chief: William T. Cochran

Pittsburgh Research Center PRC
Cochrans Mill Road
P.O. Box 18070
Pittsburgh, PA 15236
(412) 675-6601
Research Director: John N. Murphy

Twin Cities Research Center TCRC
5629 Minnehaha Avenue South
Minneapolis, MN 55417
(612) 725-4610
Research Director: Lewis V. Wade

Western Field Operations Center WFOC
E. 360 Third Avenue
Spokane, WA 99202
(509) 456-5350
Chief: Richard B. Grabowski

Figure 3: Respirable Dust Center university locations.

RESEARCH

CONTROL OF GENERATION

- Amount
- Fracture

DILUTION, TRANSPORT AND DEPOSITION

- Concentration
- Size Consist
- Modeling

MINE WORKER, MINING SYSTEM, SEAM GEOLOGY

- Seam Sections
- Silica
- Trace Elements
- System Configuration
- Worker Location

- Coal Data Bank
- Mine Samples

SUITE OF GENERATED RESPIRABLE DUSTS

- Anthracite
- Medium Volatile Bituminous
- High Volatile Bituminous
- Silica
- Fireclay
- Rock Dust

CHARACTERIZATION

- Size/Shape/Composition
- Surface/Functional Groups
- Particle Interaction

DUST LUNG INTERACTION

- Medical/Cellular
- Medical/Animal
- Medical/Human
- Medical/Engineering

TRAINING

Figure 4: Train engineers, scientists, medical personnel, graduate students and undergraduate students in the interdisciplinary aspects of respirable dust.

on request to research organizations for their use. Inputs to an equipment manufacturer have been provided on modifying the inlet to an aerosol sampler.

The various interdisciplinary aspects of the Dust Center's research are presented in Figure 4. Each proposed project is designed not only to attack an important problem but to train at least one graduate student. Time is projected to allow for a full development of student involvement and to ensure that students fulfill the graduate program requirements. The scope of work and the time duration of each project for the proposed center have been developed taking into account the needs of the graduate research program and training. WVU and PSU have accredited mining engineering curricula and have two of the largest enrollments of graduate students in mining engineering in the nation. The number of undergraduate students in WVU and PSU account for approximately 20 percent of the total undergraduate enrollment in the U.S. mining schools. Avenues for student involvement in respirable dust research are greatly strengthened and expanded by the center. The facilities and equipment that are available to the center in the participating universities are diverse, complementary and comprehensive.

Significant technology transfer has taken place in the Dust Center. The center organized two conferences--one national and one international--on respirable dust with presentations by investigators both in the center and other organizations. These conferences were co-sponsored by the U.S. Bureau of Mines, Mine Safety and Health Administration, National Institute for Occupational Safety and Health, and American Conference of Governmental Industrial Hygienists. These conferences provided a major forum for interchange and exchange of ideas on dust research and findings. The proceedings of these conferences are available from NTIS and ACGIH. A State-of-the-Art Biomedical Seminar was also held by the Dust Center.

A Reference Center Library for the Dust Center is maintained. The most important goal of the Reference Center Library is to identify what information is available at each location and provide the means of access for others to obtain this information. The second goal is to have both maximum input and retrieval capabilities to all the research personnel in the Reference Center. Another goal is to ensure that the service provided to the inquiring public is complete and cost-effective. The combined library facilities of the five large universities in the center represent one of the most extensive and comprehensive collection of information on respirable dust research available in the United States. The Dust Center encompasses two major medical schools and includes national and international experts from such diverse disciplines as geology, geomechanics, mining engineering, mineral processing, electrical engineering, industrial engineering, mechanical engineering, material science, physics and the various fields of medicine. The Reference Center network enhances the coordination, communication and unity efforts between the universities and other institutions.

In Section 2 of this report the philosophy and scope of the dusts, tests, samples and analyses utilized in the Dust Center are discussed as follows:

A. Suite of Characterized Dust Samples
B. Suite of Medical Tests
C. Sampling and Dust Generation Methods
D. Size, Chemical and Mineralogical Analyses

In Section 3 an introduction to each of the five major research areas in the Dust Center is presented followed by an abstract of the center research projects in that area.

In Section 4 each research project is discussed in detail.

2
Dusts, Tests, Samples and Analysis

2.1 Suite of Characterized Dust Samples

2.2 Suite of Medical Tests

2.3 Sampling and Dust Generation Methods

2.4 Size, Chemical and Mineralogical Analyses

DUSTS, TESTS, SAMPLES AND ANALYSES

As stated earlier the primary goal of the Generic Mineral Technology Center for Respirable Dust is to reduce the incidence and severity of respirable dust disease through advancing the fundamental understanding of all aspects of respirable dust associated with mining and milling and the interaction of dust and lungs. While initial work was directed to coal dust the charge to the dust center has been expanded to include diesel particulates and asbestosis, the latter of deep concern not just to workers in the mineral sector of the economy but also to the general populace.

A major facet of Dust Center research has been the analysis and documentation of comprehensive research protocol and procedures that are appropriate state-of-the-art in the various areas of respirable dust. In addition to definition of standardized research protocols and procedures which would be utilized by center personnel for uniformity and reproducability there is a considerable need for utilizing standardized respirable dusts in experiments with consistent, reproducible characteristics which simulate those of actual mine dust. This respirable dust needs to be available in large quantities for a wide variety of research uses that include animal and medical experiments. The dust must be free of the lubricating oils and grinding wheel contaminants that are frequently encountered in laboratory generated dusts.

The holistic approach to establishing standardized protocols and procedures applicable to the five major research areas of the center is presented in Figure 5.

In one hypothesis, range in coal volatility is considered to be a major causal factor in the incidence and severity of pneumoconiosis. Therefore a suite of characterized standard respirable dust samples have been prepared for researchers from coals representing the western (high volitile A bituminous), central (medium volatile bituminous) and eastern (anthracite) mining areas of Pennsylvania. Quartz, limestone (rockdust) and kaolin clay samples, representing important mineral constituents of coal dust have also been prepared.

A suite of medical investigations have been developed utilizing small and medium size animals as well as non-human primates in a variety of dust/lung interaction projects which will be discussed in the next section. A number of respirable dust sampling and dust generation methods have been investigated and selected techniques utilized for both in-mine and in-laboratory research investigations. These will also be discussed in more detail later. A wide range of respirable dust size, chemical and mineralogical analyses have been investigated, standardized and documented for use in various research investigations.

This interaction and documentation of various respirable dust sample procedures, animal and medical tests, sampling and dust generation methods, plus size, chemical and minerological analysis applied in the five major areas of research investigation have served to create a very favorable synergism and rapid technology transfer in the respirable dust center.

The Generic Mineral Technology Center for Respirable Dust

SUITE OF CHARACTERIZED DUST SAMPLES	SAMPLING AND DUST GENERATION METHODS	SUITE OF MEDICAL TESTS
1. Anthracite (Low Volatile)	Dust/Lung Interaction	1. Rats
2. Bituminous (Medium Volatile)	Particle Characterization	2. Guinea Pigs
3. Bituminous (High Volatile)	Mine Workers. Mining System Seam Geology Dust Relationship	3. Dogs
4. Fireclay	Respirable Dust Dilution. Transport and Deposition	4. Non-Human Primates
5. Silica	Control of Dust Generation	5. Black Lung Patients
6. Rockdust		6. Healthy People
	SIZE, CHEMICAL AND MINEROLOGICAL ANALYSIS	

STATEMENT OF GOAL

The primary goal of the Generic Mineral Technology Center for Respirable Dust is to reduce the incidence and severity of respirable dust disease through advancing the fundamental understanding of all aspects of respirable dust associated with mining and milling and the interaction of dust and lungs.

Figure 5: The holistic approach to standardized protocols and procedures.

2.1 SUITE OF CHARACTERIZED DUST SAMPLES

A major hypothesis of the respirable dust center is that dust characteristics **do make a difference** in the incidence and severity of respirable dust disease in people. Therefore, to establish a common denominator or foundation for research investigations there is a need for standardized respirable dusts with consistent, reproductible characteristics which simulate those of actual mine dust. The availability of such materials should be a significant factor in promoting coordinated research into dust characterization and mine monitoring, dust control, and the biomedical aspects of dust toxicology. To achieve this goal an opposed-jet, fluid- energy grinding system in closed circuit with a cross-flow, centrifugal air classifier for preparing bulk quantities of respirable-size dust has been investigated, and appropriate, standardized procedures have been established. By stage-crushing, screening, and fine-grinding with a Donaldson Acucut classifier/mini-grinder system, it is possible to produce bulk quantities of respirable dust at relatively high rates for supplying center researchers. Using minor modifications to the system, broader or narrower size distributions can be prepared to order within the desired respirable range. The system has been shown to reach steady-state with respect to product size distribution very rapidly. However, preferential grinding/ classification effects appear to lead to a slow build-up of mineral matter in the circulating load with a corresponding slow change in product composition with time. In those applications where the dust composition is required to match that of the feed coal, it has been necessary to allow considerable time for a true steady-state to be established.

Standard respirable dust samples have been prepared from coals representing the western (high volitile A bituminous), central (medium volatile bituminous) and low volatile eastern anthracite mining areas of Pennsylvania. Silica (quartz), limestone (rockdust) and kaolin clay samples, representing important mineral constituents of coal dust have also been prepared (Figure 6). Extensive characterization studies have been performed on the samples to evaluate chemical and mineralogical composition and the distributions of particle size and specific gravity. Detailed information on the original coals is available from the thirteen hundred sample Penn State Coal Data Base. The standard coal dust samples appear to simulate actual mine dust very well with respect to particle size and shape, but generally have somewhat lower ash content. Samples of these standard dusts have been made available to center researchers as well as research groups concerned with respirable dust in mines. The characteristics of the coals and dusts used to prepare the standard dusts supplied to researchers in the center are presented in Appendix 2. The coal designated MP3 was used largely for preliminary test work etc., and was selected on the basis of immediate availability in the laboratory. The PSOC coals were obtained from the Penn State Coal Data Base and were originally collected as channel samples. The kaolin clay was obtained from the Georgia Kaolin Company, Dry Branch, Georgia, and the quartz was obtained from the Ashibor Quarry, Staley, North Carolina.

The standard respirable dusts have been characterized in terms of overall particle size distribution, size-specific gravity distribution, ash content and chemical and mineralogical composition.

Particle size distribution were determined by centrifugal sedimentation using a Ladal pipet centrifuge (3) and by light scattering using a Leeds and Northrup Microtrac Small Particle Analyzer.

Specific gravity distributions were evaluated by sink-float analyses in heavy liquids, using centrifuges.

Ash analyses were performed by conventional high-temperature methods (4) and also by means of a Branson/IPC Low Temperature Asher.

Chemical (elemental) and mineralogical analyses were carried out by the Mineral Constitution Laboratory at Penn State. Elemental analyses were conducted by plasma arc emission spectrometry and the mineralogical composition was determined by pressed KBr pellet infrared spectroscopy and powder x-ray diffraction techniques.

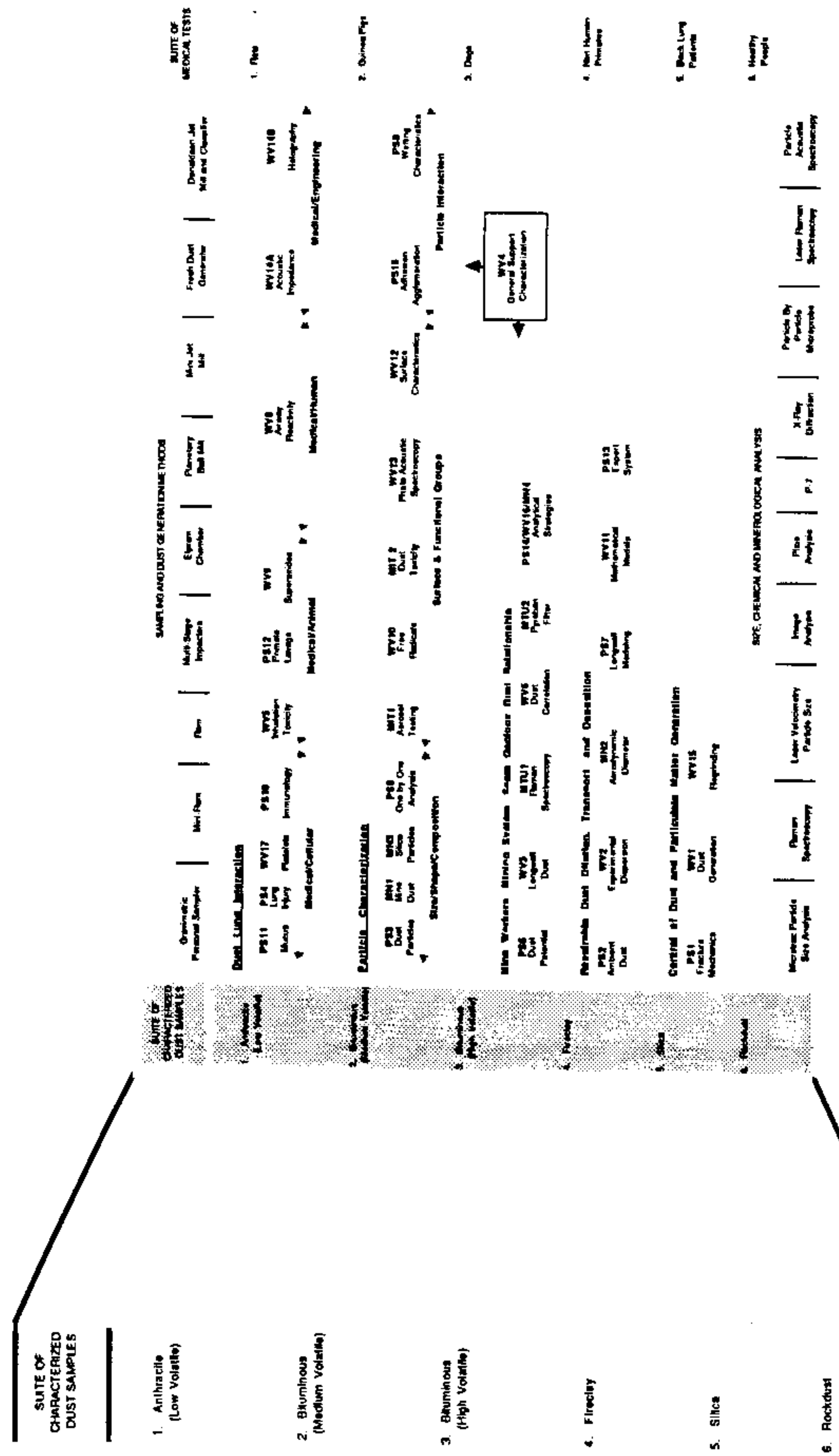


Figure 6: Characterized dust samples.

2.2 SUITE OF MEDICAL TESTS

The goal of reducing the incidence and severity of respirable dust disease in people involves a number of dust/lung interaction research projects across the spectrum of medical/cellular, medical/animal, medical/human and medical/ engineering. These projects utilize a variety of animals including rats, guinea pigs, hampsters, and dogs exposed in-vivo in inhalation chambers and also investigated in-vitro. The findings developed in small animal investigation will be extended to non-human primates by utilizing members of the monkey colony at the Penn State Hershey Medical Center. The non-human primate is considered an experimental "bridge" between the small laboratory animals that can be used only once and the repeatable procedures being developed for the monkey lungs (Figure 7). Methods of mapping the bronchial tree of the individual monkey has been developed making it possible to deposit respirable dust particles in a selected lung location in a reproducable fashion. Utilizing the equipment and procedures that have been standardized from bronchoscopy and alveolar lavage of pulmonary alveolar macrophages (PAM) the cells recovered from the monkey will be studies. As an ultimate extension to human beings cells from these monkey lung experiments can be compared to cells lavaged from healthy people as well as Black Lung victims.

Examples of other medical research projects utilizing animals include:

- Rats and guinea pig cells are used to investigate how coal mine dusts injure the lungs including the effects of dusts and dust-exposed pulmonary alveolar macrophages on the growth of lung fibroblasts.
- Rats and guinea pig cells are used in vitro to assess a specific family of mediator substances produced by the PAM from arachidonic acid when these cells are in contact with activating substances such as coal dust.
- Electro-optical techniques are used to quantitatively measure the amount of superoxide released from single rat lung cells which have been obtained from rats exposed in-vivo in inhalation chambers or in-vitro to respirable quartz or in-vitro to kaolin dust.
- Rats are exposed in vivo to coal dust to determine the distribution of mucus secreted by control and coal dust treated rat trachea.

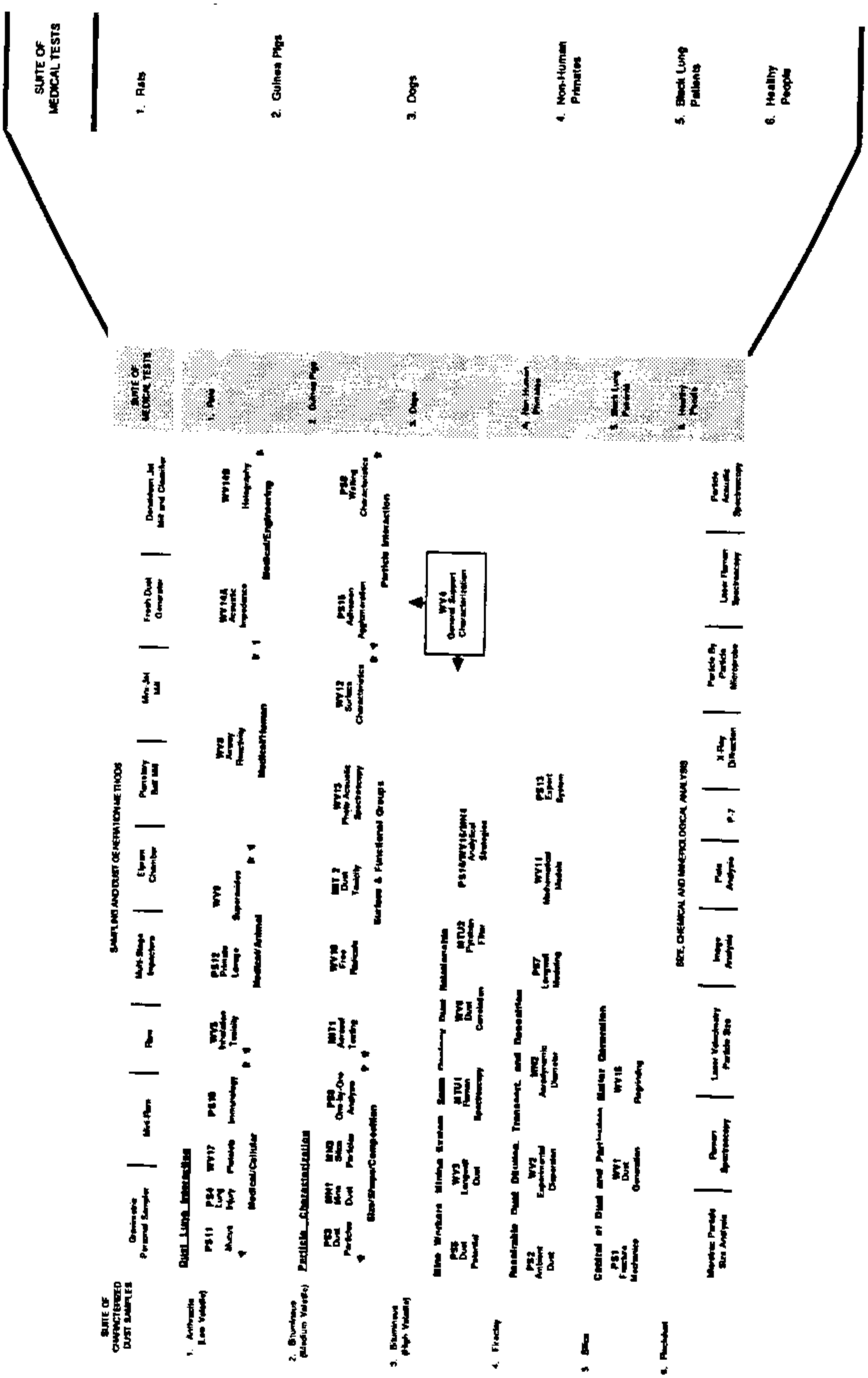


Figure 7: Medical tests.

2.3 SAMPLING AND DUST GENERATION METHODS

A number of dust sampling strategies and dust generation techniques have been investigated in the dust center (Figure 8). Initial field sampling strategies are generally tested in the laboratory to determine the variability which may be encountered in the mine. The lab is equipped with an aerosol test chamber by Elpram Systems, Inc. and auxiliary equipment consisting of a TSI Model 3400 fluidized bed aerosol generator, a TSI Model 3012 aerosol neutralizer, and a TSI model 3074 air supply system. A Mettler Model M-3 microbalance is used for dust mass determination.

The field equipment for underground use consists of sets of Sierra model 298 eight-stage impactors with accompanying Dupont Model P2500A constant-flow pumps. These sets of instruments are routinely tested in the mine ventilation laboratory to insure consistancy and accuracy of work.

Another instrument of note here is a GCA Corporation Mini-Ram real-time aerosol monitor (Model PDM-1). This equipment is supplemented with a compatible printer and a cyclone filter. The Mini-Ram is used for a variety of purposes including monitoring of laboratory runs and determination of proper sampling times for the field tests.

Typical Mine Sampling Plan Development

The example sampling plan has been designed for use in a continuous miner section. The basic plan will utilize about eight sampling stations with the stations located in the section as shown in Figure 1. The prime objectives of this sampling plan are to:

(1) determine the characteristics of the respirable coal dust at numerous points in the mine layout,

(2) relate the characteristics of the coal seam, the roof, and the floor to the characteristics observed in the respirable coal dust,

(3) identify the source of the dust by mass and characteristics in the section,

(4) provide a mass balance for the dust in the working section, and

(5) establish a data set to be used in the identification of dust behavior underground that can be used in further laboratory work.

Within the layout all stations will be equipped with Sierra model 298 eight-stage impactors powered by Dupont Model P2500A pumps. All of the stations except stations 2, 3, and 6 will be stationary.

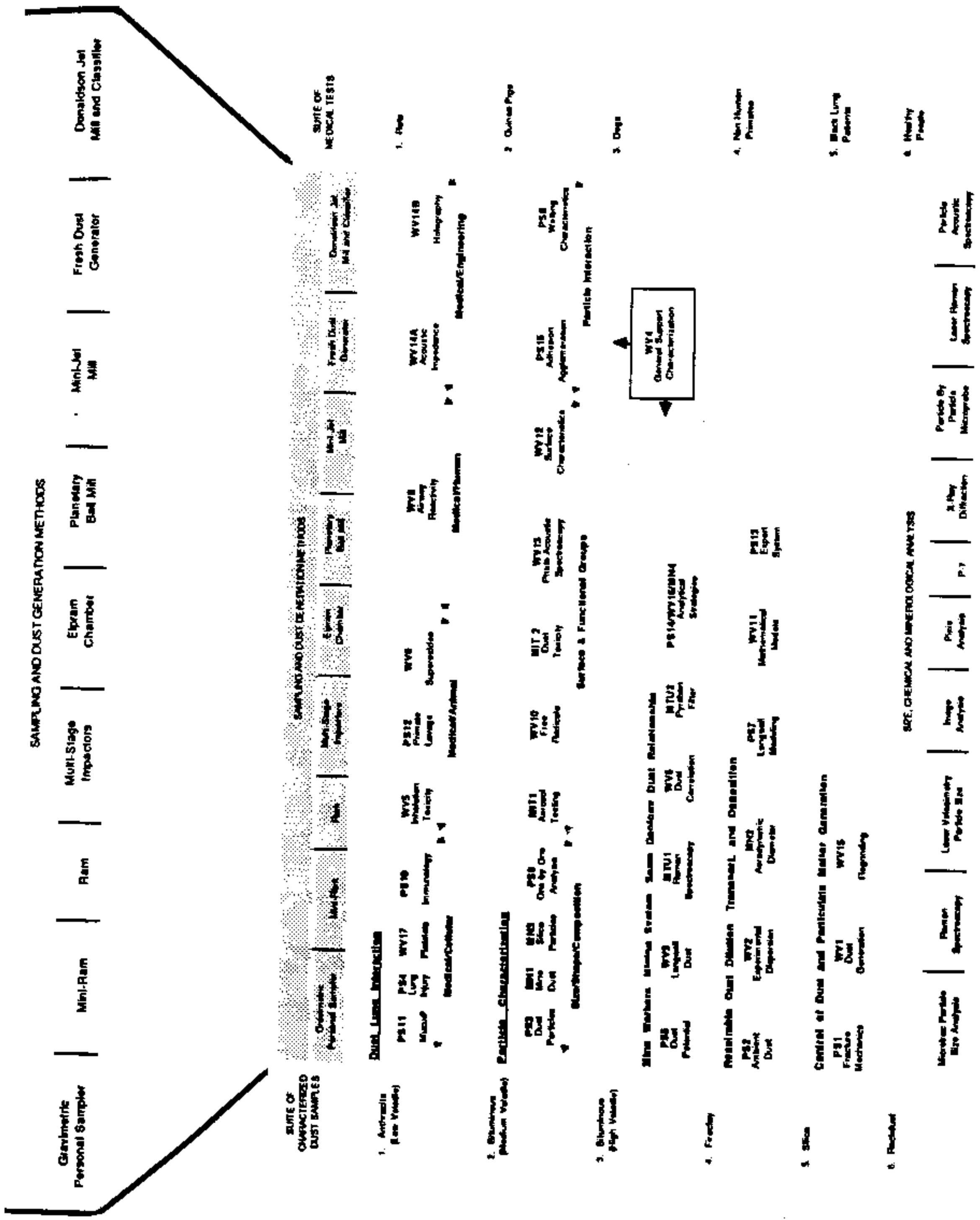


Figure 8: Sampling and dust generation methods.

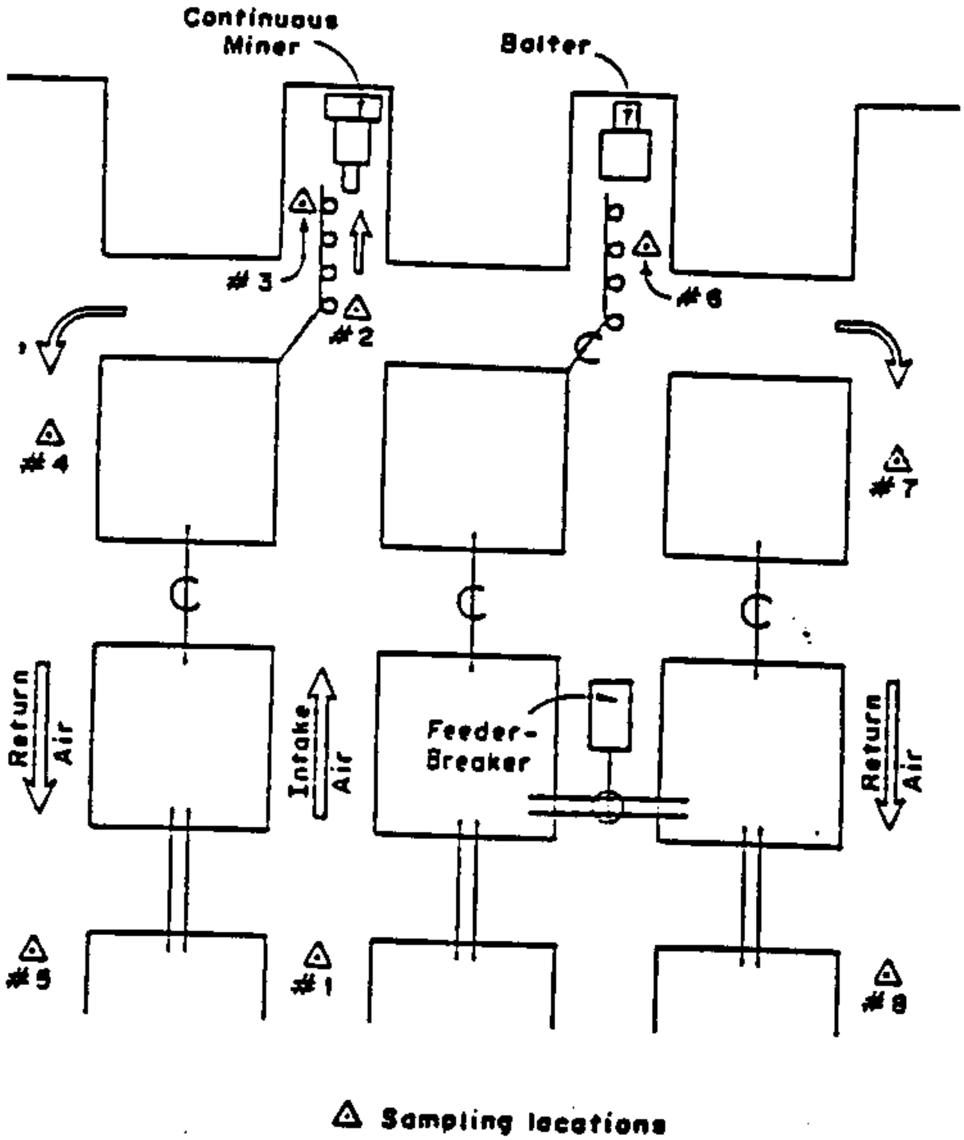


Figure 9: Generalized layout of sampling locations.

2.4 SIZE, CHEMICAL AND MINEROLOGICAL ANALYSES

Investigations of particle size, chemical and minerological analysis plus in-mine characterization of respirable dust include a number of basic fundamental studies, evaluations and improvements of instrumentation used for particle size measurement (Figure 9). Examples of instrumentation include the Micro-Orifice Uniform Deposit Impactor (MOUDI), the TSI Aerodynamic Particle Sizer (APS) and a new personal diesel particle sampler. The MOUDI work has developed an optimized design for the impactor nozzles and a thorough understanding of the operating principles of the impactor. Field work with the MOUDI has proved it to be unique for measuring the size distribution of diesel exhaust and coal dust particle mixtures in underground mines. From the size distribution of the particle mixture, the existence of a bimodal size distribution, that can be separated on the basis of particle size, has been discovered. This finding is currently leading to the development of a personal diesel sampler capable of measuring the respirable mass concentration of diesel particulate matter and respirable mass concentration of coal dust in underground mines. In addition, an important breakthrough for the dispersion of dust samples has lead to the development of a commercial instrument, the TSI Small Scale Powder Disperser, and a technique for redispersion of dust particles from filters. With this dust dispersion system, a technique has been developed to collect and redisperse dust particles from filter media for subsequent particle size analysis. The importance of this technique is the ability to collect airborne particle samples at the mine face using a simple filter sampler and then to analyze the particles using instrumentation that can not be taken underground because of non-permissibility and/or the complexity of the measurement technique. The particle redispersion technique is of general use to the aerosol field and has been accepted by the aerosol technology community as a useful tool.

Various other laboratory size analysis techniques including centrifugal sedimentation, Coulter Counter, and laser diffraction/scattering (Microtrac SPA) have been evaluated with regard to their applicability for respirable dust characterization. Comparative studies using the standard dusts indicate that the Microtrac system is especially suitable for respirable dusts and that test results can be directly correlated with **in situ** measurements. Furthermore, there is evidence that comparisons of **in situ** and laboratory measurements can provide information on the existence of dust agglomeration in the mine environment.

Procedures for evaluating the chemical/mineralogical composition of respirable dust are also being investigated. Included in these studies are a variety of techniques which can provide compositional information at three distinct levels: macroscopic (whole sample), size-by-size, and particle-by-particle. In general, these provide increasingly detailed information but at the cost of increasing experimental complexity and with some loss of overall precision. Techniques for macroscopic characterization include bulk chemical and mineralogical analyses and the P7 method for quartz determination in very small samples. Size-by-size analyses require fractionation of the sample on the basis of size or composition followed by analysis of the individual fractions. Fractionation methods studied include cascade impactors and specific gravity separations using heavy liquids. Procedures for determining the composition of individual size fractions are being investigated. These include the application of Proton-Induced X-ray Emission Spectroscopy (PIXE) to the individual stages of standard cascade impactors and a modification of the P-7 technique applied to stages of the MOUDI instrument. Alternatively, size distribution for individual, composition-based fractions can be obtained by standard techniques such as Microtrac SPA.

The use of a computer controlled scanning electron microscope (SEM) in conjunction with an energy dispersive x-ray detector for the simultaneous determination of size, shape and composition on a particle-by-particle basis is also being investigated. Size and shape analyses are quite reliable within the resolution limits of the instrument. Compositions determined by SEM are in good agreement with bulk spectrochemical analyses for particles larger than about 10 μm but become increasingly unreliable for smaller particles due to a significant reduction in the volume of material excited by the electron beam. Emphasis in these studies is placed on the need for precise, quantitative analysis of each particle in order to provide a basis for determination of the carbon content by difference.

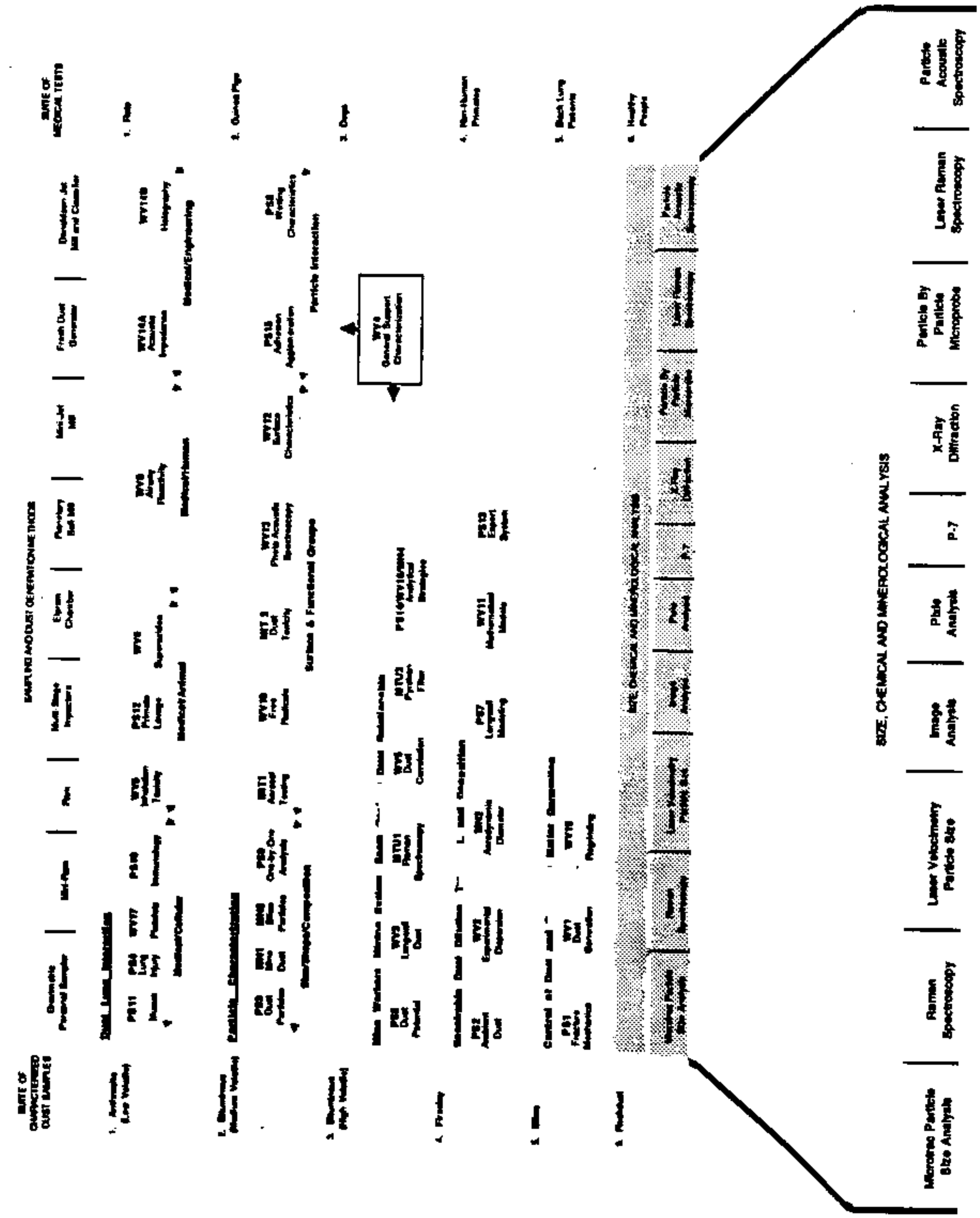


Figure 10: Size, chemical, and mineralogical analyses

3
Dust Center Projects: Introduction and Abstracts

3.1 Interaction of Dust and Lung

3.2 Dust Particle Characterization

3.3 Mine Workers, Mining System and Seam Geology Dust Relationships

3.4 Dust Dilution, Transport and Deposition

3.5 Control of Dust Generation

CONTENTS

3 Dust Center Project Abstracts page 29

3.1 Interaction of Dust and Lung Projects 35

Introduction 37

Mechanism of Lung Injury
(PS4/USBM 4204) *Bartlett* 40

Alveolar Macrophage and Polymorphonuclear Leukocytes
(PS10/USBM 4209) *Demers* 41

Biochemical Alterations in Respiratory Tract Mucus
(PS11/USBM 4210) *Bhavanandan* 42

Interaction of Dust and Nonhuman Primate Lungs
(PS12/USBM 4211) *White/Drazdowicz/Bowman* 43

Pulmonary Inhalation Toxicity of Respirable Dust
(WV5/USBM 5405) *Lantz/Stanley/Dalal* 43

Airway Reactivity in Coal Miners
(WV8/USBM 5407) *Abrons/Petsonk* 44

Effects of Dust on Release of Superoxide
(WV9/USBM 5408) *Cilento/Lantz* 45

Tracheal Acoustic Impedance of Air Passage
(WV14A/USBM 5413) *Sneckenberger* 46

Topographical Laser Holography for Detection of Black Lung
(WV14B/USBM 5413) *Stanley* 47

The Role of Platelet Activating Factor in Pneumoconioses
(WV17/USBM 5423) *VanDyke/Castronova* 48

3.2 Particle Characterization Projects 49

Introduction 51

Characterization of Dust Particles
(PS3/USBM 4203) *Hogg/Luckie* 53

Wetting Characteristics in Relation to Dust Abatement
(PS8/USBM 4207) *Chander/Aplan* 54

Analysis of Coal Dust Particles Using an SEM
(PS9/USBM 4208) *Hogg/Austin* 55

Adhesion, Aglomeration and Deposition of Dust
(PS15/USBM 4223) *Chander/Hogg* 55

Support for Dust Characterization (WV4/USBM 5404) *Bajura* page 56

Magnetic Resonance of Paramagnetic Ions and Free Radicals (WV10/USBM 5409) *Dalal/Vallyathan* 57

Shape and Surface Characterization of Dust Particles (WV12/USBM 5411) *Meloy/Vallyathan/Wallace* 58

Dust Testing in Mines and Metallurgical Operations (MIT1/USBM 4202) *Ring* 59

Effect of Physical Properties of Dusts on Toxicity (MIT2/USBM 2521) *Elliott/Bolsaitis* 59

Coal Mine Dust Characterization (MN1/USBM 2701) *Marple/Rubow* 60

Determination of Silica Particle Concentration (MN3/USBM 2703) *Marple/Rubow* 61

Determination of Active Silica Using PA Spectroscopy (WV13/USBM 5412) *Seehra/Wallace* 61

3.3 **Mine Workers, Mining System, Seam Geology Dust Relationship Projects** 63

Introduction 65

Standard Procedures for Characterization of Dust Potential (PS5/USBM 4205) *Mutmansky/Bise/Frantz* 67

Improved Dust Sampling/Analytical Strategies for Mine Use (PS14/USBM 4222/5422/2722) *Mutmansky* 68

Longwall Dust (WV3/USBM) *Peng* 69

Correlations of Respirable Dust Characteristics (WV6/USBM 5406) *Stobbe/Grayson* 70

Analysis of Diesel Particulate by Raman Spectroscopy (MTU1/USBM 2601) *Johnson/Cornilsen* 71

Monitoring and Control of Diesel Particulate in a Mine (MTU2/USBM 2621) *Johnson/Cornilsen* 71

3.4 **Dust Dilution, Transport and Deposition Projects** 73

Introduction 75

Prediction of Ambient Dust Concentration in Mines (PS2/USBM 4202) *Ramani* 77

Computer Modeling of Longwall Face Ventilation (PS7/USBM 4206) *Ramani* 78

An Expert System for Planning Mine Ventilation Systems (PS13/USBM 4221) *Ramani* 79

Development of Mine Dust Distribution Models (WV11/USBM 5410) *Wang/Chiang* page 80

Aerodynamic Diameter Analysis of Coal Dust (MN2/USBM 2702) *Marple/Rubow* 80

3.5 **Control of Dust Generation Projects** 83

Introduction 85

Fracture Mechanics Study of Crack Propagation in Coal (PS1/USBM 4201) *Bieniawski* 87

Mechanisms of Dust Generation and Entrainment (WV1/USBM 5401) *Khair* 88

Correlation of Dust Due to Regrinding at the Face (WV15/USBM 5421) *Khair* 89

EXPLANATION OF ABSTRACT FORMAT

The information contained in the project abstracts is described in the following example:

PS13/USBM 4221	**Project Number**
A Knowledge Based Expert System for Planning Mine Ventilation Systems	**Title**
Ramani, R. V.; Prasad, K. V. K.; Swaminathan, M.	**Principle Investigator(s)**, Graduate Students and Research Staff

Project Status Summary

The objective of the research in this project is to develop a knowledge based expert system for aiding the planning of mine ventilation systems. This system focuses on mine ventilation system design from a coal mine dust control standpoint. It is recognized that mine ventilation system design is an engineering problem involving not only rote numerical calculations to solve the pressure quantity problem but also substantial judgement and expertise to analyze a problem situation and interpret the results of an algorithmic program. The thrust of this project is to i) extract this knowledge from public domain sources and recognized experts in industry, government and academia, ii) represent this knowledge in the form of IF...THEN rules in an expert system (ES) and iii) interface the developed expert system with a mine ventilation network analysis program vis. PSUMVS (Pensylvania State University Mine Ventilation Simulator). By providing the numerical computing and qualitative reasoning aspects of mine ventilation system design in a single integrated system, better quality decision support will be made available to apprentice users.

Project Summary

3.1
Interaction of Dust and Lungs

INTERACTION OF DUST AND LUNGS

Respirable dust disease is a crippling affliction of coal miners and persons in related occupations. Respirable dust injures the lung tissue, resulting in severe pulmonary scarring (fibrosis) and compromise of pulmonary function. Too little is yet known about deposition, cellular or molecular events that lead to pulmonary fibrosis to permit biological or other intervention in the disease process. The characterization of dust-lung interaction is critical for the development of effective engineering control measures in mines and milling operations. Research in this area concentrates on developing an understanding of the basic processes that occur with the deposition of dust in the lungs and the interactions that occur between the dust and lungs. The objective of research in this area is to characterize dust-lung interrelationships necessary to relate dust control strategies in environments likely to create an occupational lung problem in the medical/cellular, medical/animal, medical/human and medical/engineering areas (Figure 10).

The dust/lung research of the Dust Center has several long-range objectives:

- Better methods for the early diagnosis of coal workers' pneumoconiosis (CWP);
- Methods to modify the disease process;
- Tests to identify toxic products; and
- Tests to identify individuals with heightened susceptibility to pneumoconiosis

The major immediate objective is to define the mechanism of dust-induced lung disease. This means determining:

- Dust characteristics that are important in causing lung diseases;
- Important interactions between dust and lungs; and
- Earliest detectable stages of the disease.

Mechanisms

Several of the Dust Center projects involve exposing lung cells in culture (in vitro) or animal lungs (in vivo) to samples of the suite of characterized mineral dusts described earlier. The responses of the lung cells or tissues to the dusts are being studied in order to better understand how inhaled dusts cause lung disease.

One project is studying the effect of dust exposure on the production of mucus by rat trachael explants in vitro as mucus is a major factor in clearing inorganic dusts from the lung. Results thus far have shown that exposure of tracheal cultures to coal dust caused a decrease in mucin production in comparison to parallel cultures without dust. To examine the effect of in vivo coal dust exposure, rates were maintained in an inhalation chamber for two weeks, and control rats were in an identical, but dust-free chamber. Tracheal explants from those animals were studied in culture. The preliminary results indicate that the effect of in vivo dust exposure is similar to that noted in the in vitro experiments.

Pulmonary alveolar macrophages (PAMs) are a key component of the lung's response to inhaled particulates, and they play several important roles in pulmonary inflammatory and repair processes. PAMs are the cells that actually ingest dust particles. Other studies have shown that they play a critical role in the development of silicosis and abestosis. In one project, the Dust Center is studying the effect of dust exposure on the release of oxygen free radicals (superoxides) by PAMs. Intracellular production of superoxide occurs when PAMs phagocytize particles, such as inhaled bacteria, and is an essential mechanism by which PAMs kill ingested bacteria. A number of complex physiological events occur during this process which are not clearly understood. It is thought PAMs containing indigestible materials, such as material dusts, overproduce superoxides, or inappropriately release it into the surrounding tissues. If true, this would cause toxicity to surrounding lung cells by peroxidation of the lipids in the cell membranes. In vitro exposure of PAMs to low or high doses of kaolin or quartz has shown that quartz is biologically active while kaolin is inert. Preliminary studies indicate that coating the quartz particles with a surfactant reduces toxicity.

PAMs that are responding to exogenous materials also release a variety of signal chemicals ("mediators") that affect the behavior of surrounding lung cells. One project is studying the effects of dust exposure on the production by PAMs of one class of mediators, the arachadonic acid metabolites. A consistent pattern of response has been seen following in vitro exposure of PAMs to coal dusts. The pattern is generally "proinflammatory", meaning that the other components of the lung will respond as if there has been tissue injury or death. Preliminary studies of cells from rats exposed in vivo to dust aerosols have shown that the basic response pattern is similar to that after in vitro exposure. Two other classes of PAM mediators are the fibroblast growth factors and interleukin-1. Among other actions, these two mediators stimulate the accumulation of fibroblasts, the cells that produce collagen, the scar protein. Results during the first few years of the program, using guinea pig PAMs in vitro, indicated that there are no detectable release of either FGF or IL-1 during 24 hours of dust exposure. Those studies have not yet been replicated using freshly ground dusts. Facilities are being established to provide both "fresh" and "stale" dusts to each of the investigators studying dust-lung interactions because of the potential higher reactivity of fresh dust.

In yet another project, a nonhuman primate (monkey) animal model is being developed for studies of dust-lung interactions. These animals are considered a useful experimental "bridge" between the small laboratory rodent models [which can be used only once, and which may differ from humans in unknown ways] and humans [in which intentional exposures and controlled experiments are difficult or impossible]. Equipment and procedures have been standardized for bronchoscopy and alveolar lavage of PAMs from monkey lungs. Yields range from 12 to 35 million cells total recovery. Methods for mapping the bronchial tree of individual animals have been developed, making it possible to reproducibly position the bronchoscope into the same lung lobe in separate sessions several weeks apart. The bronchoscope can also be used to instill particulate material into selected lung segments. Cells recovered from the monkeys are being studied in vitro for their production of arachadonic acid metabolities, FGF and IL-1, and the mucin in the lavage fluid is being characterized. In the future, with further standardization of procedures and biological responses, these primates may be available, on a limited basis, as a central resource for other dust center investigations.

Early Detection

Live animals are used to detect the earliest effects of dust exposure including cell injury, scarring, and regeneration. Methacholine is being investigated as a predictor of future changes in lung functions. Work is ongoing to study a group of active coal miners and compare findings with a group of non-mining control people. Respiratory systems are being investigated based on revised standards developed by the British Medical Research Council. Results are being analyzed to determine if increased airway reactivity by Methacholine Challenge is associated with symptoms of chronic bronchitis or decreased ventilatory capacity. To date, a total of 315 volunteers have been enrolled in the project.

Acoustic impedance may prove useful as a non-invasive detection device, as may laser holography, used in conjunction with spirometry to assess lung functions. The objective of this research is to examine new methods for detecting small alterations in the mechanical properties of the lungs. This may result in the potential for detection CWP in its early stages.

Individual Susceptibility

It is recognized that general susceptibility to disease varies from individual to individual. Dust Center researchers hope to develop a test to identify persons at high risk to dust-induced lung diseases. Such a test would permit taking personalized precaution.

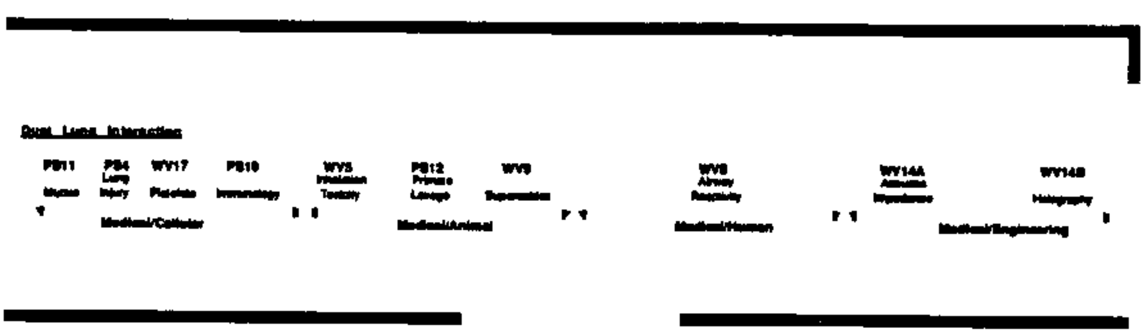


Figure 11: Individual Dust Center projects in the Dust Lung Interaction Area.

INTERACTION OF DUST AND LUNG

PS4/USBM 4204

Characterization of the Mechanism of Lung Injury by Coal Mine Safety

Bartlett, G. L.

The major objective of this project is to develop a better understanding of the processes that occur in the lung between the time that dust is inhaled into the pulmonary alveoli and the development of pulmonary disability due to coal workers' pneumoconiosis. Additional knowledge in this area could help to reduce the incidence and severity of coal workers' pneumoconiosis by helping in the design of more sensitive means for early diagnosis of the disease, for identification of high-risk persons, and for detection of specially hazardous dusts. In addition, such information could aid in the development of drugs or other treatments to halt or delay disease progression once started.

The focus of the project is on the responses of pulmonary alveolar macrophages to dust-exposure and how those responses may affect the behavior of lung fibroblasts. Experiments were performed to test the hypothesis that dust exposed alveolar macrophages produce interleukin-1 or fibroblast growth factor(s) that can contribute to the process of pulmonary fibrosis. Standardized, characterized coal dusts, as well as coal mine dust and noncoal mineral dusts, were used to determine if dusts with different chemical, physical or mineralogical characteristics would have different effects on the macrophages. In a large series of experiments, the predominant result was that neither IL-1 nor FGF activity was present in the culture media collected from dust-exposed macrophages. Several factors that have come to light during the course of these experiments tend to limit the scope of the negative results. All of the tests were performed using dusts that had been stored for weeks to months since characterization and distribution, so none of the tests involved freshly produced dusts that would be expected to contain free-radical constituents. Dusts were routinely heat-sterilized prior to use to prevent bacterial contamination of cell cultures; there is reason to believe that the heating may alter components important in cellular interactions of dusts. Likewise, the standardized dusts have recently been found to possess a minor surface coating of oil, which may have affected cellular responses to the particles.

Work is underway to test dust samples that are more nearly representative of dusts that would be encountered in the mine atmosphere. Equipment has been purchased to produce "fresh", free-radical containing dusts in the laboratory for these bioassays. We have begun to evaluate preparation of dusts without the necessity for heat sterilization. Experiments are planned to remove surface oil from dust samples by washing in dichloromethane prior to testing, and we expect to receive oil-free, standardized dust samples from the GTCRD in the near future. Each of these characteristics must be evaluated before drawing final conclusions about the response of PAMs to these dust preparations.

PS10/USBM 4209
Alveolar Macrophage and Polymorphonuclear Leukocytes in the Dust/Lung Interaction
Demers, L. M.

The objective of this project is to identify the cellular mechanism through which coal mine dust in the pulmonary environment elicits a local inflammatory response which, if present chronically, can produce lung injury and debilitating disease. The focus of the project is the study of the potent biologically active metabolites of arachidonic acid (AA) and the characterization of their production in the pulmonary alveolar macrophage (AM) in the presence of the dust-related factor which could influence that production. These studies are designed to determine 1) if AM production of AA metabolites is altered by exposure to coal dust, 2) to determine if different types of dust (eg. high rank vs. low rank) produce different responses in relation to AA metabolism in the AM and 3) to examine if the response of the AM to coal dust produces changes in AA metabolism which are consistent with physiological changes seen in the lung of the exposed miner. In addition, the possibility that the AM response to coal dust can be modulated through the administration of general or selective regulators of the AA metabolic pathway is being examined. These studies are designed to provide basic insights which, when coupled to future proposed studies, will be valuable in the design of therapeutic approaches to coal miner's pneumoconiosis. Finally, the AM response, is being studied in several species in order to determine which animal best serves as the most suitable model for dust-elicited alterations in AA metabolism in man. These studies will provide not only basic scientific information related to species differences in AM responses but, more importantly, will suggest the most cost-effective and scientifically valid model for the study of pneumoconiosis in man.

In the studies conducted to-date, we have used several experimental approaches to achieve the objectives of the project. Experiments have been conducted to ensure the specificity of AM response to coal dust when exposed to coal dust *in vitro*. In this regard, culture media composition has been modified to eliminate extraneous factors which can influence the metabolism of AA in the AM. Further studies have demonstrated that AA metabolism is altered in the dust-exposed rat AM in a manner which is distinct from that seen when AM are exposed to other known mediators of AA metabolism. In addition, exposure of AM from guinea pigs and monkeys to coal dust elicits a different pattern of altered AA metabolism than observed in AM from the rat. Likewise different types of coal dust elicit quantitatively different responses to coal dust. Thus, when rat AM were exposed to anthacite coal dust, the pattern of AA metabolism was altered to a greater extent than when exposed to bituminous coal. Finally, we have compared changes in AA metabolism by AM exposed to coal dust *in vitro* with that of AM from rats exposed *in vivo* to respirable dust in a controlled dust chamber at West Virginia University. The results of the studies of this project suggest that alteration of AA metabolism in the AM is a key factor in the dust/lung interaction and has provided the scientific basis for the suggestion that the AM response to coal dust may be modulated by pharmacologic agents which affect AA metabolism. Studies are now in progress to determine the validity of such a suggestion and the result of such intervention on AM function. In addition, studies composing AM response to coal dust in animal models with that in the human are being initiated. Together these studies should provide additional valuable information on the cause and treatment of coal worker's pneumoconiosis.

PS11/USBM 4210

Biochemical Alterations in Mammalian Respiratory Tract Mucus Caused by Coal Mine Dust

Bhavanandan, V. P.

Objective of this project is to understand the influence of the coal dust exposure on the quantity and/or quality of respiratory secretions. The alterations in the mucus production are determined under both *in vitro* and *in vivo* conditions. In *in vitro* studies in addition to the tracheal explants, the effect of short term dust exposure on rat tracheal epithelial cells are also examined. Once the nature of the alteration is understood, the underlying mechanism for the altered mucus production will be elucidated. The long term objective is to understand the role played by the alterations in respiratory mucin secretion in predisposing the coal miner to chronic bronchitis and pneumoconiosis.

Studies carried out, so far, have demonstrated that exposure of *in vitro* tracheal explant outgrowth cultures to coal dust caused a decrease in mucin production. The experimental design included parallel cultures under identical conditions but without dust. During a two week culture period, mucin production in the control explants decreased by 10 to 30%, which is most likely due to cell death. In the explants treated with coal dust, the decrease in mucin production is by 40 to 50%. At the present it is not clear whether this additional decrease is due to increased cell death as a result of coal dust exposure or due to other specific effects such as inhibition of glycosyltransferases by the soluble or insoluble components in coal dust. The observation that synthesis of macromolecules containing [^{3}H]glucosamine (mucins and glycoproteins) was decreased more than the synthesis of macromolecules containing [^{14}C]leucine (proteins) suggests specific effects of coal dust on mucin metabolism.

In preliminary experiments explant cultures of trachea from rats exposed to coal dust in inhalation chambers also showed a decrease in mucin synthesis. It is now essential to extend the studies to tracheal epithelial cells in culture to further confirm our findings. The explant outgrowth cultures used in our studies so far have advantages and disadvantages. An advantage is that it attempts to mimic the *in vivo* conditions of the trachea and is likely to maintain control on the differentiation of the outgrowth cells. A disadvantage is that the explant contain a number of different cell types (fibroblasts, goblet cells, macrophages, platelets, connective tissue, *etc.*) and therefore the interpretation of noted responses is complicated. A culture system containing airway epithelial goblet cells would allow one to examine the effect of coal dust on mucin secretion by these cells without the complexity introduced by the presence of mixed cell types.

PSU12/USBM 4211

Interaction of Coal Mine Dusts and Nonhuman Primate Lungs

White, W. J.; Drozdowicz, C. K.; Bowman, T.; Childe, S..

The main objective of this study is to determine the effects of coal mine dusts on specific cellular constituents found within the lung and how these alterations relate to the development of pulmonary fibrosis. Major emphasis has been placed on defining the role of the alveolar macrophage in mediating pulmonary fibrosis initiated by coal mine dust. The nonhuman primate has been selected as the animal model because of its size advantage over laboratory rodents and its potential similarity to man in its response to coal mine dusts.

The major accomplishment of this project has been the development of a bronchoalveolar lavage technique using nonhuman primates. A flexible fiberoptic bronchoscope enables the collection of alveolar macrophages and other pulmonary components in a repeatable and non-destructive manner. Macrophage yields range from 12 to 35 million cells total recovery. Positioning of the bronchoscope into individual lung lobes can be reproduced in that the same lung lobe could be located and lavaged at separate sessions several weeks apart. In addition, the bronchoscope can instill particulate material into defined areas of the lung which can then be monitored by radiographic techniques. Recovered cells are incubated with and without coal dust and the supernates are examined for interleukin-1 activity and stimulation of fibroblast proliferation. Continued research will include further characterization of pulmonary macrophages using in vitro techniques.

Preliminary work on devising techniques to expose nonhuman primates to aerosolized coal mine dust has begun. This portion of the project will be a cooperative effort with investigators at The Milton S. Hershey Medical Center and The West Virginia University. The potential applications of this model include examining cells exposed to coal mine dust in a similar manner as exposure occurs in man. Results from this research will lead to a better understanding of the mechanisms involved in the development of pulmonary fibrosis with the potential of advancements in its diagnosis and treatment.

WV5/USBM 5405

Pulumonary Inhalation Toxicity of Respirable Coal Mine Dust: A Morphometric Study

Lantz, C.;Stanley, C.; Dalal, N.; Dey, R.; Abrons, H.; Pavlovic, A.

The overall objective of this project has been to quantitatively assess the effects of inhalation of respirable coal mine dusts on pulmonary structure. The overall working hypothesis has been the following. A relationship exists between the physical and chemical makeup of the inhaled dusts and the alterations in lung structure caused by dust inhalation. Therefore, by controlling and knowing the physical and chemical makeup of the inhaled dusts, the important factors which lead to pulmonary injury following inhalation of coal mine dusts can be determined.

An inhalation facility has been established at WVU and is being used to expose experimental animals to dusts. The facility consists of two Hazelton 2000 chambers. Both chambers receive air (15 scfm) which has been filtered and conditioned to 70°F and 50% relative humidity. Animals are selected at random and placed in either the control chamber, which receives only conditioned air, or the exposure chamber which receives coal mine dust in addition to conditioned air. Stale dust is aerosolized using a TSI 9310 fluidized bed aerosol generator while fresh dust is made and aerosolized in a Fluid Energy Processing and Equipment Model 0101-C6P Jet-O-Mizer mill.

The inhalation facility is used to test hypotheses as to the causative agents in, and the cell types which react to, inhaled dusts. The causative agents are tested by alteration of the physical and chemical makeup of the dusts and the reacting cell types are determined by supplying exposed animals to a number of experimental groups who examine different cell types or pulmonary tissue and determine the changes brought about by inhalation of the dusts.

Exposed pulmonary tissues have been supplied to researchers at NIOSH, Penn State, and WVU. These tissues have been used to assess the function and morphology of pulmonary alveolar macrophages, for the determination of the effect on detoxification enzymes in the lung, and for biochemical determination of the extent of fibrosis.

In addition, morphometric, x-ray diffraction, and electron spin resonance techniques are being used to determine the site, extent, and cause of pulmonary injury following inhalation of dusts.

Exposures have been made using stale silica dust and Bureau of Mines Pittsburgh seam (20/20) stale coal mine dusts. To date, examination of animals three months following the termination of exposure has shown that inhalation leads to changes in the makeup of the interstitial space and in the capillary blood space. The changes implicate certain cell types and chemical mediators as being important.

This research indicates that there are many areas that need further study. For example, what exposure concentrations and durations are relevant, what is the effect of fresh dusts as opposed to stale dusts, where are the locations and local concentrations of inhaled minerals, and continued examination of the effects of the different dusts on the release of cellular mediators.

WV8/USBM 5407

Airway Reactivity in Coal Miners

Abrons, H.; **Petsonk**, E. L.; Daniloff, E.; Niggemyer, M.

The effects of coal mine dust on the human lung have been studied extensively. Several conditions, including pneumoconiosis, are recognized as resulting from underground coal mine dust exposure. Particularly in its advanced form (progressive massive fibrosis), coal workers' pneumoconiosis is often a disabling lung disease. However, controversy remains concerning why, among apparently similarly exposed miners, only some will develop severe lung impairments. Different authorities propose cigarette smoking, individual susceptibility, or variation in dust exposures as explanations for the disparate responses.

The exact mechanism(s) for development of lung damage in coal miners remain unclear. The acute response of the lung to inhaled nonspecific irritants, such as dust, can be measured using pharmacologic agents such as methacholine. An individual's response to these agents is termed his or her "airway reactivity". Several investigations have suggested that airway hyperreactivity may be an important factor in the development of chronic, irreversible lung disease in the general population and in dusty occupations, including coal miners.

This project has been investigating the relationship between airway reactivity and long term changes in symptoms and lung function in current underground coal miners and controls. Major hypotheses being tested are: 1) The presence of airway hyperreactivity in underground coal miners is related to coal mine dust exposure, and 2) Irreversible loss of lung function in underground coal miners is related to the degree of airway reactivity. Upon completion of the final two years of this five year investigation we will determine if prolonged coal mine dust exposure leads to increased airway reactivity, and whether airway reactivity testing can predict the development of symptoms and decreasing ventilatory capacity in coal miners.

Analysis of initial symptom and lung function data has suggested several hypotheses. The frequency of symptoms in non-mining controls appear to be consistently greater in persons with airway hyperreactivity. In miners, this does not appear to be the case, although exposure status is a significant determinant. Regarding lung function, both miners and control groups show significantly lower lung function in the presence of increased airway reactivity. On analysis of the baseline data, no interaction is apparent between reactivity and exposure status, but this may become manifest as long term follow-up is continued. The prevalence of increased airway reactivity is inversely correlated to duration of work at the mine face. This could simply represent selection bias, but it also suggests that the development of increased reactivity may be a mechanism for selection out of the work force. Longitudinal data currently being collected will clarify the significance of these findings.

WV9/USBM 5408

Effects of Respirable Dust on Release of Superoxide From Pulmonary Alveolar Macrophages

Cilento, E. V.; **Lantz**, R. C.; DiGregorio, K.

The major objective of this project is to develop a better understanding for the health effects associated with inhalation of airborne mine dusts; especially the role phagocytosis by PAM plays in removing dusts from the lung. In this process, superoxide (O2-) and other antimicrobial agents are produced that destroy the inhaled foreign microbes. It is not understood whether dusts inhaled over a period of time can cause dysfunction of PAM which results in an underproduction or overproduction of superoxide; either of which may be harmful to normal lung tissue. O2- production is heterogeneous and highly complex and the mechanisms of activation, initiation, and termination as well as the kinetics of O2- release remain to be elucidated. A novel technique has been developed to quantify O2- release by single PAM which permits study of the effects of different dusts and time of exposure on O2- release.

A multifaceted approach is used which encompasses the following: (1) study of O2- release by single PAM when contacted acutely with different concentrations of dusts suspended in the medium; (2) study of O2- release by PAM after in vivo exposure to dusts in inhalation chambers for known periods of time; (3) development of a mathematical model to describe the kinetics of O2- release; and (4) development of computer analysis methods to provide further insight into intracellular events occurring during O2- release. This may ultimately provide a quantitative clinical assay to assess antimicrobial functions of PAM.

Acute *in vitro* exposure to quartz decreased the amount and rate of O2- produced while CMD resulted in increased O2- production compared to control. In contrast, kaolin (non-fibrogenic) did not significantly change O2- release. These results suggested that O2- production may be a better indicator of PAM dysfunction than cell death, which gives comparable results for quartz and kaolin, and that O2- release may be an important indicator of pathogenicity and PAM dysfunction. In the presence of surfactant no changes in O2- production were observed following *in vitro* exposure of quartz or CMD suggesting that lung surfactant may alter their acute toxicity. More recent findings show that O2- production from adherent PAM, when incubated with serum, permits restimulation of the same cell. Serum alone did not stimulate PAM indicating it is a necessary but not sufficient condition supporting suggestions that *in vivo* serum may condition PAM to produce O2-.

The effects of length of *in vivo* exposure to respirable quartz was tested by housing animals in the WVU inhalation facilities. Respirable quartz increased O2- release for upto 10 d after exposure followed by a decrease to control by 31 d. The 3 d group suggested that there was activation and/or recruitment of PAM into the lung. This is being studied further by analyzing PAM after brief exposure to quartz and CMD.

A kinetic model has been developed to describe O2- release by single PAM. Model predictions compared favorably with experimental results and appear to explain the kinetics involved and the considerable heterogeneity observed in production by individual PAM. Further experimental and model studies are underway to assess the role of PAM in removal of mineral dusts from the lung in health and disease.

WV14A/USBM 5413

Development of New Early Detection Methods for Black Lung: Tracheal Acoustic Impedance of Lung Air Passages

Sneckenberger, J. E.

The main objective of this research project is to systematically develop the tracheal acoustic impedance measurement as the clinical method for detecting the onset and progression of CWP. As a medical diagnostic tool, this non-invasive two-microphone technique could also become a useful means to monitor the effectiveness of lung CWP drug treatment studies.

This project, since its start in the fourth year of the Generic Mineral Technology Center for Respirable Dust, has encompassed both experimental and theoretical research into the mechanics of lung airway dysfunction. In its first year during 1986-87, laboratory capabilities were developed to induce a CWP-type lung exposure in individual animals using an inhalation chamber with an improved silica concentration control system. Laboratory capabilities to monitor the progressive lung quality of life of the exposed animals using a traditional breathing spectrum chamber were also developed. Laboratory capabilities were also developed to measure any incurred lung airway deterioration in excised lungs using the conventional plethysmograph as well as the new lung acoustic impedance method. The implementation of laboratory facilities to measure invivo lung P-V performance and tracheal acoustic impedance were pursued. A comprehensive data acquisition/analysis computer system was specified to centrally manage the data from all of these lung monitoring and measurement facilities for later correlation study.

Two main animal studies were performed using these developed laboratory facilities to quantitatively assess the sensitivity of the non-invasive acoustic detection of lung airway function. In the first study, the bronchial tube smooth muscle constriction behavior was measured during the first hours after death for young and older guinea pigs. The second study compared the progressive development of lung dysfunction over a three-week period for silica and saline tracheally injected rats.

Modeling of lung mechanics based on theoretical principles and interpretations of acoustic impedance data has progressed rather well. A lung model of modified exponential horn shape that permits various lung wall and termination conditions to be included theoretically has been developed.

An in-vivo lung acoustic impedance facility has been conceived for implimentation during this second year of the project. Revalidation and possible improvements to the acoustic impedance system that was developed for the excised lung facility are being considered. The requirements for an adequate maximum acoustic source signal and appropriate flexible mouthpiece have also been considered, with consideration given to future clinical application implications.

WV14B/USBM 5413

Topographical Laser Holography to Infer Pulmonary Function for the Early Detection of Black Lung

Stanley, C. F.; **Fraser**, D. G.; **Pathak**, M.

The overall objective of this study is to determine if modern, very sensitive laser holography techniques applied to the chest surface could detect early coal workers pneumoconiosis (CWP) disease patterns. Initial investigatory efforts are to determine if the techniques can detect disease states in the excised lungs of rats. A technique has been developed to detect surface movements of excised lungs with a resolution of a few microns. Different patterns of lung surface movement could be indicative of lung disease.

The technique used to detect lung surface movement is termed time-averaged holographic interferometry. A laser beam is split into two beams with one directed toward a photographic plate and the other reflecting from the excised lung before falling onto the photographic plate. At the plate the interference of the two beams produces a hologram of the lung with light and dark bands superimposed. These interference bands are contours of equal displacement on the lung surface. The value of this technique is its extreme sensitivity, detecting lung movements approaching the wavelength of light. To vibrate the lung surface, a small conical speaker is attached to the trachea of the lung via an impedance tube. The lung is vibrated at different frequencies between 800 Hz and 4000 Hz and at different power levels.

The technique thus far has been very successful. The holograms of the excised lung show a progression of fringes from the trachea to the bottom of the lung as the amplitude of vibration is increased. The right lobe, being divided into four parts, has a different response than the left lobe which is undivided. From the fringe patterns the amplitudes of lung surface movement have been calculated.

The success of this research indicates a need to apply this technique to normal rat lungs and diseased rat lungs to detect differences in lung surface response. The technique is capable of providing insight into the fundamental functioning of the lung. Application of the technique to the chest wall of animals and eventually of humans should also be considered.

WV17/USBM 5423

The Role of Platelet Activating Factor in the Etiology of Coal or Silica Induced Pneumoconioses and the Effects of Fresh Cleavage Planes on This Response

VanDyke, K.; Castronova, V.

Inhalation of dusts causes lung diseases in both surface and underground miners. The diseases are the result of normally protective systems that exist in the lung causing inflammation, irritation and degradation of normal lung tissue. If the dust is a certain composition and size, it goes deeply into the breathing system and interacts with specific cells that normally protect the lung from bacteria and other foreign invaders. The specific cells are two different types of white cells termed - neutrophils and macrophages. These cells eat or engulf foreign particles or substances and they have specific chemical systems that produce toxic oxygen containing substances and enzymes that destroy various types of microbes. However when they encounter particles such as freshly cleaved coal mine dust or silica (sand) on a continuous basis they produce excess amounts of toxic oxygen compounds and degrading enzymes which can destroy normal tissue of the lung. Furthermore, the body attempts to isolate the toxic particles and produces fibrous material which further blocks the exchange of oxygen to the red blood cells needed for respiration of tissues. This causes loss of lung function, emphysema, black lung and fibrosis.

Part of this cycle of inflammation is caused by a lipid substance known as platelet activating factor (PAF). This substance is formed at the time of particulate exposure. It causes bronchoconstriction and a cycle of irritation and inflammation. Recent studies from our laboratory have implicated PAF as a factor in cotton dust caused respiratory problems and in asthma. Current studies in our laboratory are focused on coal mine dust and silica causing similar problems with loss of lung function.

We will measure the effects of platelet activating factor on the release of toxic reactive products from lung phagocytic cells, i.e., alveolar macrophage and leukocytes. We will also determine whether coal mine dust or silica can stimulate the release of platelet activating factor from macrophages. In addition, newly developed drugs which block the synthesis and or activity of PAF have been shown to be effective in asthma. We will use similar drugs in attempting to reverse the effects of coal mine dust and silica.

Furthermore, a Chinese drug, tetrandrine, used in the treatment of toxic dust inhalation, e.g. silicosis, will be tried to reverse the effect of particles (coal mine dust or silica) causing chronic inflammatory reactions with the white cells of the lung - macrophages and neutrophils. This drug has a similar structure to PAF activity - blocking drugs. If we can block the toxic reactions which follow inhalation of these particles then the body can repair itself and we can stop and possibly reverse the disease process.

3.2
Characterization of Dust Particles

CHARACTERIZATION OF DUST PARTICLES

The importance of identifying the physical, chemical, mineralogical, size consist, shape and surface condition of respirable dust samples can hardly be overemphasized. There is considerable evidence that all mine dusts do not present the same health hazard. Rank of coal and composition, especially silica content, of the mine dust; shape; and surface charge are risk factors that affect the incidence and severity of CWP. The dust characterization studies are aimed firstly at evaluating the characteristics of the dust collected in the various field investigations, secondly at the characterization of the dust samples for dust/lung relationship studies in the laboratory for particular objective and scope of dust/lung study and thirdly, at fundamental research for developing better dust characterization methods.

A suite of standard samples including anthracite, medium volatile and high volatile bituminous coals; quartz; clay; and rock dust have been prepared and thoroughly characterized with respect to the distributions of particle size and compositions. A comparison of the morphology of the standard dust particles with similar particles collected in an underground coal mine has been established. Samples of these characterized (standard) dusts have been distributed among various research groups associated with the Dust Center.

The aerodynamic diameter of a particle is a particularly important characteristic since this parameter determines the point of deposition in the human respiratory tract. A 3-dimensional numerical model for theoretically determining the equivalent aerodynamic diameter of irregular shaped particles has been developed and used to analyze coal dust particles and a particle shadowing technique has been developed for experimental 3-dimensional shape analysis. The technique is quite accurate in that the aerodynamic diameter of several coal dust particles have been numerically determined to be within 5% of experimentally measured values.

Physical and chemical characterization of respirable dust in mines is severely constrained by the inherently fine size of the particles and by the limited sample quantities (typically milligrams) normally available.

Another dust characteristics study has grown out of the observation that fresh dusts have a higher level of free radicals than dust that has been stored for some time. Biological effects of "stale" versus "fresh" dust are being compared. Preliminary studies have established a positive correlation between the higher concentration of free radicals and biological toxicity.

Investigation of the relationships between physical characteristics of respirable dust particle surfaces and their potential cytotoxicity is in progress.

Coal, quartz or other mineral particles in dusts undergo several kinds of interactions in mine and lung environments. For example, the amount of dust becoming airborne is influenced by the relative effectiveness of two basic processes which occur naturally and serve to prevent the majority of the dust particles from being airborne. These are: adhesion of dust particles to larger fragments and agglomeration of airborne particles to form larger aggregates. Similarly, the behavior of inhaled particles depends upon interactions of particles with surfactants and other lung constituents. It is noted that freshly broken respirable dust particles have free radicals (unpaired electrons). In the same environment lung cells generate superoxides which also have free radicals. Is there some interaction between the freshly broken dust free radicals and the lung cells free radicals to cause aerosol size coal dust particles to lodge in the lungs rather than breathe in and out with the airflow? Furthermore the effectiveness of water sprays in the capture of dust particles depends upon the nature of the interactions between water droplets and airborne particles. As a part of the research supported through the Dust Center, research is underway to delineate the nature of such interactions.

Dust suppression in coal mines using water sprays is inherently difficult because of the nature of the coal seam, as mined. The raw coal particles show a great variation in their degree of hydrophobicity due to such factors as coal rank, degree of surface oxidation and the nature of contained mineral matter.

The investigations in the Dust Center suggest that a wetting agent should be tailored to the specific coal dust to be suppressed. Investigations are under way to understand the nature of coal-surfactant interactions and to relate them to their performance as wetting aids.

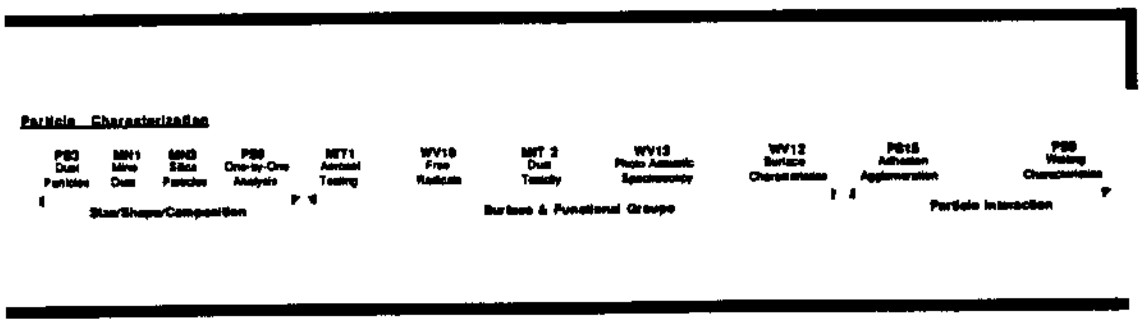


Figure 12: Individual Dust Center projects in the Particle Characterization Area.

DUST PARTICLE CHARACTERIZATION

PSS/USBM 4203
Characterization of Dust Particles
Hogg, R.; **Luckie**, P.; Dumm, T. F.; Bunnaul, P.

The principal objectives of this project are to prepare and characterize standard respirable coal dust samples and to develop and evaluate techniques and procedures for the characterization of respirable dust. Characterization of the distributions of particle size and composition is of particular interest. An additional objective is to provide service to other projects and research groups in the areas of dust sampling and characterization, preparation of special synthetic dusts, etc.

Respirable dust in coal mines is a heterogeneous mixture of coal, associated mineral matter derived from the coal seam and adjacent strata, rock dust, diesel particulates, etc. Any sample will include a distribution of sizes; at any size there will be distribution of particle shape and chemical/mineralogical composition. Complete physical/chemical characterization of the dust would require the determination and description of a complex, multidimensional distribution. Recognizing that a complete description of this type is quite impractical, a three-level approach has been adopted in which limited measurements on the bulk sample, on separate size intervals and on a particle-by-particle basis are combined to provide an optimum description.

A broad variety of particle size measurement techniques including sedimentation, light scattering, electrical sensing, inertial collection and scanning electron microscopy has been evaluated with respect to respirable dust characterization. Limitations on the applicability of the techniques have been determined and appropriate correlation factors have been obtained. Based on these studies, standardized techniques have been selected for dust characterization. A laser diffraction/scattering instrument has been adopted as a practical, working standard for laboratory analysis.

A procedure has been developed for estimating the distribution of composition by size based on specific gravity fractionation of the particles using heavy liquids and analysis of composition and size distribution on the individual fractions. The information obtained by this approach can be further augmented by SEM analysis of individual particles in the fractions.

A suite of standard respirable dusts has been prepared from coals representing the western (high volatile A bituminous), central (medium volatile bituminous) and eastern (anthracite) mining areas of Pennsylvania, as well as quartz and kaolin clay which represent important mineral constituents of coal dust. Extensive characterization studies have been performed on the samples to evaluate chemical and mineralogical composition and the distributions of particle size and specific gravity. Samples of these standard dusts have been made available to research groups concerned with respirable dust in mines.

PSS/USBM 4207

Wetting Characteristics of Dust Particles in Relation to Dust Abatement

Chander, S. ;Aplan, F.F.; Mohal, B.R. and Alaboyun, A.

Dust suppresion in coal mines using water sprays is inherently difficult because of the nature of the coal seam, as mined. The raw coal particles show a great variation in their degree of hydrophobicity due to such factors coal rank, oxidation and contained mineral matter (silica, clays, carbonaceous shales, etc.). The successful development of a surfactant-containing dust suppresion system would offer the user an additional degree of freedom in controlling, especially, those dust not readily wettable by water alone.

The capture of dust particles by a water spray may be visualized as composed of these sequential sub-processes:

- collision between water droplets and dust particles.
- adhesion of the dust particles to the droplets.
- spreading of water on a particle and its engulfment by the droplet.

The use of a surfactant offers the possibility of improving the dust capture efficiency of these sub-processes.

The main objective of this research is to enhance the effectiveness of water droplets in suppressing mine dusts. Such factors as the wetting behavior of coal particles, the role of coal rank, the role of surfactant type and the effect of coal aging (oxidation) is emphasized in this report.

A new test procedure was developed to demonstrate that the individual particles comprising coal mine dust often show a great deal of variation in their degree of wettability and imbibition by water. Using a modified Walker sink test and the initial rate of wetting, it has been shown that the rate of wetting of coal particles with an ethoxylated alkyl phenols (the Triton and Tergitol wetting reagents) is a function of coal rank and the type of surfactant. With a nonyl phenol containing 9.5 moles of ethylene oxide, the wetting rate of coal by rank is: HVA Bit > anth > sub-Bit while with octyl phenol, containing the same amount of ethylene oxide, the wetting rank is: anth > HVA Bit > sub-Bit. Note in both cases the sub-Bit coal is the most difficult to wet.

An investigation of a series of ethoxylated phenols showed that the hydrophile-lipophile balance (HLB) of the surfactant was optimum for wetting at HLB=13.4 for a HVA-Bit coal and 11.6 for a sub-Bit coal. Fresh and aged coal responded differently to the wetting agents. It is apparent that the surfactant should be tailored to the specific coal dust to be suppresed.

Continuing work will focus on: (1) clarifying the mechanisms by which various wetting agents function, and (2) making dust suppression tests in our newly assembled dust chamber equiped with a particle measuring device. In this way we can study a broad range of spray, surfactant and dust particle parameters.

PS9/USBM 4206

Analysis of Coal Dust Particles on a One-By-One Basis Using an Automated Computer Controlled SEM with X-ray Fluorescense

Austin, L. G.; Hogg, R.; Dumm, T. F.; Gomez, C. and Rabinovich, A.

The main objective of this project is the development of automated, particle-by-particle analysis technique using a computer-controlled SEM and an energy dispersive X-ray spectrometer. The technique will ultimately be able to measure the size, shape and chemical composition of several thousand coal dust particles in relatively short periods of time.

With a computer-controlled SEM, it is possible to move the electron beam across a field of particles and locate individual particles. When a particle is located, the electron beam traces around the perimeter of the particle storing the X and Y coordinate points which correspond to a digital matrix. After the particle has been traced, size and shape values are then calculated. The electron beam then samples one or more points within the particle to obtain characteristic X-ray emission values for Na, Al, Si, S, K, Ca and Fe. A ZAF correction procedure has been developed which converts the characteristic X-ray intensities into the respective absolute elemental mass fractions. Oxygen is determined by stoichiometric association and carbon is determined by difference to 100%. The correction includes allowances for peak overlap and dead time plus a background subtraction procedure has been developed and implemented.

Particles in the size range of about 10 to 100 μm are analyzed by embedding the particles in an iodine-laced epoxy resin. The cured resin is then polished to provide a mirror-flat surface which is necessary for the most accurate quantitative analysis. Particles must first be screened into $\sqrt{2}$ sieve fractions and analysis is performed only on the polished cross-sections which fall within the original size range. Particles less than 10 μm are less amenable to this type of sample preparation. In this case particles are dispersed on a flat surface (usually beryllium or carbon) and approximate analysis performed.

Although the size and shape analysis routines are not affected by this type of sample preparation, the rough and irregular surfaces displayed by the dispersed particles introduces the well known 'geometric effect' into the chemical composition analysis. This results in very large standard deviations in X-ray intensities even for particles of uniform composition especially those less than about 10 μm. Below this size, there becomes a size/X-ray intensity relationship which results from the X-ray excitation volume exceeding the volume of the particle.

Efforts have been focused on developing rapid but meaningful shape indices and improving the chemical analysis of very small, dispersed particles.

PS15/USBM 4223

Adhesion, Aglomeration and Deposition of Respirable Dust

Chander, S.; Hogg, R.; Kohen, M.; Palat, M., Mohal, B.

The quantity of airborne dust in mine atmospheres depends upon a number of processes which occur naturally in the mine environment. These processes are adhesion, agglomeration, deposition and re-entrainment of particles. The main objective of this research program is to determine the factors which control the effectiveness of these processes. Considerable evidence exists to suggest that a significant portion of the adhesion and agglomeration occurs within a short time after fragmentation has occurred. Since it is known that freshly created surfaces undergo a variety of aging processes including atomic rearrangements, adsorption of water vapor and other gases from the environment, etc., it is important to specify the age of the dust and, if possible, to evaluate the nature and time scale of the aging processes. To carry out these investigations it was therefore necessary to generate fresh dust. We have designed and fabricated a fresh dust generator. This device can be used to produce particles for which the time of generation is precisely known, and which are available for study within a very short time. We plan to use the fresh dust generator to determine the effects of such variables as humidity, mineral type and coal rank, on the amount and characteristics of the airborne dust. The characteristics to be determined include, size distribution, surface charge, and wetting behavior. The influence of these parameters on the extent of agglomeration will also be determined. Preliminary studies show that particles produced by the fresh dust generating device might be agglomerated. Studies are in progress to determine the extent of agglomeration and to characterize the size, structure and integrity of the agglomerates present.

Procedures are being developed for investigating the aging process and its effects on adhesion and agglomeration. Short-term aging can be studied by measuring changes in, for example, surface charge during transport away from the fresh dust generator. Longer term effects can be evaluated by comparative studies of fresh dust and regenerated dust. Since adhesion, agglomeration and deposition occur simultaneously in many situations, the experiments must be carefully designed so as to separate contributions from each of these effects.

WV4/USBM 5404

Support for Dust Characterization

Bajura, R.; **Renton**, J.; **Pavlovic**, A.; Simonyi, T.; Andre, R.; Kannan, R. and Chien,T.

The purpose of this project is to provide laboratory support for the analysis and characterization of coal mine dusts. During the previous year, an additional activity was initiated to study the effects of coal mine dusts on lungs as evidenced by the analysis of lung tissues obtained from experiments conducted under the program of Project WV05-USBM 5405.

A major activity of this project has been the purchase of a Hitachi Scanning Electron Microscope (SEM) system to reduce the time required to analyze the dust samples, plus extend the capabilities of dust characterization experiments. Parts of the system were received in the last quarter of 1987, but the major assembly and protocol development is taking place this year.

Work is continuing on the installation. Calibration experiments and other sample studies are being conducted to familiarize the operators with the equipment. Use of the SEM to obtain data for the projects conducted under WV06 are being initiated.

T. Simonyi, R. Bajura, R. Grayson, R. Plummer, and T. Stobbe participated in a workshop session on sampling strategies conducted in Morgantown on December 9-10 as part of a group discussion of needs and instrumentation capabilities in the area of sampling. Conclusions from the meeting will be presented in the report project BOM 5422.

The work load on this project will be minimal during the present year since the major effort for characterizing samples will be funded under project WV06. Work on the microtome lung slices has been transferred to WV05 for reporting purposes.

WV10/USBM 5409

Magnetic Resonance Characteristics of Paramagnetic Ions and Free Radicals in Coal Dust, Black Lung Tissue, and Lung Tissue Under Controlled Dust Exposure

Dalal, N.; **Vallyathan**,V.; Kahol, P.; Jafari, B.; Shi, X.; Deloose, J. and Martin, J.

The overall objective of this project is to gain an understanding of the role of chemical properties of the surface of freshly broken coal and quartz particles in relationship to the pathogenesis of coal workers' pneumoconiosis (CWP). This research is important because mine workers are exposed to coal and quartz particles within seconds or minute (at most) of their generation.

This project comprised of both theoretical and experimental studies of chemical structures of the surfaces of the coal and quartz particles. Our hypothesis is that carbon - or silicon - centered free radicals are generated at the instance of the severage of the particles from the lumps of coal and quartz respectively. On the experimental front, the objective was to develop an electron spin resonance (ESR) methodology since ESR is the most direct spectroscopic technique for characterizing free radicals. The developed ESR methodology was then used for evaluating the structural and kinetic behavior of the free radicals detected on the surfaces of the coal and quartz particles. Furthermore biochemical tests were developed for evaluating the role of the surface characteristics in relationship to the cytotoxicity of variously prepared dust samples.

The Experimental data clearly shows that freshly prepared dust particles of both coal and quartz contain free radicals whose lifetimes and reactivities depend on the dust's storage time after preparation via grinding (or crushing). Parallel cytotoxicity studies using standard biochemical assays (erythocyte hemolysis, release of hydrogen peroxide, superoxide anion and other lytic enzymes) showed that indeed fresh dust is significantly more cytotoxic than 'old' (stored) dust. Because of the significance of these results to other projects, it was necessary to come to a common definition of 'fresh' and 'stale' dusts. Based on our ESR-biochemical studies, the half-life of anthracite coal dust was found to be about a half-a-day while that of quartz dust was found to be about one and a half day. Thus further laboratory animal studies aimed at simulating CWP should employ freshly made dusts.

WV12/USBM 5411

Shape and Surface Characteristics of Respirable Mine Dust Particles

Meloy, T.; **Castranova**, V.; **Wallace**, W.; Hurter, P.; Flemmer, R.; Van Egmond, J.; Saus, F.; Keane, M.; Hill, C.; and Mike, P.

Coal workers pneumoconiosis is a prevalent debilitating lung disease. Current regulations of respirable dust exposure and of free-silica exposure presumably have reduced the current disease incidence. However the exact mechanisms of pneumoconiosis initiation and progression are unknown; and consequently the adequacy and efficiency of the current prevention efforts are uncertain.

Dust analysis methods do not predict the pathogenic potential of various dust exposures, other than the general recognition of hazard associated with high quartz concentrations. And failures of conventional bioassays to distinguish the pathogenic potential of quartz and clay dust, or to define disease-inducing properties of quartz-bearing respirable dusts, compromise prediction of respirable dust induction of pulmonary disease.

The objectives of this project are to identify initial interactions of respired dusts which can occur within pulmonary alveoli and which may distinguish the pathogenic potentials of respirable quartz-bearing dusts, and to determine dust surface structure or compositional properties which are predictive of the dusts' disease inducing potential.

The properties of respirable quartz dust which are responsible for its strong pathogenicity for pulmonary disease induction as compared to alumino-silicate dusts are unknown. While quartz is highly cytotoxic to pulmonary macrophages <u>in vitro</u>, clay dusts such as kaolin dust are comparably cytotoxic. We have found that incubation of quartz and kaolin respirable sized dusts in a fluid modelling the material which coats the lung results in complete neutralization of the cytotoxic potential of both dusts. That is, our research indicates that mineral dusts are promptly de-toxified upon deposition in the lung. Our research hypothesis is that these coated dust particles are then subjected to uptake and digestion processes by lung cells, resulting in removal of the protective coating from the dust surfaces and re-toxification of the dusts within the cells. Our research models this by incubating a quartz and a kaolin dust with the primary component of the surface active materials coating the lung, and then by incubating the coated dusts with phospholipase enzymes.

We have found the rate of restoration of quartz cytotoxicity by this modelled digestive process to be one to two orders of magnitude greater than that for kaolin. Our current research using radiolabelled surfactant to monitor digestion rates in the interior of the cell is designed to determine if this rate difference can be the basis for distinguishing the relative disease inducing potentials of the two dusts.

As a spinoff of this line of reasoning we have investigated the interaction of organic respirable particulate material with pulmonary surfactant, and the effect of that on the genotoxic potential of particles such as diesel soot. Our results appear to have solved a puzzel as to how hydrophobic organic particles can express their mutagenic potential in pulmonary fluids and initiate a possible progression to lung cancer.

MIT1/USBM 2501

Respirable Dust Testing in Metal, Non-Metal Mines and Metallurgical Operations

Ring, T. A.

The principal goal of this project was to obtain more complete information on the physical and chemical nature of respirable dusts to be found in certain types of quarrying, metallurgical, and ceramic operations. This information is important in the consideration of the conditions in the atmosphere to which the work force may be exposed in such operations.

The dusts in the respirable size range arising in quarrying rock, in welding operations, in metal powder processing, and in a ceramic processing facility were collected and examined for size distribution and chemical character. A portable apparatus containing an Anderson cascade impactor and two Sierra personal cascade impactors were employed in the studies. Various electron optics methods were employed to determine the concentrations of major and minor chemical elements present in the various size segments of samples collected, and to study the physical character of the particles.

The results of the study show generally that the chemical character of respirable dusts arising from several different types of operations may differ significantly from the materials being processed in a given operation. The measurements reported indicate that the details of the operation, and the properties of materials involved in the process can be of importance. For example, a minor constituent present in the rock being quarried that is much more friable than the rock itself may be broken and ground readily to a fine powder. Thus, this constituent may become concentrated in the finer portions of the dust arising from the operation. Similarly, in a high-temperature metallurgical operation, the more volatile portions of the material being processed can be expected to appear in the dust that may be generated in the operation.

MIT2/USBM 2521

Effect of Physical Properties of Respirable Dusts on Their Toxicity

Elliott, J. F.; McCarthy, J. F.; Boisaitis, P.; Eppelsheimer, D.

The principal objectives of this project are:

(1) To identify the particular physical and chemical properties of certain respirable size dust particles that make them particularly toxic, and thus a health hazard to persons engaged in mining and mineral processing operations.

(2) To develop methods for identifying the properties most related to toxicity and to extend methods of detection to a broad range of materials (silica, asbestos, metal oxides, etc.).

(3) By identifying the most hazardous features of respirable dust particles to suggest better methods for monitoring, warning, and abatement, thus minimizing exposure to hazardous conditions.

In its present scope, the project focuses on the study of silicon oxide particles which are common in coal and mineral mining, and quarrying industries and a recognized factor in silicosis, pneumoconiosis, and related health hazards. These particles may have broadly different characteristics in terms of particle size, shape, crystallinity, surface structure and composition, etc. It has long been recognized that some types of particles are much more toxic than others, but there are still important uncertainties regarding the particular characteristics that cause these differences.

In this project the most up-to-date methods of surface structure analysis, size classification and physical characterization are used to study particles obtained from different sources. The toxic activity of these particles is measured in terms of their capability for rupturing the walls of red blood cells, and this toxicity is related to various physical parameters of the particles.

The particles screened for high levels of cytotoxicity are studied further for interaction with cells more directly related to the pathological effects induced by dust particles, and are eventually tested by in-vivo experiments in other laboratories.

Some of the important findings to date are the following:

(a) It has been found that fumed, amorphous silica particles exhibit a much higher cytotoxicity than has been usually ascribed to amorphous materials.

(b) Surface modifications by chemical treatment, calcination, or boiling may lead to significant changes in the toxicity of respirable silica particles.

(c) The surface characteristics of particles as measured by photoacoustic IR spectroscopy and by zeta-potential measurements can be related to the cytotoxicity of particles.

The results of this research promise improved methods for monitoring particles of enhanced toxicity and suggest concepts for the better understanding of the interaction of mineral particles with living cells.

MN1/USBM 2701

Coal Mine Dust Characterization

Marple, V. A.; **Rubow**, K. L.; **Pui**, D.; Fang, C. P.; Ananth, G.; Behm, S.; Cladow, R.

This project has been very successful in the development of instrumentation and techniques for studying the concentration and size distribution of dust particles in the respirable size range. In particular, an important breakthrough for the dispersion of dust samples has lead to the development of a commercial instrument, the TSI Small Scale Powder Dispersion and a technique for redispersion of dust particles from filters. The prototype of the dust dispersion system coupled to the TSI Aerodynamic Particle Sizer (APS) is shown in Figure 1a. With this dust dispersion system, a technique has been developed to collect and redisperse dust particles from filter media for subsequent particle size analysis. The importance of this technique is the ability to collect airborne particle samples at the mine face using a simple filter sampler and then to analyze the particles using instrumentation that can not be taken underground because of nonpermissibility and/or the complexity of the measurement technique. Figure 1b show a comparison of the coal dust size distribution as measured in an underground mine with a microorifice uniform deposit impactor (MOUDI) and that simultaneously collected on a Teflon membrane filter and subsequently redispersed and measured with a APS. The particle redispersion technique is of general use to the aerosol field and has been excepted by the aerosol technology community as a useful tool. For example, Environmental Protection Agency (EPA) has used this technique as one of their main diagnosist technique for analyzing the unique behavior of the recently developed PM-10 ambient air sampling inlets.

Furthermore, several basic fundamental studies, evaluations and improvements of instrumentation used for particle size measurement have been conducted. This instrumentation includes the MOUDI, the APS and a new personal diesel particle sampler. The MOUDI work has developed an optimized design for the impactor nozzles and a thorough understanding of the operating principles of the impactor. Field work with the MOUDI has proven it to be unique for measuring the size distribution of diesel exhaust and coal dust particle mixtures in underground mines. From the size distribution of the particle mixture, the existence of a bimodel size distribution that can be separated on the basis of particle size has been determined. This finding is currently leading to the development of a personal diesel sampler capable of measuring the mass concentration of diesel particulate matter in underground mines. The APS work has involved the development of a new inlet for sampling particles in the 8 to 30 μm size range.

MN3/USBM 2703

Determination of Silica Particle Concentrations in Respirable Size Range

Marple, V. A.; **Rubow**, K. L.; **Pignolet-Brandom**, S.; **Reed**, K.; Fang, C. P.; Tongen, W.

A technique has been developed for determining the mass concentration and particle size distribution of quartz particles in the respirable size range. The technique uses the microorifice uniform deposit impactor (MOUDI) for in-mine particle sampling together with modified MSHA quartz analysis technique. The MOUDI, which has a sampling flowrate of 30 L/m, collects 15 times more dust per unit time than either the standard personal respirable dust sampler or the personal cascade impactor. Consequently, sufficient particle mass is collected on each stage of the cascade impactor to not only obtain the total mass concentration in each particle size range, but also to perform silica analysis. A method for silica analysis was developed with MSHA ulitizing Fourier transform infrared spectrophotometry. Figure 3 shows the particle size distribution of dust sampled in an underground coal mine located in the Pittsburgh No. 6 seam, together with the corresponding size distribution of the quartz particles. The quartz particles, which are 6% of the total mass concentration, have nearly the identical size distribution as the total dust for particles in the 1 to 15 μm diameter size range.

WV13/USBM 5412

Determination of Biologically Active Silica Using Photoacoustic Spectroscopy

Seehra, M. S.; **Wallace**, W. E. (NIOSH) and Cheng, L.

The major goal of this project (initiated in October 1986) has been to develop Photoacoustic (PA) spectroscopy to characterize mine dusts for SA (surface available) silica and total free silica, and to determine the role of

SA silica vis-a-vis free silica in causing lung damage. SA silica is that part of free silica which is not covered or occluded by clays and other materials. This project is to also test the hypothesis that it is the SA silica and not the total free silica in mine dusts that causes lung damage.

The scope of work consists of the following five major tasks:

1. Acquisition and calibration of a PA/FTIR spectrometer;
2. Theoretical analysis of the PA effect;
3. PA spectroscopy of silicas and kaolin and criteria for distinguishing between SA and free silica;
4. Biological and toxicity studies (collaborative work); and
5. PA spectroscopy of mine dusts.

So far tasks 1 and 2, and parts of tasks 3 and 4 have been completed and one M.S. thesis, one publication and three presentations have resulted from this work.

Our theoretical analysis of the data in silica has shown that the Rosencwaig-Gersho theory which was developed for a thin film appears to work well for respirable-size particles. The dependence on chopping frequency follows the theory well and this effect is likely to be the main criterion for distinguishing between SA and free silica. We have also shown that PA spectroscopy is well suited for quantitative analysis of kaolin and silica for sample mass less than 2 mg. The PA spectroscopy of fumed and crystalline silica shows that fumed silica is amorphous and this may account for its higher toxicity observed by Prof. Bolsaitis of MIT. In collaboration with Wallace et al at NIOSH, we have shown that silica and kaolin interact differently with DPL (Dipalmitoyl Lecithin), a major component of pulmonary surfactant.

Successful completion of all the tasks shall result in the development of a new technique (PA spectroscopy) for better characterization of mine dusts and in a greater understanding of how silica damages lungs. This may allow us to devise new ways to reduce the severity of lung damage in miners.

3.3
Relationship of Mine Environment, Geology and Seam Characterization to Dust Generation and Mobility

RELATIONSHIP OF MINE ENVIRONMENT, GEOLOGY AND SEAM CHARACTERISTICS TO DUST GENERATION AND MOBILITY

During the mining of a seam, dilution from the roof and floor and from partings and inclusions in the seam, is a standard occurrence. In coal mining, since the roof and floor strata and inclusions and partings often have greater strength than coal, the mass of adverse dust generated can be much more than if only coal is cut, especially if quartz or other toxic material is present. The size distribution, chemical and mineralogical properties of the respirable dust can also be different from that obtained from cutting coal only. Therefore, the relationship between the coal and out-of-seam material characteristics and the characteristics of the mine respirable dust are explored through underground experiments. Several projects are being performed in this area including development of comprehensive facilities at both PSU and WVU for performing detailed seam characterization.

Recognizing the uniqueness of underground coal mining, research investigations involving seam characteristics, mining system and worker position are being conducted in the Dust Center to establish standard procedures for characterizing some coal properties that may be involved in workers contracting CWP. This has been accomplished by the in-mine sampling of airborne dust at various worker locations and mining systems configurations and by performing laboratory analyses of mined material (coal and rock) taken from the mines.

The investigations includes a method of classifying coal seams according to their potential to generate respirable dust. It includes statistical analyses of the size and locational variations of the elemental compositions of respirable coal mine dust in operating underground mines from seams located in the eastern, midwestern, and western United States, and the relationship between the elemental compositions of respirable dust sampled near a continuous-mining machine and a laboratory-produced respirable dust.

A major area of investigation in the Dust Center has been the formulation, evaluation, and verification of improved dust sampling and analytical strategies for use in surface and underground mines and preparation plants. A particular concern has been the need for obtaining valid dust samples with a large mass for use in scientific, medical and engineering research studies. Methods of analysis that can improve the reliable determination of dust characteristics are also being studied. This includes the proper method of synthesizing, collecting, storing, and utilizing respirable dusts and the effects of other contaminants and particulates that exist in the mine atmosphere or may be encountered in the laboratory.

A definition of fresh versus stale dust has been achieved. While the research group has been concentrating initial efforts on coal dusts, the ramifications of silica, diesel particulates, asbestos, and other confounding variables have been a major topic of concern for characterized and standardized field investigations. After standard procedures have been established, certain factors contributing to increased CWP may be identified and prevented during pre-mine planning, or remedied by engineering controls in an operating mine.

Diesel research in the center involves the engineering control of airborne particulate and gaseous pollutants to which a miner is exposed in a diesel underground coal mine. Pollutant concentrations must be accurately measured to control them. This research is directed at the development of both measurement and control techniques. The measurement methods under study include Laser Raman Quantitative Analysis (LRQA) and the control technology under study is the Pyroban dry-type explosion-proof safety package and diesel particulate filter (DPF).

The determination of significant variations in coal mine dust characteristics occurring in different coal seams, at different worker locations and for longwall and continuous mining methods has also been studied. Thus far in this research investigation, results for two coal seams of very different rank indicate that not only is the mineralogical composition different for the seams but so, too, is the contamination of mineral species with respect to the stoichiometric elements that comprise them. The relationship between coal and out-of-seam dilution material and the airborne dust quality is being explored. Results from this project can be useful in predicting the variation of the mineral constituents in respirable coal mine dusts by worker locations in a mine, and then using this information to "construct" respirable dust exposures.

In summary, this area of research will help understand the inter-relationship between respirable dust exposure levels, mineral types, work positions, and the development of CWP in various mine environments as the findings are related to the more fundamental knowledge gained in medical and scientific investigations concerning the potential toxicity of various mine dust components.

Mine Workers, Mining System Seam Geology Dust Relationship

PS5	WV3	MTU1	WV6	MTU2	PS14/WV16/MN4
Dust Potential	Longwall Dust	Raman Spectroscopy	Dust Correlation	Pyroban Filter	Analytical Strategies

Figure 13: Individual Dust Center projects in the Mine Workers, Mining Systems, Seam Geology Dust Relationship Area.

MINE WORKERS, MINING SYSTEM AND SEAM GEOLOGY

PS5/USBM 4205

Establishment of Standard Procedures for Characterization of Respirable Coal Mine Dust Potential

Mutmansky, J. M.; **Bise**, C. J.; **Frantz**, R. L.; Johnson, C.; Xu, L.; Padmanabhan, S.

It is evident that the incidence of coal worker pneumoconiosis (CWP) or black lung disease varies in different coal producing regions of the United States. Many people have hypothesized about the reasons for the differing occurrences, but because underground coal mining involves many mining methods under changing geological conditions, several factors may be involved in contracting CWP such as: the trace elements in the respirable dust, the amount of quartz in the respirable dust, the rank of the coal that produced the respirable dust (bituminous, anthracite), the amount of respirable dust, etc.

Recognizing the uniqueness of underground coal mining and CWP, the main purpose of this project is to establish standard procedures for characterizing some coal properties that may be involved in contracting CWP. This has been accomplished by the in-mine sampling of airborne dust at various worker locations and by performing laboratory analyses of mined material (coal and rock) taken from the mines. After standard procedures have been established, certain factors contributing to CWP may be identified and prevented during pre-mine planning or remedied by engineering controls in an operating mine.

This project has developed a method of classifying coal seams according to their potential to generate respirable dust, has performed statistical analyses of the size and locational variations of the elemental compositions of respirable coal mine dust in operating underground mines from seams located in the eastern, midwestern and western United States, and is currently completing research which has investigated the relationship between the elemental compositions of respirable dust sampled near a continuous mining machine and a laboratory-produced respirable dust.

The project has also been investigating the best means of determining the mineralogical content of small dust samples using a scanning electron microscope (SEM) and the P-7 methods. In addition, SEM methods for characterizing some of the physical parameters of the dust have been attempted.

The ultimate goal of the project is to provide methods for obtaining the chemical, mineralogical and physical characteristics of respirable coal mine dust samples. In addition, the methods will be applied to dust samples taken from twenty coal mines of varying rank throughout the country and statistically related to CWP occurrences obtained through the medical records of the National Institute of Occupational Safety and Health.

PSU14/USBM 4222/5422/2722

Formulation, Evaluation and Verification of Improved Dust Sampling and Analytical Strategies for Use at Surface and Underground Coal Mines

Mutmansky, J. M.; Li, J.

The primary thrust of this project is the provision of better sampling and analytical technology for application to the sampling and characterization of respirable coal mine dusts. The need for this research has been obvious for some time due to the gap that is apparent between compliance sampling and analysis procedures and those available to dust researchers for use in coal mines. A research team comprised of Penn State, West Virginia University and University of Minnesota researchers was assembled for this effort.

The study was proposed to be oriented toward the extraction of information from the engineering, medical, coal industry and government personnel involved in the collection of aerosol dust samples from both underground and surface coal mines. To date, a variety of personnel from NIOSH, the Bureau of Mines, MSHA, West Virginia University Medical Center, Hershey Medical Center, the University of Minnesota and the South Dakota School of Mines and Technology have been consulted for problems and suggestions pertaining to the dust sampling and analysis areas. The meetings, have been very productive to date. Additional meetings have been scheduled with personnel from the EPA, Lovelace Research Institute and the University of Maryland over the next few months.

One of the primary specific issues attacked to date has been the need for obtaining valid samples with a larger mass for use in medical and in engineering research studies. This has clearly been an important issue in the determination of the various dust characteristics that have been considered important by dust researchers. Second, methods of analysis that can improve the determination of dust characteristics has been and will continue to be sought. The interaction between dust sampling and dust analysis is an important consideration in the project in addition and project personnel have been working to achieve an effective strategy for maximizing the ability to get meaningful data from sampling efforts.

Since the beginning of the project about six months ago, a number of related problems have also been discussed and analyzed to study their affects on sampling and the subsequent medical studies. These include the proper methods of synthesizing, storing and utilizing respirable dusts and the effects of other contaminants and particulates that exist in the mine atmosphere.

Analysis is still being performed or methods of producing respirable dusts for medical studies but some achievements have been made. With the help of Dr. Dalal of West Virginia University, a definition of fresh versus stale dust has been achieved. Production and storage of dusts is currently being studied and conclusions on this subject will be completed soon.

Other particulates and contaminants in the mine have also been an important issue in the research as a result of repeated urgings from the various research groups being consulted in the project. While the research group has been concentrating efforts on coal dust, the ramifications of silica, diesel particulates and other confounding variables has been a major topic of concern. The project team has decided to issue an annual report to outline the first-year findings on these variables and all other technical aspects of the project.

WV3/USBM 5043

Measurements and Construction of Dust Distribution Maps for Longwall Faces

Peng, S. S.; **Chiang**, H. S.

The major objective of this study is to construct airborne dust distribution maps for better understanding of the behavior of the airborne dust transportation, diffusion and distribution in longwall face area. This project was designed to include field instrumentations and theoretical studies on the behavior of the distributions of the airflow and airborne dust.

7,650 Real-time dust concentration values using Real-time Aerosol Monitors (GCA RAM-1) and 360 respirable dust samples using gravimetric samplers by both mobile and stationary methods were obtained. The Real-time airflow velocity data were also obtained using both velometer and vane anemometer. Based on the measured data, the statistical models and the distribution maps of airflow and airborne dust for each surveyed longwall face were developed and constructed. In addition, the dust samples collected from longwall faces were analyzed by the Coulter Counter. Moreover, the smoke tube tests were also performed for visual observations of the dust-laden airflow.

The analyses have shown that shearer operation and support advance are the two major dust sources and also the major factors for airflow and airborne dust dust distributions; that there exist some positions with repect to the shearer where the dust exposure to the shearer operators and the shieldmen is the lowest; that the quartz content in the dust-laden air is mainly generated by the support advance, instead of the shearer operation as normally perceived

At present, the most effective technique of airborne dust control is the water spray system mounted on the shearer. In addition, controlling the airflow distribution will be beneficial to reduce the airborne dust exposure to the workers. However, a more in-depth study of airflow distribution is needed for better prediction of airborne dust distribution.

WV6/USBM 5406

Correlations of Respirable Dust Characteristics to Coal Seams, Worker Positions, and Mining Methods

Stobbe, T. J.; **Plummer**, R. W.; **Grayson**, R. L.; Pavlovic, A.; Andre, R.; Simonyi, T.; Kim, H. W.; Zhao, L. J.

The major objective in this project has been to determine if significant variations in coal mine dust characteristics occur in different coal seams, at different worker locations and for different longwall mining methods.

The initial focus of the research was dedicated to determining the dust characteristics that should be studied. The literature on respirable dust research indicated that a relationship exists between the incidence of coal workers' pneumoconiosis (CWP) and the rank of the coal seam in which miners worked. This finding holds true throughout the world. Since the mechanism of disease development is a biochemical one, occurring on a lung cell-dust particle level, emphasis in this project was placed on studying characteristics of dust particles.

Coal mine dust particles, which range in size from less than one micrometer in aerodynamic diameter to just less than ten micrometers, can be studied using a scanning electron microscope (SEM). The elements composing particles can be determined using an energy dispersive x-ray (EDX) detector and spectrometer interfaced with the SEM. Particle sizing and imaging can also be accomplished, thereby permitting characterization of particles by both physical and chemical parameters. Knowing the relative elemental occurrences within a dust particle, one can determine its mineral species. Thus information can be obtained about both elemental and mineralogical compositions of a dust sample.

Past research has attempted to correlate mineralogical properties to occurrences of CWP, in Europe as well as the US. No absolute relationships have yet been found, even though the evidence indicates that the existence of quartz may play a role in the disease process. The evidence is less clear for other minerals and their interaction with quartz.

This research has thus been dedicated to finding the "rank factor(s)" which undoubtedly exist but have yet been discovered. It is hypothesized that analysis on a dust particle basis, rather than on a bulk basis, holds the key eventually to give the desired answers. Thus far in this project, results for two coal seams of very different rank indicate that not only is the mineralogical composition different for the seams but so, too, is the contamination of mineral species with respect to the stoichiometric elements that comprise them.

MTU1/USBM 2601

Quantitative Analysis of Diesel Particulate Matter in Respirable Coal Dust by Raman Spectroscopy

Johnson, J. H.; **Cornilsen**, B. C.; **Carlson**, D. H.

The engineering control of airborne particulate to which a miner is exposed in a diesel underground coal mine requires that the diesel particulate fraction be measured accurately. In mines throughout the U.S., respirable coal dust samples are presently collected on filters and the airborne particulate concentration is calculated using the weight of material collected and volume of air sampled. While diesel particulate often makes up 50 % or more of the sample, there is no fully-proven quantitative measurement method which can distinguish the diesel and coal particulate on a filter.

Earlier Bureau of Mines sponsored research at Michigan Technological University had successfully demonstrated the ability of the Laser Raman Quantitative Analysis (LRQA) method to determine the fractions of diesel and coal particulate on filters prepared in the laboratory containing coal/diesel particulate mixtures.

The Laser Raman Quantitative Analysis (LRQA) method is emphasized in this research. Methods to collect and measure diesel-only and coal-only reference samples needed for quantitative LRQA were developed and have proven successful. Michigan Technological University and the University of Minnesota have cooperated to collect simultaneous samples. This initial comparison of composition measurements for samples collected and analyzed by the LRQA and size-selective methods shows reasonable agreement. The initial analysis of mine samples has shown that further refinements can increase precision and accuracy.

MTU2/USBM 2621

Improved Methods for Monitoring and Control of Diesel Particulate in an Underground Mine

Johnson, J. H.; **Cornilsen**, B. C.; **Carlson**, D. H.

The major thrust of this research, which began in Fiscal Year 87, is the engineering control of airborne particulate and gaseous pollutants to which a miner is exposed in a diesel underground coal mine. Pollutant concentrations must be accurately measured to control them. This research is directed at the development of both measurement and control techniques. The measurement methods under study were developed in earlier Bureau of Mines supported research at Michigan Technological University. The control technology under study is the Pyroban dry-type explosion-proof safety package (Dry System) and diesel particulate filter (DPF), which earlier Bureau of Mines sponsored and in-house research have found to be the most advanced of the diesel-vehicle controls under development.

At the present time, there is no fully-proven quantitative measurement method which distinguishes diesel from coal particulate. The Laser Raman Quantitative Analysis (LRQA) method is emphasized in this research. Earlier Bureau of Mines sponsored research at Michigan Technological University had successfully demonstrated this method on coal/diesel particulate mixtures prepared in the laboratory. The present research involves testing and refinement of the method on samples collected in a diesel underground coal mine. Methods to collect and measure diesel-only and coal-only reference samples needed for quantitative LRQA were developed in 1987 (see Project M101 report herein). Analyses of mine samples showed that further refinements could increase precision and accuracy. These refinements are being made and tested in the FY 88 research.

Michigan Technological University is cooperating with the Bureau of Mines Twin Cities Research Center (TCRC), the University of Minnesota (UM), and the Colorado Mining Association in the current evaluation of the Dry System/DPF. The safety, durability, and effectiveness of the system is being tested on a diesel-powered haulage vehicle in an underground production coal mine. Baseline test data were recently collected (August 88), with the Dry System/DPF tests scheduled in February 1989. A more extensive comparison of airborne coal and diesel particulate measurements is being made between the LRQA and size-selective methods.

3.4
Dilution, Dispersion and Collection in Mine Airways

DILUTION, DISPERSION AND COLLECTION IN MINE AIRWAYS

The U.S. Bureau of Mines research has shown that only a small fraction of the respirable dust produced at the face becomes airborne. Experimental determinations have placed the amount of non-airborne respirable dust as ranging from 100 to 1,000 times that of airborne dust. There are several fundamental and applied studies in this area to understand more fully the role of mine ventilation and dust control practices in respirable dust control and its relationship to dust particle characteristics. The depositional characteristics of dust particles in mine airways and the velocities at which these deposited dusts may become airborne need to be studied. These studies are important for the design of equipment and the development of operating practices to remove dust from the worker zone or the worker from the dust zone and must include theoretical, laboratory, and field components.

Investigations have encompassed both experimental and theoretical research into the behavior of dust in mine airways. Experiments were performed in mine airways under both controlled and normal operating conditions. On the theoretical front, a convection-diffusion model of the dust flow phenomenon in mine airways has been developed considering dominant mechanisms affecting dust transport and deposition in mine airways. Mechanisms modeled include turbulent and gravitational deposition, coagulation, and dispersion. Comparative analyses of results of the controlled experiments with the predictions of the mathematical model were carried out. In addition to the overall validity, the adequacy of the individual components of the model, such as deposition in the total and respirable range, and dispersion were examined in light of the experimental observations. Potential applications of the model include prediction of ambient dust concentrations and depositions in straight sections of airways. This can be helpful in designing mine ventilation systems and estimating rock dusting requirements. The impact of multiple dust sources can be studied using the superimposition concepts.

The objective of several studies is to contribute to a better understanding of longwall ventilation schemes with particular reference to respirable dust concentrations along longwall faces. One research project has developed longwall dust distribution maps from extensive underground experiments. In another project, the research includes experimental design and underground experiments in both operating longwall faces and the Lake Lynn Laboratory Mine of U.S. Bureau of Mines, development of a mathematical and computer model for describing and predicting airborne dust concentration in longwall face, and comparative analysis of the computer model outputs and experimental results. The moving dust generation source makes the longwall dust problem unique and complex. Therefore, time study data of cutting activities in longwall face become extremely important when interpreting RAM-1 respirable dust data.

The mine ventilation system design is an engineering design problem involving not only numerical calculations to solve the pressure/quantity relationships, but also requires substantial judgement and expertise to analyze a specific problem situation and interpret the results of an algorithmic program. Therefore one of the Dust Center's projects has the objective to develop a knowledge based expert system for aiding the planning and design of mine ventilation systems considering the problems of respirable dust.

Respirable Dust Dilution, Transport, and Deposition

PS2	WV2	MN2	PS7	WV11	PS13
Ambient Dust	Experimental Dispersion	Aerodynamic Diameter	Longwall Modeling	Mathematical Models	Expert System

Figure 14: Individual Dust Center projects in the Respirable Dust Dilution, Transport, and Deposition Area.

DUST DILUTION, TRANSPORT AND DEPOSITION

PS2/USBM 4202

Prediction of Ambient Dust Concentration in Mine Atmospheres

Ramani, R. V. and Shankar, S.

The major thrust of this project is directed towards a better understanding of the behavior of airborne dust particles in underground mine airways. Research into the spatial and temporal behavior of airborne coal dust has been assigned high priority for further reduction in airborne dust in mines by a Committee of the National Academy of Sciences.

This project encompassed both experimental and theoretical research into the behavior of dust in mine airways. Experiments were performed in mine airways under both controlled and normal operating conditions. The controlled experiments included the documentation of the concentration and deposition patterns for two types of dust under three different velocities. Real-time dust concentration data were obtained using Real-time Aerosol Monitors (RAM-1). On the theoretical front, a convection-diffusion model of the dust flow phenonmenon in mine airways was developed considering dominant mechanisms affecting dust transport and deposition in mine airways. Mechanisms modeled include turbulent and gravitational deposition, coagulation, and dispersion. Comparative analyses of results of the controlled experiments with the predictions of the mathematical model were carried out. In addition to the overall validity, the adequacy of the individual components of the model, such as deposition in the total and respirable range, and dispersion were examined in light of the experimental observations.

The experimental data from controlled experiments compared more favorably with model predicted results for similar conditions as opposed to the comparative analysis results for in-mine experiments. Specifically, the model predictions for an 800-meter stretch of a mine airway reveal some significant differences from the behavior noticed in the mine. The deposition was lower than that predicted by the model. Consequently, concentrations were higher than those predicted by the model. The comparative analyses have shown that, in general, the floor deposition part of the model is better correlated with experimental data, while the ambient concentration is better predicted at lower flow velocities.

Potential applications of the model include prediction of ambient dust concentrations and depositions in straight sections of airways. This can be helpful in designing mine ventilation systems and estimating rock dusting requirements. The impact of multiple dust sources can be studied using the superimposition concepts.

This research indicates that there are areas that need additional experimental and modeling studies. For example, experimental results at the first few stations may be subject to error due to inadequate mixing at the source. However, the divergence between the experimental and modeled respirable concentration data at distances further from the source may be due to some phenomena which may not have been incorporated in the model. Clearly, the respirable portion of the model needs critical examination, especially at higher flow velocities.

PS7/USBM 4206

Computer Modeling of Longwall Face Ventilation

Ramani, R. V. and Qin, J.

The major objective of this project is to contribute to a better understanding of longwall ventilation schemes with particular reference to dust concentrations along longwall faces. The coal production from longwall faces is projected to increase significantly in coming years. At the present time, control of the concentration of airborne coal dust in longwall faces to below the specified maximum has not been completely achieved.

This project consists of literature survey on longwall face ventilation schemes and dust concentration models, experimental design and underground experiments in both operating longwall faces and the Lake Lynn Laboratory Mine of U.S. Bureau of Mines, development of a mathematical and computer model for describing and predicting airborne dust concentration in longwall face, and comparative analysis of model outputs and experiment results. Gravimetric total and respirable dust samples were collected in three sets of preliminary experiments in fully operational longwall faces. These samples provide average total and respirable airborne dust concentrations along longwall face. The instantaneous respirable airborne dust concentrations were recorded using real-time aerosol monitors (RAM-1). Moving dust source makes the longwall dust problem unique and complex. Therefore, time study data of cutting activities in longwall face are extremely important when interpreting RAM-1 data.

The experimental results obtained so far show that the cumulative effect on dust level along longwall face is more significant when the shearer is cutting in the direction of air flow that when it is cutting against air flow. Although the major dust source is shearer, the effect of secondary dust sources, such as, from movement of shields and falls of roof, are noticeable in RAM-1 outputs.

A model is in the process of being developed. The controlled mine experiments are scheduled to be performed this summer (1988). Potential applications of the model include description and prediction of dust concentration distributions along longwall face as a function of time and average dust concentrations in different places in the longwall face.

PS13/USBM 4221

A Knowledge Based Expert System for Planning Mine Ventilation Systems

Ramani, R. V.; Prasad, K. V. K. and Swaminathan, M.

The objective of the research in this project is to develop a knowledge based expert system for aiding the planning of mine ventilation systems. This system focuses on mine ventilation system design from a coal mine dust control standpoint. It is recognized that mine ventilation system design is an engineering problem involving not only rote numerical calculations to solve the pressure quantity problem but also substantial judgement and expertise to analyze a problem situation and interpret the results of an algorithmic program. The thrust of this project is to i) extract this knowledge from public domain sources and recognized experts in industry, government and academia, ii) represent this knowledge in the form of IF...THEN rules in an expert system (ES) and iii) interface the developed expert system with a mine ventilation network analysis program viz. PSUMVS (Pennsylvania State University Mine Ventilation Simulator). By providing the numerical computing and qualitative reasoning aspects of mine ventilation system design in a single integrated system, better quality decision support will be made available to apprentice users.

This project was started on October 1, 1987 and consists of three one year phases. The first two phases are shell evaluation and expert system development phases and the third one is a demonstration phase. The work in Phase I includes the selection of an appropriate ES shell for the knowledge based system development and the development of input/output interfaces to PSUMVS. The selection the ES shell is an important task in this phase and several commercial shell vendors have been contacted and the respondents products evaluated. Since the objective is to develop a system which would interface with the numerical aspects of mine ventilation system design, only shells which allow calls to external algorithmic programs are being considered. Further, since the portability of the developed system is important for technology transfer, a PC version of PSUMVS is being used for input/output interface development and only PC based shells are being considered.

Phase II of the project is the knowledge acquisition and representation phase. In this phase, in addition to information in the public domain literature, interviews with selected experts in industry, government and academia will be conducted to acquire the relevant rules of judgement which are used in mine ventilation system design. This phase will also involve the acquisition of the information and knowledge being generated by other projects in the Dust Center relating to dust generation, flow and characterization. The ES shell selected in Phase I will be used to code in the obtained information. The final phase of this project will involve a demonstration of the developed system to users in industry and government with a view to evaluate the system and modify it, if necessary.

Successful completion of this three phase work will result in a useful decision support tool for people involved in mine ventilation system design and will bring the expertise of recognized experts in the field to bear on the proper analysis, interpretation and solution of ventilation problems.

WV11/USBM 5410

Development of Mine Dust Distribution Models For Working Faces

Wang, Y. J.; **Chiang**, H. S.; Tsang, P. and Ueng, H. S.

The objective of this study is to develop a mathematical model for airborne dust distribution at longwall working face, integrating the results of field measurements.

The project involves with the following: (1) field instrumentation for airborne dust concentration, size distribution, and airflow distribution in the longwall face area; (2) development of a mathematical model for predicting airborne dust distribution, based on the characteristics of dust sources, airflow distribution, and mining conditions; and (3) model validation.

The field measurements were carried out in five longwall faces, with airborne dust samples collected through RAM-1 and gravimetric samplers. An analysis of the data for two longwall faces indicated that about one-third of the dust samples exceeded the 2 mg/m^3 limit. The curves for dust size distribution along the face skewed to the fine dust range. The portion of fine dust (under 5 microns) was generally more than 70%. An average velocity profile function was obtained for each working face. In general, the air velocity varied with the movements of shearer and support as well as water spray.

In order to develop a computer model for determining the dust distribution in the working area, an explicit form of finite-difference equations for turbulence dispersion of incompressible flow were derived. Based on these equations, a FORTRAN 77 coding for predicting the dust concentration was developed and tested. Since the velocity profile function obtained from the field measurements was one dimensional, the numerical results were not very satisfactory. More effort, therefore, has been made in solving the air velocity and pressure distributions assuming an isothermal incompressible turbulent flow and considering the working-face geometry.

MN2/USBM 2702

Experimental and Theoretical Aerodynamic Diameter Analysis of Coal Dust

Marple, V. A.; **Rubow**, K. L.; Zhang, X. and Ananth, G.

A 3-dimensional numerical model for determining the equivalent aerodynamic diameter of irregular shaped particles has been developed and used to analyze coal dust particles. Furthermore, a particle shadowing technique has been developed for the 3-dimensional shape analysis. Knowledge of the aerodynamic diameter of a particle is importance since this parameter determines the point of deposition in the human respiratory tract. The numerical work is an extremely strong analytical tool while the shadowing technique is an experimental tool for 3-dimensional shape analysis of particles.

This project has led to important advances in several areas of the studies of particles. First, a theoretical technique has been developed by which the aerodynamic diameter of any regular or irregular shaped particle can be determined as a function of the particle's orientation or as an average over all particle orientations. The equivalent aerodynamic diameter of the particle is numerically determined from computation of the fluid drag on the particle.

Secondly, a technique has been developed for examining irregular shaped particles with an scanning electron microscope after the particles have been shadowed in two orthogonal directions. In the course of this development, it has been found that inspecting particles with an SEM or optical microscope, where only one 2-dimensional view of the particle can be observed, can lead to drastically erroneous conclusions about the particle size and shape. A far more detailed view of the particle is obtained by looking at the shadows of the particle as well as the plane view of the particle. A micrograph of a shadowed coal dust particles is showed in Figure 2. Note the projection protruding out of the top of the particle on the left side of the photograph. This projection would not be observable without the shadowing.

Thirdly, the 3-dimensional modeling technique has been developed to a point where the aerodynamic diameter of an irregular shaped coal dust particle can be numerically determined. The shape and physical size of the particle are determined from SEM analysis of particles that have been shadowed in two orthogonal directions. As an example, the aerodynamic diameter of several coal dust particle have been numerically determined to be within 5% of the experimentally measured values.

st

3.5
Control of Dust Particle Generation

CONTROL OF DUST PARTICLE GENERATION

In any fragmentation process, particles will be produced in all size ranges below a top size. Fragmentation in underground mines occurs as a result of many processes: impact, crushing, grinding, blasting, etc. There has been a considerable body of literature developed that describes the results of research on respirable dust production by coal cutting machines (continuous miners/shearers, etc.). The influence of factors such as depth of cut, pick design, pick lacing, and cutting speed have been studied extensively both in the U.K. and the U.S.A. In reviewing these results, the National Academy of Sciences study found many disparities and recommended that studies on these factors be undertaken with the objective of understanding the fragmentation process and its relationship to respirable dust particle generation and characterization. Research on coal fragmentation and dust particle generation is vitally important to both fully understand the generation and entrainment of respirable dust and to develop control measures to reduce dust generation in the mine or the mill.

The main objective of the Dust Center's research is to identify the mechanisms of control of respirable dust generation in coal mines. In one project, fracture toughness tests were conducted, and fracture propagation velocity were discussed. Full understanding of the mechanics of crack propagation in coal is of fundamental importance in studies of the generation and control of respirable dust. Other respirable dust generation investigations involve three major areas: (l) indentation tests, (2) rotary coal cutting tests and (3) an analytical study to examine the dust effects of plunging a tool into a coal block.

Parametric study suggests that by applying optimum energy by a sharper tip angled bit which has a narrow and smooth configuration, coal can be cut efficiently and respirable dust can be reduced significantly.

A rotary coal cutting device was fabricated and instrumented to monitor and vary the simulated mining machine operating parameters and in-situ conditions. Parametric experimental studies were conducted and a statistical model was developed to predict the force requirements, specific energy and size distribution. It was concluded that efficient coal fragmentation and reduce respirable dust generation can be achieved by limiting the degree of bit-coal interaction by choosing the optimum machine operating parameter predicted by the statistical model for seam specific in-situ conditions.

Investigations of the fundamental bit-coal interaction which is believed to be the major source of respirable dust generation resulted in the conclusion that research on secondary dust generation was also necessary. Therefore, the subject of regrinding is the focus of one research project. Modification of the test facilities to carry out the necessary experiments has been completed.

Control of Dust and Particulate Matter Generation

PS1	WV1	WV15
Fracture Mechanics	Dust Generation	Regrinding

Figure 15: Individual Dust Center projects in the Control of Dust and Particluate Matter Generation Area.

CONTROL OF DUST GENERATION

PS1/USBM 4201

A Fracture Mechanics Study of Crack Propagation Mechanism in Coal

Bieniawski, Z. T. and Zipf, Jr., R. Karl

Direct costs of dust induced illnesses from coal mining exceed $1 billion per year, yet fundamental mechanical knowledge of particle generation is meager. This research utilizes fracture mechanics theory, experiment and application to explain how fine coal fragments (respirable dust) are generated during coal cutting.

The following four step mechanism is proposed: 1) development of a crush zone, 2) macrocrack propagation, 3) shear movement along macrocracks and 4) additional fragmentation from shear. The cutting tool interacts with coal material and its inherent flaw structure producing fine coal fragments near the tool grading into coarser fragments further away. Two fine fragment sources exist: the crush zone and the rough fracture surfaces. Fine particle creation is controlled in part by fracture toughness and also the inherent flaw geometry. Basic relationships are developed between the flaw geometry and fine fragment generation.

Experimentation centers on extensive mixed mode fracture toughness testing. The system developed herein provides a record 117 measurements concluding that K_{Ic} is a reliable material property despite coals' enormous heterogeneity. Strain energy density theory adequately describes the onset and direction of crack growth under mixed mode loading conditions. Tentative relations exist between K_{Ic} and fracture surface roughness and fracture velocity.

Fracture toughness values are applied in crush zone size calculations with a boundary element program containing a failure criteria based on strain energy density theory. From postulates about the role of inherent flaws in fragmentation, the crushing extent is the locus of active 10 micron flaws. The calculations demonstrate the effect of attack angle and tool geometry on crushing extent and fine fragment formation. Future research must measure the fracture toughness of coal constituents at a microscopic scale and quantitatively describe their inherent flaw structure.

WV1/USBM 5401

An Experimental and Analytical Approach to Study the Mechanisms of Respirable Dust Generation and Entrainment

Khair, A. W.; **Siriwardane**, H. J.; Reddy, N. P.; Jung, S. S.; and Begley, R. D.

The main objective of this project was to identify the mechanisms of respirable dust generation in underground coal mines. The study involves three major areas: (1) indentation tests, (2) rotary coal cutting tests and (3) an analytical study to examine the effects of plunging a tool into a coal block.

In the first part both quasi-static and dynamic indentation tests were conducted. From the quasi-static tests on rock and coal, it was found that failure of the specimen at zero and low confining pressures was in extension mode. But at high confining pressures the failure mode changed to tension and shear for rock while it remained the same for coal. However, failure of coal specimen preceded with a high degree of crushing as the confining pressure and wedge angle increased. This crush zone is a major source of respirable dust. In the dynamic tests the distribution of energy in the crush zone of a laterally confined specimen was studied. Parametric study suggests that applying optimum energy by a sharper tip angled bit which has a narrow and smooth configuration, coal can be cut efficiently and respirable dust can be reduced significantly.

The rotary coal cutting involved development of the laboratory facilities which includes the design and fabrication of an automated rotary coal cutting simulator. The simulator was instrumented to monitor and vary the machine operating parameters and in-situ conditions. Parametric experimental studies were conducted and a relationship was established between the size distribution and the fracture surface for bit type, bit spacing, depth of cut, equivalent in-situ confining pressures and cleat orientation. A statistical model was developed to predict the force requirements, specific energy and size distribution. It was concluded that the key to achieve efficient coal fragmentation and reduce respirable dust generation is to limit the degree of bit-coal interaction by chosing the optimum machine operating parameters predicted by the statistical model for site specific in-situ conditions.

The bit-coal interaction which is the major source of respirable dust generation is better understood today than before this research was carried out. However, to reduce the respirable dust in the mine environment research on secondary dust generation was necessary. Therefore, for the past year, this subject has been the focus of the research. Modification of the test facilities to carry out the necessary experiments has been completed.

The analytical study involved two stages. They are: 1) to examine the damage effects of plunging a tool into a coal block and 2) to characterize the damage zone in a coal block around a tool bit due to rotary cutting. In the first stage a parametric study was conducted by dropping different tools from different heights and weights. In the second stage the damage zone was characterized with a single bit configuration using different values of, attack angles, and depths of penetration and normal and tangential loads on the tool under plane strain conditions. Results indicated that the volume of damage zone increased in a nonlinear manner as the ratio of the loads was increased from 0 to 10. However, the increase in damage volume corresponding to an increase in the ratio of the loads from 3 to 10 was only about 20 percent.

WV15/USBM 5421

Correlation of Dust Due to Regrinding at the Face

Khair, A. W.; Reddy, N. P. and Xu, D.

The main objective of the proposed research is to quantify the magnitude of dust produced per unit volume of coal cut due to regrinding. Project objectives for the 1987-88 year were to design and fabricate a coal cutting chain saw, to design and fabricate the necessary modifications on the Automated Rotary Coal Cutting Simulator (ARCCS) to suit the testing procedures for secondary dust generation experiments, to establish the experimental procedures for simulating regrinding conditions in the laboratory, to develop an analytical model, and to conduct preliminary experiments on regrinding.

The design and fabrication of a hydraulically powered chain saw has been completed. This saw is being used to obtain large coal blocks from the mines. Also four containers were fabricated to retrieve coal from the face after cutting and to transport it without any damage. The design and modifications on the ARCCS include (a) change in bit spacing from 1.5 in. to 0.5 in. and increase in the number of bits from 7 to 22, (b) a cowl to hold a coal block at the bottom of the existing confining chamber in order to simulate the downward movement of the cutting head, (c) a hopper like feeder with variable speed to feed a predetermined size of coal on the entire width of the drum in order to simulate the coal/coal impact and the drum and/or coal face impact which are the two major mechanisms for dust generation due to regrinding and (d) an enclosure to prevent the coal fragments and dust from escaping during cutting. All the modifications were completed on schedule.

In order to analyze the effects of the multiple factors involved in the secondary regrinding experiments, the most suitable experimental designs were investigated. The orthogonal fractional factorial design, which not only enables the experimentor to determine the effects of the multiple factors involved but will also enable the experimentor to determine their interactions with each other, is being used. With this design the experimental error can be determined and the confidence limits can be placed on the results.

Preliminary experiments to establish the experimental procedures and calibrate the measuring instruments are being conducted on Waynesburg coal at the present time. Coal blocks from Pittsburgh seam have been obtained and samples are being prepared for testing the physical and mechanical properties and conducting the regrinding tests. A more detailed description of all the above mentioned segments of this research is given in the project detail.

4
Dust Center Project Reports

4.1 Interaction of Dust and Lung

4.2 Dust Particle Characterization

4.3 Mine Workers, Mining System and Seam Geology Dust Relationships

4.4 Dust Dilution, Transport and Deposition

4.5 Control of Dust Generation

4.1
Interaction of Dust and Lungs

PS4/USBM 4204

Characterization of the Mechanism of Lung Injury

Bartlett, G. L.

INTRODUCTION

The major objective of our research is to help reduce the incidence and severity of coal worker's pneumoconiosis (CWP). To that end, this project is designed to improve our understanding of the processes that lead to pulmonary dysfunction following mine dust exposure, and how those processes might be interrupted or attenuated. The response of the lung to inhaled particles is complex, and the course of development of disabling CWP is slow and unpredictable. From among the numerous cellular and molecular interactions involved in the pulmonary response to inhaled particles, this project is focussed on the role that the pulmonary alveolar macrophage (PAM) may play in regulating the activity of fibroblasts.

The PAM is the lung cell that has the most immediate and the most obvious interaction with inhaled particles. Within a short period after particles are arrested in the alveolus of the lung, they are phagocytized (engulfed) by these specialized cells. The PAM then has a diverse potential repertoire of subsequent activities. Which reaction actually ensues is determined, in large part, by the nature of the phagocytized particles. Activated PAMs produce a variety of products that may affect adjacent lung tissue, including superoxide free radical, elastase, collagenase, prostaglandins, platelet activating factor, etc. Those may well be important in the pathogenesis of CWP, but they are beyond the scope of this project. Background information that is cogent to this project has come primarily from investigations using animal models of silicosis and asbestosis. PAMs that have ingested silica particles synthesize and release molecules that control the behavior of surrounding cells. One such mediator is interleukin-1 (IL-1), a molecule that plays a central role in many aspects of the response to injury. It can stimulate fibroblasts (the cells that help to hold tissues together) to release the enzyme collagenase, resulting in breakdown of the structural collagen fibers that support the lung tissue. IL-1 also stimulates fibroblasts to undergo mitosis and to proliferate, which is an initial stage of fibrosis. Certain stimulants cause PAMs to release fibroblast growth factors (FGFs) that are distinct from IL-1. Under other circumstances activated PAMs synthesize and release molecules that stimulate fibroblasts to accelerate synthesis of collagen fibers, thus contributing to fibrosis. Although these observations provide a valuable precedent for analysis of the mechanisms involved in CWP, their relevance to CWP cannot be assumed since most of those studies involved macrophages or fibroblasts obtained from tissues other than the lung, and because almost none of them have used CMD as the stimulating particles. Therefore, the goal of this project is to learn how exposure to CMD affects the behavior of PAMs, and in turn how products of dust-exposed PAMs affect fibroblasts and the process of fibrosis in the lung.

RATIONALE

One specific aim of this study is to test the hypothesis that exposure of PAMs to CMD will cause the PAMs to produce mediators that affect the behavior of lung fibroblasts. The first mediator of interest is IL-1, which in some systems stimulates fibroblast proliferation and also can stimulate production of collagenase by fibroblasts. A functionally related but distinct group of molecules, known as fibroblast growth factors (FGF), stimulate fibroblast proliferation but do not have other activities of IL-1. To test this portion of the hypothesis, culture media from dust-exposed PAMs are tested in bioassay for IL-1 activity and for FGF activity. A third class of mediators of interest includes products of PAMs that can stimulate the rate of collagen synthesis by fibroblasts.

A second specific aim of this project is to test the hypothesis that different CMD will induce different responses in PAMs. A suite of dusts has been developed by the Generic Technology Center for Respirable Dust (GTCRD), including specimens that represent a range of coal characteristics. Thus, the biological effects of these standardized coal dusts, of dusts collected in mines and of a group of noncoal mineral dusts are compared in the cellular bioassys.

The initial studies involved exposure of PAMs to dusts in vitro (in cell culture); collection of the "conditioned medium" (CM) after a period of incubation. Then the CM are added to a second (bioassay) culture, either of thymocytes (to test for IL-1) or of lung fibroblasts (to test for fibroblast growth activity or collagen synthesis stimulation). That approach provides optimal control over each component of the interaction and permits close observation of individual responses. A drawback of the in vitro exposure procedure is that normal PAMs cannot be maintained in cell culture for more than a few days, so the interaction is limited to the acute, short-term aspects of the dust-lung interaction, whereas CWP is clearly the result of chronic CMD exposure. Therefore, a later phase of the project is to study the responses of PAMs and lung fibroblasts after exposure in the living animal ("in vivo"), which permits exposures over longer periods of time. This may be done easily in our laboratory by intratracheal instillation of a dust suspension in anesthetized animals. In addition, it is now possible to have animals for this project exposed to dust aerosols in the inhalation chamber at the GTCRD laboratories in Morgantown. The aerosol/inhalation procedure is the most realistic means of exposing lung cells to dusts, but for a variety of reasons it is much less flexible than the instillation method (can only expose animals to one kind of dust at a time; requires much larger quantities of standardized dusts, etc), so the two methods are used in a complementary fashion.

SCOPE OF WORK

An initial task of this project was to select an experimental animal model for the dust-lung cell interactions. Previous studies of experimental pneumoconiosis (caused by other dusts) have commonly been done in laboratory rats, with fewer studies being performed in guinea pigs, hamsters or mice. We examined several strains of inbred rats and outbred guinea pigs, evaluating the ease and reliability of obtaining adequate numbers of PAMs and comparing the responses of the recovered cells to a standard stimulant. The stimulant for this purpose was tetradecanoyl phorbol acetate (TPA), and the measure of macrophage response was release of superoxide radical. PAMs from several strains of rats were unresponsive to TPA, while macrophages from other sites in the same animals, or macrophages from all sites in guinea pigs were responsive. In addition, the yield of PAMs from guinea pigs was substantially better and more consistent than that from rats. Therefore, guinea pigs have been used for the remainder of the experiments. (Since the guinea pigs are outbred, we do not pool the cells obtained from different animals, but we do pool the conditioned media produced by cells of different animals.)

In conjunction with the above studies, we also tested the superoxide response of guinea pig PAMs to a few of the standard dusts. Dusts MP3, 867 and 1192 all stimulated superoxide production by guinea pig PAMs, but the kinetics of the response were much slower than the response to the chemical stimulant, TPA.

When we initially prepared aqueous suspensions of coal dusts in cell culture medium, the dusts went into suspension very poorly, appearing to be very hydrophobic. The suspensions were incomplete and nonuniform, with both macroscopic and microscopic clumping of the coal particles. Particles and clumps adhered to the walls of the vessels (either glass or several kinds of plastic), and upon standing the suspensions were unstable, with clear settling of the particles and clumps to the bottom of the vessel. Based on prior experience preparing aqueous suspensions of hydrophobic bacterial cell walls for vaccine use, we used Tween 80 as a surfactant to suspend the dust in aqueous media. Because of the toxicity of low concentrations of Tween in bioassay mixtures, the optimal method for suspension was temporary suspension in 0.4% (w/v) Tween in medium, followed by washing and suspending the dust in Tween-free medium. The resultant suspensions were consistently uniform and stable. Several other methods of dust suspension not requiring surfactant were evaluated: Alkali wash, sonication, gamma-irradiation. None of those procedures produced uniform, unclumped, stable dust suspensions. Dusts are sterilized, to prevent bacterial contamination of cell cultures, by autoclaving prior to preparation of the suspensions. Dose ranging studies with several dusts revealed direct toxicity of dust suspensions for cultured cells at concentrations above 100 ug/ml. Therefore, all experiments have involved doses ranging down from that concentration, usually by ten-fold dilutions.

To test for IL-1 in CM of dust-exposed PAMs we have primarily used the mouse thymocyte comitogenesis assay, in which IL-1 present in test samples stimulates proliferation in mouse thymocytes that have been primed by exposure to substimulatory levels of phytohemagglutinin. In standardizing the assay, we found that cells from mice killed by lethal injection of sodium pentabarbital (a common method for euthanasia of laboratory animals) responded very poorly, while cells from comparable animals killed by cervical dislocation or by inhalation of carbon dioxide were highly responsive. Therefore, we use carbon dioxide inhalation to kill animals before recovering cells for the IL-1 assay. We have also been concerned about the possible instability of CM during freezer storage, due to the possible presence of proteases (protein destroying enzymes) in the culture supernatants. We have evaluated the use of protease inhibitors to stabilize CM during storage, but we found that when commercial IL-1 standards were stored in the inhibitors they became inactive in the IL-1 assay.

A series of experiments have tested dust-induced CM for IL-1 activity. Each experiment includes standard chemical stimulants as positive controls. In five experiments, CM induced by 867, 1192, 1361 and MP3 (2 experiments) were weakly to moderately active in the IL-1 assay. In two of those experiments, CM from unstimulated ("control") PAMs were equally active, raising doubt that the dusts in those experiments were responsible for the activation of the PAMs. In another experiment the results are questionable because the data suggested an inverse dose-response relationship (lower doses were more active than higher doses). The positive results in the other two cases were not reproducible in replicate experiments. Altogether, dust-induced CM were inactive in the IL-1 assay in thirteen different experiments. We conclude that under the conditions used for these studies the coal, mine and mineral dusts tested did not induce guinea pig PAMs to produce IL-1.

Assay for FGF activity involves addition of standards or test samples (CM) to cultures of normal guinea pig lung fibroblasts that are near confluence and that are growth-arrested by maintenance in low serum concentration (0.5%). CMs induced by six different dusts were totally inactive in that assay, although commercial preparations of FGF and IL-1 used as standards did stimulate growth, as did higher levels of serum in the medium. We conclude that under the conditions used for these studies the coal, mine and mineral dusts we have tested did not induce guinea pig PAMs to produce FGF-like mediators. In one pilot experiment, dust 867 that had not been heated for sterilization induced PAMs to produce FGF-like activity, while parallel samples of the same dust that had been sterilized by dry heat or by autoclaving induced no FGF activity.

As mentioned in the rationale, one aim of this project has been to study the response of PAMs exposed "chronically" to dust, rather than simply the response in the first 24 hours as described above. Efforts were made to extend the in vitro longevity of guinea pig PAMs. To do this, culture dishes were pretreated in several ways that are known to favor better culture survival of several other kinds of cells. The pretreatments included coating the culture dishes with collagen, with fibronectin, with poly-D-lysine, or with a feeder layer of irradiated cells. None of those procedures extended survival of the PAMs at all. Therefore, the only feasible approach to study chronic interactions is during and following exposure of PAMs in vivo in living animals.

Our primary means of in vivo exposure is by intratracheal instillation of dust suspensions in guinea pigs under general anesthesia. Conventional anesthetics used for laboratory animals tend to produce a moderately profound degree of respiratory suppression which cannot be tolerated by animals that receive material instilled intratracheally. With advice from the Department of Comparative Medicine at the Hershey Medical Center we have selected a unique anesthetic regimen: 11 mg/kg body wt of ketamine and 5 mg/kg body wt of xylazine, injected intraperitoneally. This produces rapid, short term anesthesia, sufficient to permit exposure of the trachea and instillation, followed by prompt recovery of consciousness and of full respiratory function. A dose-ranging study revealed that administration of 1 ml of suspension containing 100 ug of dust (the concentration used in cell culture studies) resulted in only 10% of recovered PAMs containing phagocytized dust particles. With a concentration of 1 mg/ml, administration of 1 ml usually produces 25-50% of dust-containing PAMs. PAMs recovered from animals that had received 1 mg of dust 867 had a higher baseline level of superoxide production than cells from saline exposed animals, but their response to chemical activation (TPA) was unchanged.

Results from other laboratories in the GTCRD have indicated that coal dusts produced by crushing possess elevated levels of free-radicals when they are first produced. The free radicals are detected by electron spin resonance spectroscopy. Such free-radical containing dusts have been termed "fresh" dusts. The free radicals decay over a period of hours to days, so that dusts that have been stored for periods of several days or longer ("stale" dusts) do not possess the free radicals. Because such free radicals may be important in the interaction between dust particles and lung constituents, we are establishing the capability to produce "fresh" dust in our own laboratory for use in our biological experiments. We have purchased a planetary ball mill for that purpose. Initial runs with the device revealed that the stainless steel grinding set (bowl and balls) were undergoing excessive wear during grinding, contributing stainless steel contaminants to the final dust product. Therefore, we have recently obtained a zirconium oxide grinding set.

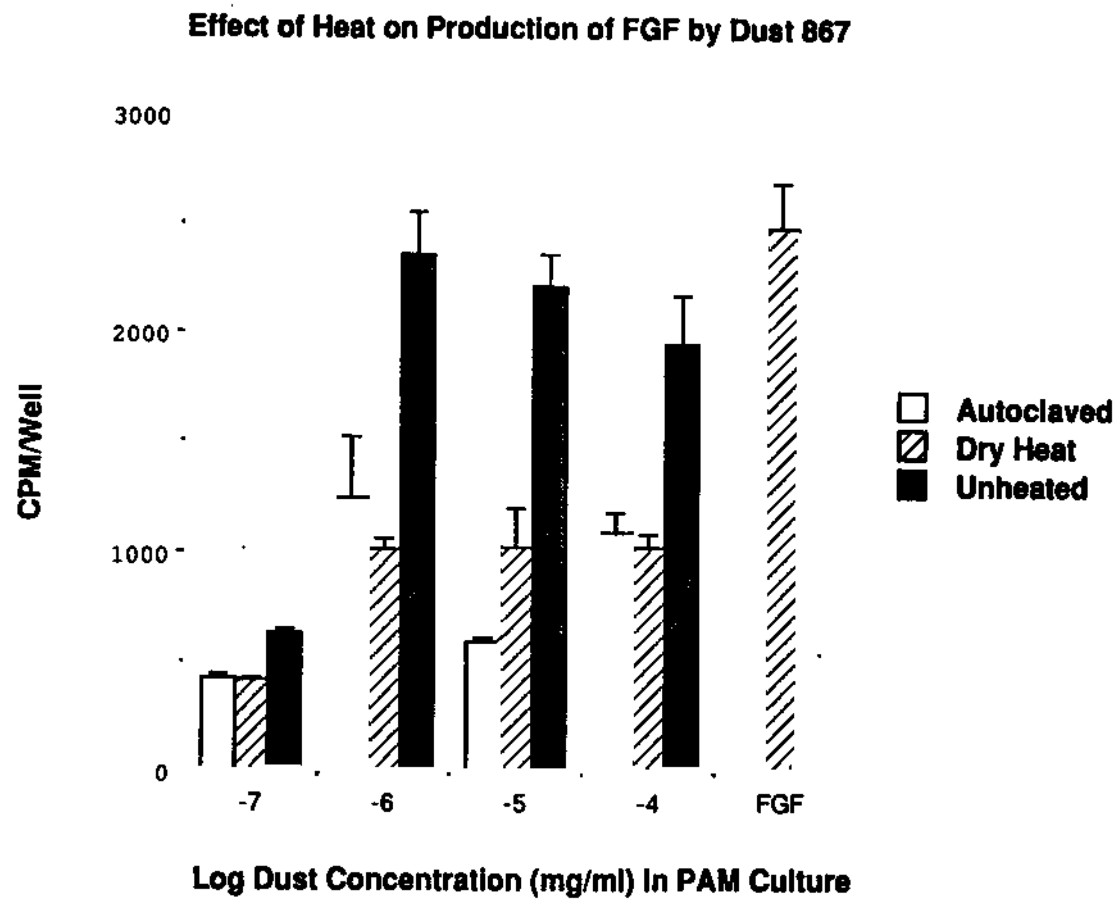


Figure 1. Dust 867 was sterilized either by autoclaving (120°, 15 psi, 20 min) or by dry heat (160°, 120 min), or was not heated. Dusts were added to cultures of guinea pig pulmonary alveolar macrophages (PAM) for 24 hours in concentrations ranging from 10^{-7} to 10^{-4} mg/ml. Supernatant media from the PAM cultures were collected and stored frozen. Presence of fibroblast growth factor (FGF) activity in the supernatant media was tested by adding the media to cultures of guinea pig lung fibroblasts that had been growth-arrested by high cell density and low serum concentrations; as positive control, commercial purified FGF was added to a set of fibroblast cultures. These bioassay cultures were labelled with ^3H - thymidine (1 uCi/ml) during the second 24 hours of culture as a measure of the numbers of proliferating cells (cells that incorporate label into DNA). Values shown represent the mean of triplicate cultures ± the standard error of the mean.

While awaiting the zircoinum grinding set, we have performed some pilot experiments with "fresh" dust produced in the stainless steel set. One experiment was our first attempt to observe the effects of longer dust exposure times in vivo on PAM function. Fresh or stale dust 867 , or saline only were instilled into guinea pigs, and their PAMs were collected 2, 5 or 8 days later. Neither dust suspension caused a difference in the numbers of PAMs recovered, compared to the saline controls. On days 2 & 5, there was no difference in the proportions of PAMs that had ingested dust particles. However, on day 8, approximately three times as many PAMs exposed to "fresh" dust had phagocytized particles compared to those exposed to "stale" dust (45% vs 16%).

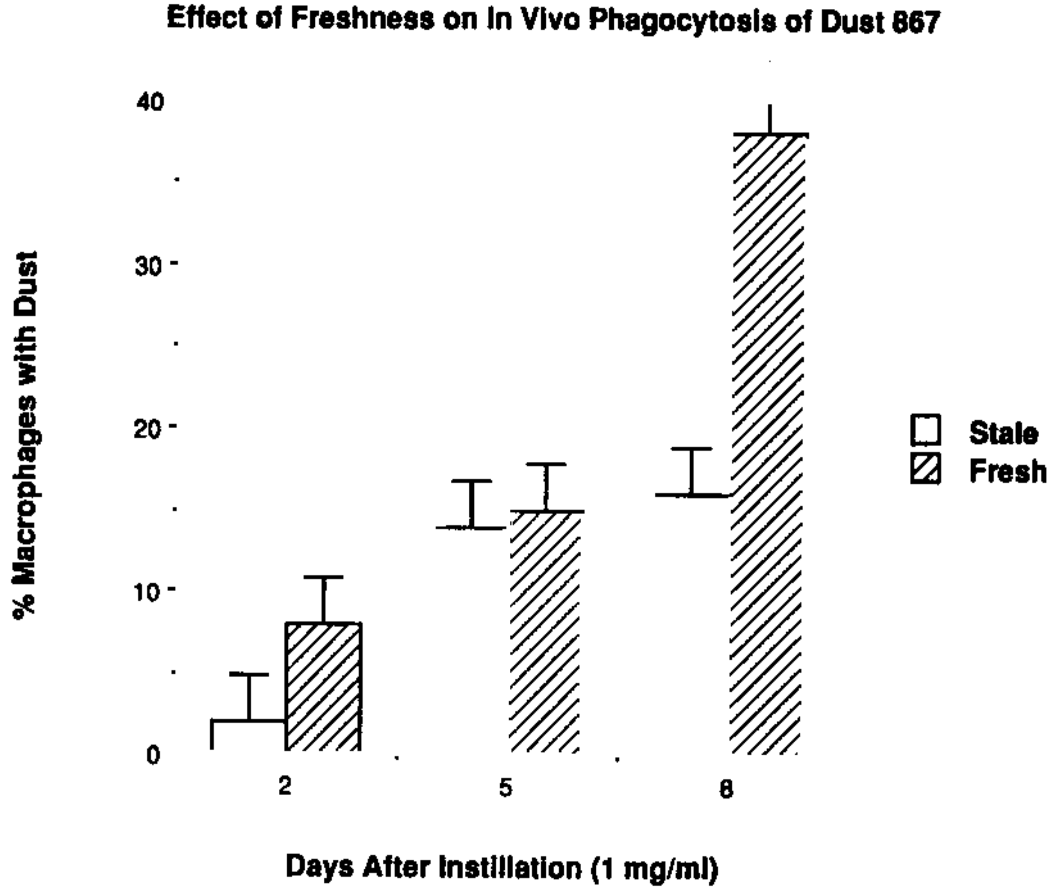


Figure 2. Dust 867 (anthracite) was prepared, characterized and distributed by the Generic Technology Center in 1984. "Fresh" dust was prepared by grinding dust 867 for 10 minutes in a stainless steel grinding bowl on a planetary micromill (Fritsch). "Stale" dust was from the stock vial, and had not been ground for three years. Dust suspensions were prepared in phosphate-buffered saline and were instilled intratracheally into guinea pigs under general anesthesia. Two, five or eight days later cells were recovered by bronchoalveolar lavage and the numbers of microphages containing phagocytized dust particles were counted (≥ 300 cells per sample). The spanners represent the standard error of the percent.

The bioassays for IL-1 and FGF activity both require use of fresh, "primary" cell cultures from laboratory animals. As a result, the assays are subject to interexperiment variability. We have begun to use, in parallel, an alternative bioassay for each activity. Each is based on the used of a permanent cell line that is maintained in cell culture under constant conditions, yielding greater consistency in the behavior of assays, greater flexibility in scheduling experiments and greater economy (using fewer animals). The IL-1 assay is based on the proliferative response of the astrocytoma (tumor cell) line U373 to IL1. A continuous line of diploid mouse fibroblasts, 3T3, is used to assay samples for fibroblast growth stimulation activity. Both of these can also be used to assay CM from other species, such as the nonhuman primates being studied in a companion project.

CONCLUSIONS

Guinea pigs are the best animal for this study of dust-lung interactions because rat PAMs are unresponsive to some standard stimulants and because guinea pigs yield greater numbers of PAMs. Coal dusts stimulate release of superoxide from guinea pig PAMs, but the response is slower than that caused by the chemical stimulant, TPA. The use of continuous cell lines (U373 and 3T3) for bioassays offers several advantages over the assays based on primary cells collected from animals.

Under the conditions tested thus far, coal dusts do not activate guinea pig PAMs to release either IL-1 or FGF-like activity. There are several possible explanations for the lace of response to dusts. Almost all of the dusts tested thus far were samples provided by the GTCRD, and had been stored in vials for weeks to months before testing. They would all be considered "stale" dusts, so the conclusion does not apply to free-radical containing, "fresh" dusts such as would be encountered in the mining environment. Most of the experiments completed thus far tested dusts that had been autoclaved (sterilized under high temperature and pressure) to prevent bacterial contamination. It is possible that those conditions altered reactive constituents of the dusts, so the conclusion does not apply to native, untreated dusts. The coal dusts we have had available for testing have recently been found to possess a minor coating of oil from the milling process, so the conclusion does not apply to oil-free dusts. Each of these conditions is being investigated as part of the continuing work currently underway (see below).

APPLICATIONS OF RESEARCH RESULTS

There are several potential benefits from a better understanding of the cellular and molecular interactions that lead to CWP. For instance, if we understood the process in detail it might be possible to devise simple, noninvasive tests ("screening tests") that could (1) detect the earliest stages of CWP long before symptoms of pulmonary dysfunction become evident, (2) accurately define the rate of disease progression or the onset of progressive massive fibrosis (PMF), or (3) identify persons who are at special risk of progression to PMF. Likewise, a test that could reliably distinguish between hazardous dusts and benign dusts would be helpful in tailoring levels of exposure commensurate with the level of risk. It would also be desirable to have treatments that could promote clearance of inhaled particles or that could diminish the fibrotic response to pulmonary deposits of inhaled dusts. The realization of any of these very useful applications will depend on more detailed and specific information about the responses of PAMs and lung fibroblasts to CMD.

CONTINUING WORK

Work is underway to test dust samples that are more nearly representative of dusts that would be encountered in the mine atmosphere. Equipment has been purchased to produce "fresh", free-radical containing dusts in the laboratory for these bioassays. We have begun to evaluate preparation of dusts without the necessity for heat sterilization. Experiments are planned to remove surface oil from dust samples by washing in dichloromethane prior to testing, and we expect to receive oil-free, standardized dust samples from the GTCRD in the near future. Each of these characteristics must be evaluated before drawing final conclusions about the response of PAMs to these dust preparations.

In order to evaluate the effects of chronic dust exposure on the responses of PAMs and lung fibroblasts, current experiments involve intratracheal instillation of dusts and examination of the recovered PAMs at different times after exposure. We also plan to examine cells from guinea pigs exposed to dusts by inhalation in the facility at Morgantown.

The molecular biology process of in situ hybridization will be used to detect specific messenger RNA molecules in cells of dust-exposed lungs. This will improve sensitivity, specificity and consistency of experiments, and will permit evaluation of a much larger number of cellular mediators than is possible using cellular bioassays.

Using the refinements described in the previous paragraphs, we plan to test the following hypotheses: (1) The nature of the surfactant coating dust particles affects the response of PAMs to the dust (comparing Tween, other chemical surfactants, biological (pulmonary) surfactant and no surfactant); (2) Particle size affects the nature of the response of PAMs to dusts (comparing dust 1-5 um in diameter to the same dust that is <1 um diameter).

TECHNOLOGY TRANSFER

Technology from this project are not yet at a state for either clinical or industrial application.

INTERACTIONS

Pursuit of this project as part of the multi-institutional GTCRD has promoted a wide diversity of interdisciplinary interactions with other investigators that would not have been possible if the project were funded under other, more traditional mechanisms. We have met several times per annum with other staff of the GTCRD, and with personnel from NIOSH and BOM, in both small and large group settings, both formal and informal. These interactions have certainly benefitted this project, and we hope that we have made useful contributions to other investigators. Specific benefits of these interactions have included:

1. Availability of a suite of characterized, standardized dusts (R. Hogg, T. Dumm, et al.)
2. Information concerning presence of free radicals in "fresh" dusts (N. Dalal)
3. Procedure for in-lab, small-scale production of "fresh" dust (V. Vallyathan)

4. Guidance in preparing dust suspensions for bioassays, and discussions concerning PAM longevity in vitro (W. Wallace).
5. Discussion and advice concerning alternatives to Tween for dust suspension (S. Chander).
6. Discussions concerning importance of trace elements, role of dimethyl sulfoxide and value of aluminum therapy (J. Mutmansky).

PS10/USBM 4209

Alveolar Macrophage and Polymorphonuclear Leukocytes in the Dust/Lung Interaction

Demers, L. M.

INTRODUCTION

The objective of this project is to provide a scientific basis for the development of practical approaches to the reduction of the incidence and severity of coal workers pneumoconiosis (CWP). The focus of our research is to study the effect of coal dust exposure on the metabolism of arachidonic acid (AA) in the pulmonary alveolar macrophage (AM). Our studies are designed 1) to develop valid laboratory techniques for the study of AA metabolism in the AM, 2) to characterize the alterations in AA metabolism in AM exposed to coal dusts *in vitro* and *in vivo*, 3) to determine if alterations in AA metabolism may be involved in the pathology of CWP and 4) to explore the possibility that pharmacological interventions which "normalize" AA metabolism in dust-exposed AM may be of therapeutic value.

The AM is the major defensive cell of the lung. AM are activated by foreign particles and microorganisms which enter the small airways (1,2). This defensive reaction involves phagocytosis, liposomal enzyme release and the generation of reactive oxygen species by the AM (3,4). A number of agents, including phorbol esters, zymosan, adenosine diphosphate, organic hydroperoxides and calcium ionophore have been shown to activate the AM *in vitro* (4,5,6). The AM response to these activators appears to be mediated in part by the oxygenated metabolites of arachidonic acid (AA, 7.8). Furthermore, the production of AA metabolites in lung tissue may help regulate both the initial response to invasion and the long-term sequelae in chronic lung disease.

The AM may metabolize AA through cyclooxygenase- and lipoxygenase-catalyzed pathways to produce a variety of eicosanoids including prostaglandin (PG) E_2, thromboxane (Tx) A_2, leukotriene (LT) B_4, LTC_4, LTD_4 and several hydroxyeicosatetraenoic acid derivatives (HETEs, 9,10,11). The production of these eicosanoids may enhance the defensive ability of the challenged lung since they stimulate chemotactic cell recruitment to the site of invasion, enhance extravasation of circulating immune cells and promote local vasodilatation. However, continued stimulation of the AM population, with the consequent production of pro-inflammatory eicosanoids, may ultimately enhance the disease process by contributing to chronic bronchoconstriction, fibrosis and the persistent release of toxic oxygen species.

It is important therefore to assess the effect of dust exposure on AA metabolism in AM not only because the AM may represent a key component in the physiological and biochemical response of the lung to inhalation of respirable coal dust particles but also because AA may play a crucial role in the immediate and long-term sequelae of both a compensatory defense response and the expression and consequences of chronic pulmonary disease.

RATIONALE

We have designed the studies in this project to test the hypothesis that the interaction of the AM with respirable coal dust alters AA metabolism in the AM in a manner which may contribute to both the short-term defensive mechanism of the lung and the eventual development of chronic disease. Furthermore, it is possible that specific pharmacologic interventions which either "normalize" AA metabolism in the dust-exposed AM or counteract the effects of the alterations may provide therapeutic value without compromising the lung's defensive capabilities.

Implicit in the development of a scientific basis for the determination of the role of AM-produced metabolites of AA in lung function is the characterization and use of valid *in vitro* methodology, advanced analytical techniques and characteristic animal models. Our initial experiments have therefore been designed to establish the most appropriate methodology on which to base our studies. Subsequently, we have determined that AA metabolism is indeed altered when AM are exposed to various types of coal dust both *in vitro* and *in vivo*. Furthermore, based on the known actions of individual metabolites in both the lungs and other biological systems, our results strongly suggest that the alterations in basal AA metabolism produced by exposure of AM to coal dust are consistent with a concerted reaction which enhances both the ability of the AM to defend the lung from particulate invasion and mount a more generalized immune response and the triggering of mechanisms which, if chronically stimulated, may eventually trigger responses which promote the pathophysiology characteristic of CWP. Finally, these studies have led us to initiate experiments to determine if the AM reaction can be controlled and, if so, can such intervention act to reduce the harmful effects of long-term dust exposure. In our approach to these studies we have sought and obtained the consultation and collaboration of other investigators in the Generic Technology Center inorder to maximize the value of this research. As such, we have coordinated the *in vivo* exposure of animals with Dr. Charles Stanley (WVU), modified *in vitro* dust exposure techniques with Dr. Gerald Bartlett (PSU), obtained AM from various species with Drs. Bill White and Carla Drozdowicz (PSU) and assessed the effect of free-radicals in dust with Dr. Dalal (WVU). We will continue to expand our collaborative efforts inorder to further the goals of this project.

SCOPE OF WORK

1. In vitro methodology. species differences. dust differences - Experiments have been conducted to assess the effect of culture medium containing phenol red on basal and stimulated AA metabolism in rat AM. These experiments are derived from those studies demonstrating a stimulatory

effect of phenolic compounds on AA metabolism by cyclooxygenase. The results of these studies showed that both coal dust and phenol red individually stimulate AA metabolism in AM and that together their effects are additive. As a result of these studies, phenol red has been eliminated from AM incubation medium.

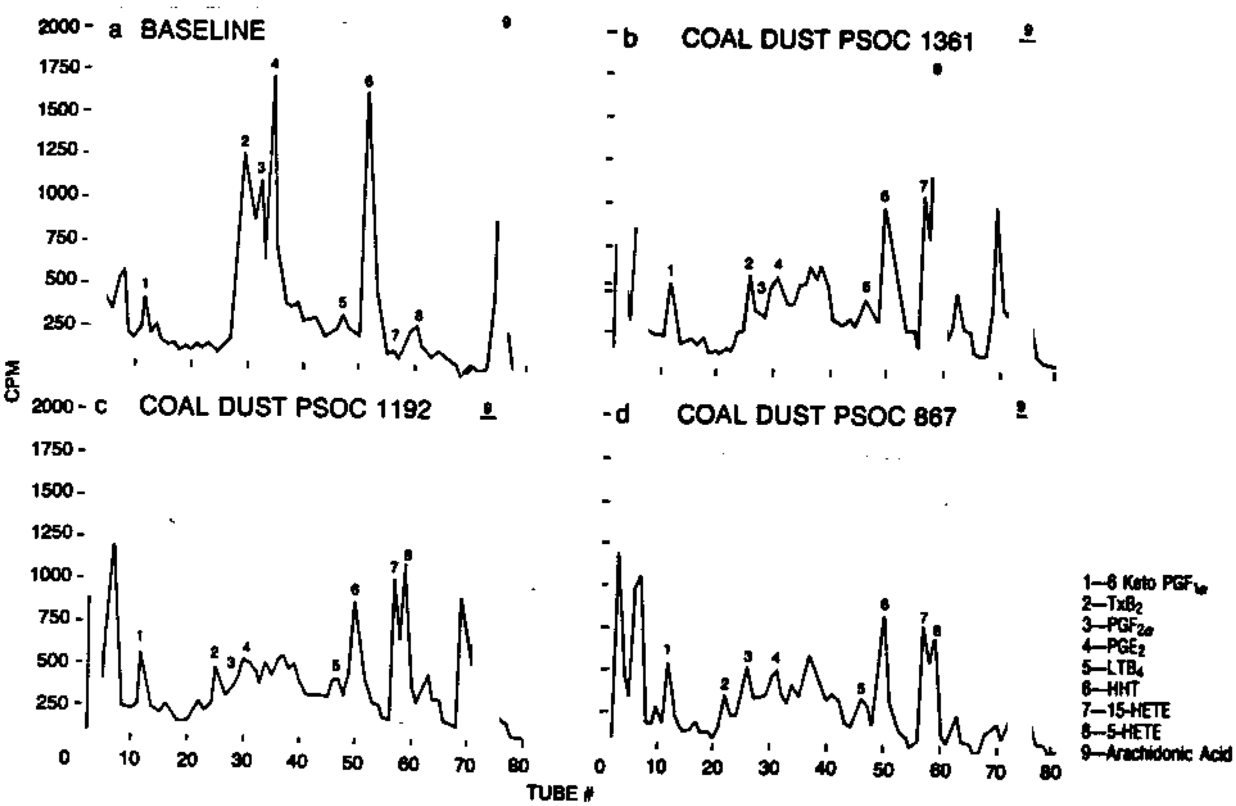


Figure 1. Effect of various coal dust preparatios on the metabolism of radiolabelled AA. a) No addition, b) Dust PSOC 1361, c) Dust PSOC 1192, d) Dust PSOC 867.

In further studies designed to determine the effects of different types of coal dust on AA metabolism in rat AM, radiolabelled AA was incubated with AM in the presence and absence of fixed concentrations of dust samples provided to us in respirable quality by the Department of Mineral Engineering, PSU. Following 4 hours of co-incubation, samples of medium were extracted and subjected to separation and identification of AA metabolites by high performance liquid chromatography (HPLC). As seen in Figure 1, AM conversion of AA to cyclooxygenase products, in particular PGE_2, was reduced by all dust preparations. However, conversion to lipoxygenase products such as the HETEs was enhanced. Qualitative differences in AA metabolism to lipoxygenase products were also apparent. For example, whereas dust 867 produced a 15 HETE- to 5-HETE ratio of 1:1, dust 1361 produced a greater increase in 5 HETE production.

In order to assess species differences in dust-elicited alterations in AA metabolism, AM were harvested from rats and guinea pigs and analyzed for the stable metabolite TxB_2. As seen in Figure 2, the guinea pig AM was not as reactive to MP3-3 dust as was the rat AM (note differences in Y-axis values). As a result of these studies, correlations between dust ranks and their effects on AA metabolism are currently being drawn from experiments with rat AM exposed to dust *in vitro* and *in vivo*. Further studies with more varied mine dusts are in progress.

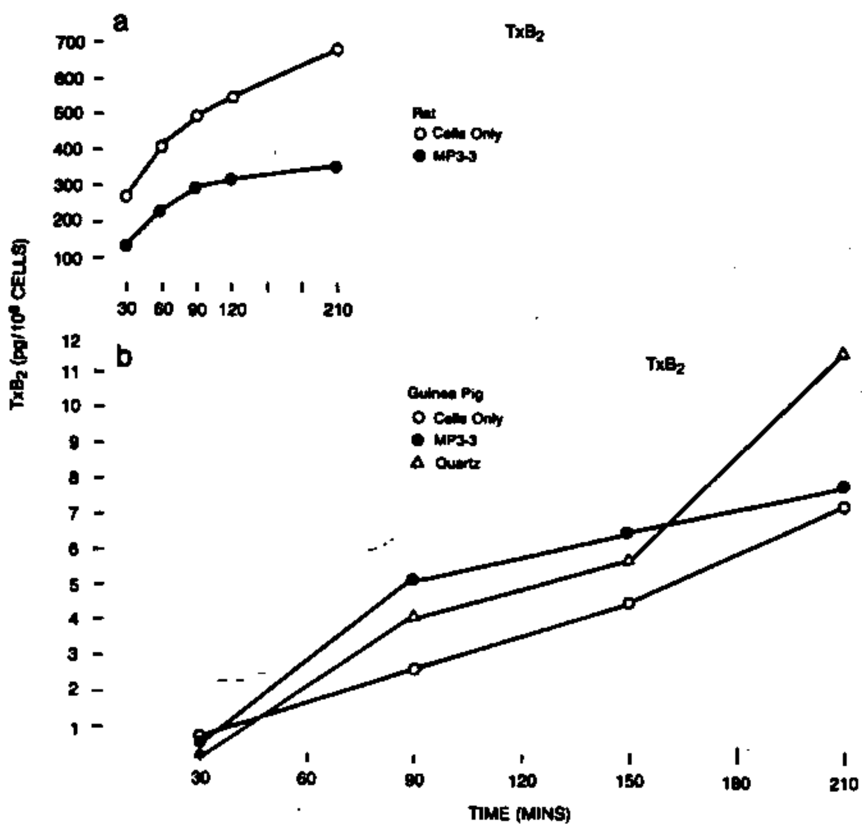


Figure 2. Time course of the release of TxB_2 by a) rat and b) guinea pig AM in the presence and absence of Dust MP3-3.

2. In vivo vs in vitro exposure of rat AM to coal dust - We have compared the alterations in AA metabolism produced by incubation of rat AM with dust particles *in vitro* with that seen in AM harvested from animals subjected to inhalation exposure to dust for two weeks at the WVU facility. In these studies, AM from control and dust-exposed (20-20 dust from PSU) animals were harvested and incubated with either radiolabelled or unlabelled AA for 4 hours. HPLC analysis of radiolabelled metabolites indicated a pattern of AA metabolism similar to that seen in *in vitro* exposure studies. That is, PGE_2 production is reduced while that of the lipoxygenase products LTB_4 and the HETEs is enhanced. However, while TxB_2 production was reduced in AM exposed to coal dust *in vitro*, *in vivo* exposure resulted in an increase in TxB_2 production.

These results were confirmed quantitatively by RIA of media from AM incubated with unlabelled AA. As seen in Figure 3, *in vivo* exposure of rat AM to respirable coal dust significantly altered AA metabolism (Figure 2). While dust exposure reduced PGE_2 production to 62% of control values, it increased TxB_2 and LTB_4 production to 222% and 181% of control values respectively (Figure 2A). The mean control values for PGE_2, TxB_2 and LTB_4 production as determined by RIA were 580, 150 and 1050 pg/ml respectively. In addition, several animals were allowed to "recover" from dust exposure for two weeks. As seen in Figure 4, following two weeks without exposure to coal dust. PGE_2 production had returned to levels which were not significantly different from control. However, TxB_2 and LTB_4 production remained elevated at 214% and 204% of control values, respectively.

3. The effect of a specific thromboxane synthesis inhibition on TxB_2 production in AM - In order to determine if dust-elicited stimulation of TxB_2 production in AM could be modulated, we incubated AM from control and dust-

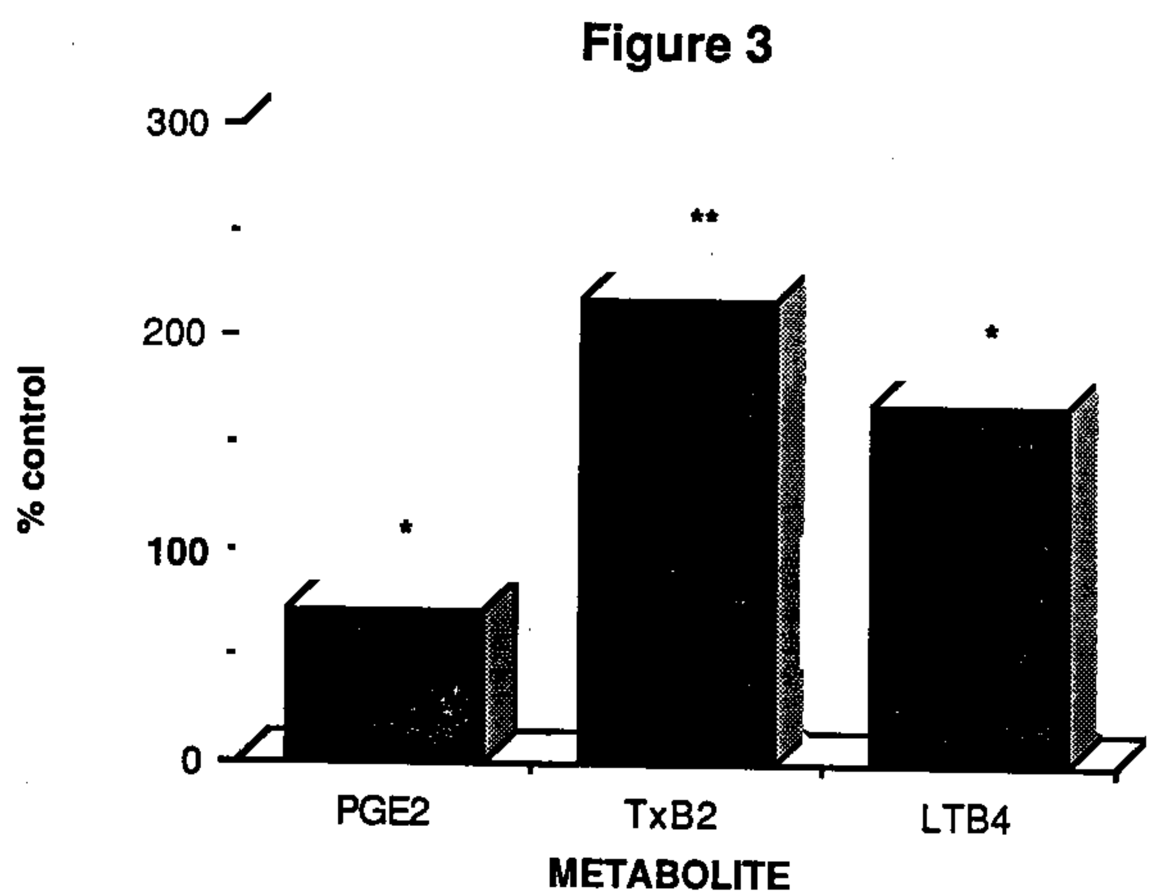


Figure 3. The effect of in vivo exposure of rat AM on AA metabolism. Values are expressed as % of unexposed control for each metabolite as measured by specific RIA. Significant differences were determined by the paired Student's t-test. (* $p < 0.05$, ** $p < 0.01$)

exposed rats with the specific TxB_2 inhibitor UK38,485 (Pfizer, Inc.). As seen in Figure 5 coincubation of AA with UK 38,485 significant reduced TxB_2 production in both control and dust-exposed AM. In control AM, TxB_2 production was reduced by 43%. In dust-exposed AM, TxB_2 was reduced from 222% to 23% of control values by the addition of UK38,485 (Figure 5A).

Following the recovery period, the addition of UK 38,485 to the incubation resulted in no change in TxB_2 production in control AM and a marked reduction in TxB_2 production in exposed AM (Figure 5B).

The administration of UK 38,485 also affected PGE_2 and LTB_4 production in AM harvested immediately after exposure. PGE_2 production was inhibited by UK 38,485 in control AM while LTB_4 production was significantly increased in both control and dust-exposed AM. Following two weeks of recovery, LTB_4 production in dust-exposed AM remained elevated in the presence of UK38,485.

The potential modulation of altered AA metabolism in AM from dust-exposed animals by biological antioxidants (eg. Vit C, Vit.E), surfactants and specific inhibitors of AA metabolic pathways is currently being investigated.

4. The effect of fresh vs stale dust on AA metabolism in *in vivo* exposed rat AM - The results of the experiments described above are currently being compared to data developed from similar experiments conducted with AM harvested from rats exposed to freshly-milled coal dust particles. Since the presence of organic free-radicals has been shown to decay as dust is stored for several days (Dalal et al, PSU), it will be important to determine if alterations in AA metabolism in AM is correlated with free-radical content of dust samples. It is likely that studies with fresh-milled dust will more closely represent the situation related to the exposure of coal workers and therefore the biological consequences of coal dust exposure.

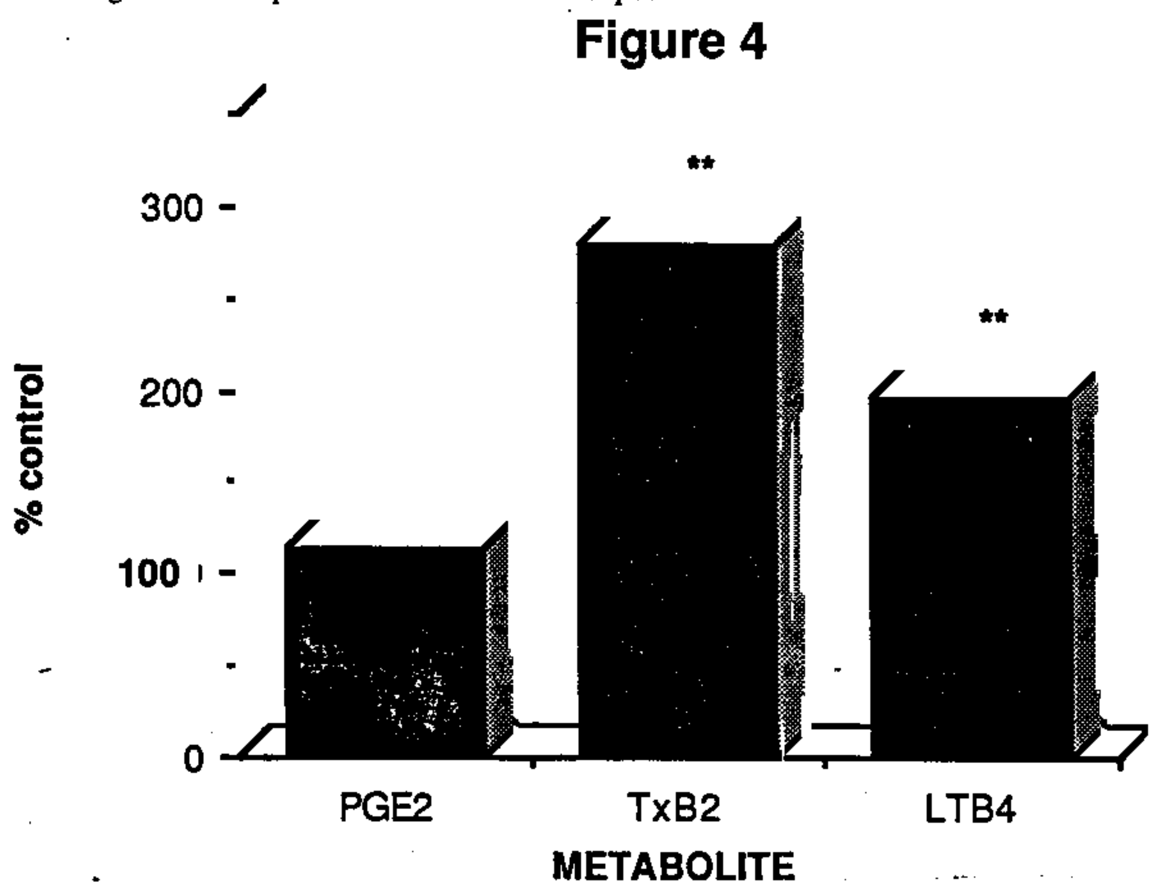


Figure 4. AA metabolism in rat AM following two weeks of recovery from dust exposure. Values are expressed as % unexposed control for each metabolite as measured by specific RIA. Significant differences were determined by the paired Student's t-test. (**$p < 0.01$)

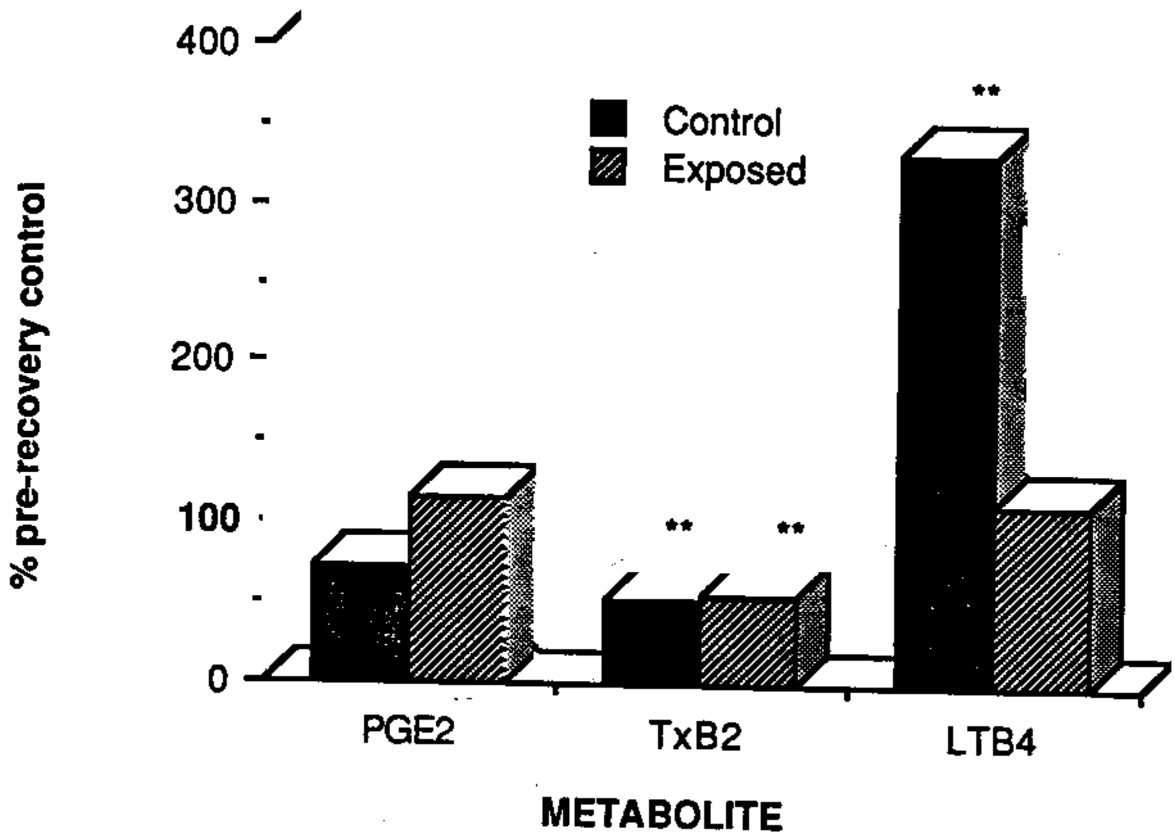


Figure 5a. Effect of UK 38-485 on AA metabolism in rat AM exposed to coal dust in vivo. Values are expressed as % pre-exposure control for each metabolite as measured by specific RIA. Significant differences were determined by the paired Student's t-test. (**p < 0.01)

CONCLUSIONS

1. We have developed suitable methodology, based on both *in vitro* and *in vivo* exposure of rat AM, for the study of the effect of coal dust on AM metabolism of AA. The suitability of a particular species for the study of human AM response will be determined in studies with isolated human AM. In addition, different dust types will continue to be tested in the most relevant biological systems.

2. Species differences exist in the absolute and relative production of AA metabolites in response to AM exposure to coal dust. The data developed in our laboratory will be compared to the results of similar experiments in AM harvested from human volunteers inorder to ascertain the appropriate model for future studies.

3. Different types of dust elicit different responses in AA metabolism in rat AM, both quantitatively and qualitatively. This information may prove valuable, when taken together with that from other laboratories, in determining the dust-related characteristics which affect dust pathogenicity. Targeting of appropriate containment techniques or therapeutic interventions could therefore be justified.

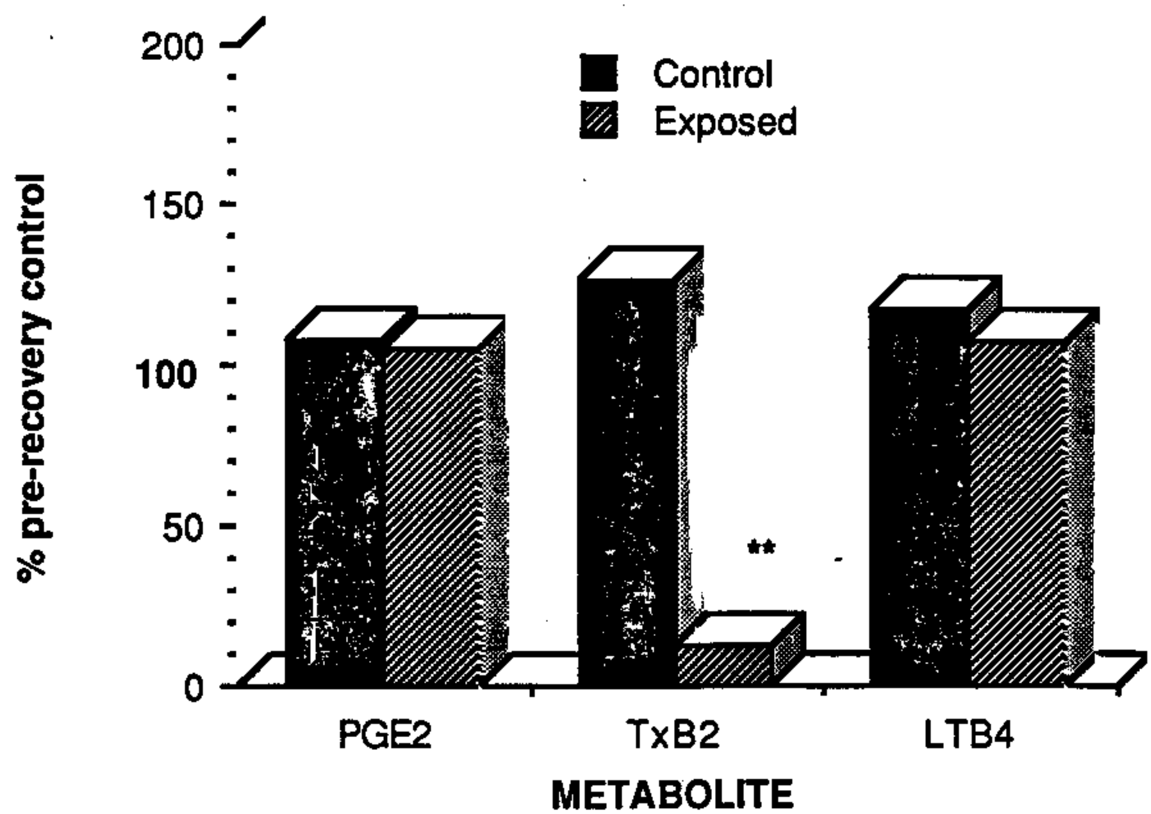


Figure 5b. Effect of UK 38-485 on AA metabolism in rat AM following two weeks of recovery from dust exposure. Values are expressed as % pre-exposure control for each metabolite as measured by specific RIA. Significant differences were determined by the paired Student's t-test (**$p < 0.01$).

4. Although certain aspects of dust-elicited AA metabolism are comparable in experiments where *in vitro* or *in vivo* exposure techniques are employed, differences are also apparent. These results suggest that data derived from *in vitro* exposure studies must be carefully interpreted and that *in vivo* exposure studies should be conducted simultaneously with *in vitro* studies.

5. *In vivo* exposure of rat AM to coal dust profoundly alters AA metabolism in a manner which suggests that the AM is a pivotal cell type in the development of CWP and that altered AA metabolism is a key mechanism by which that role is expressed.

6. Certain aspects of AA metabolism in AM from rats exposed to coal dust return to normal levels after a short recovery period. However, other alterations in AA metabolism persist and may be involved in the production of chronic lung disease. Further studies of both duration of exposure and length of recovery may provide useful information on the role of AA metabolites in the etiology of CWP.

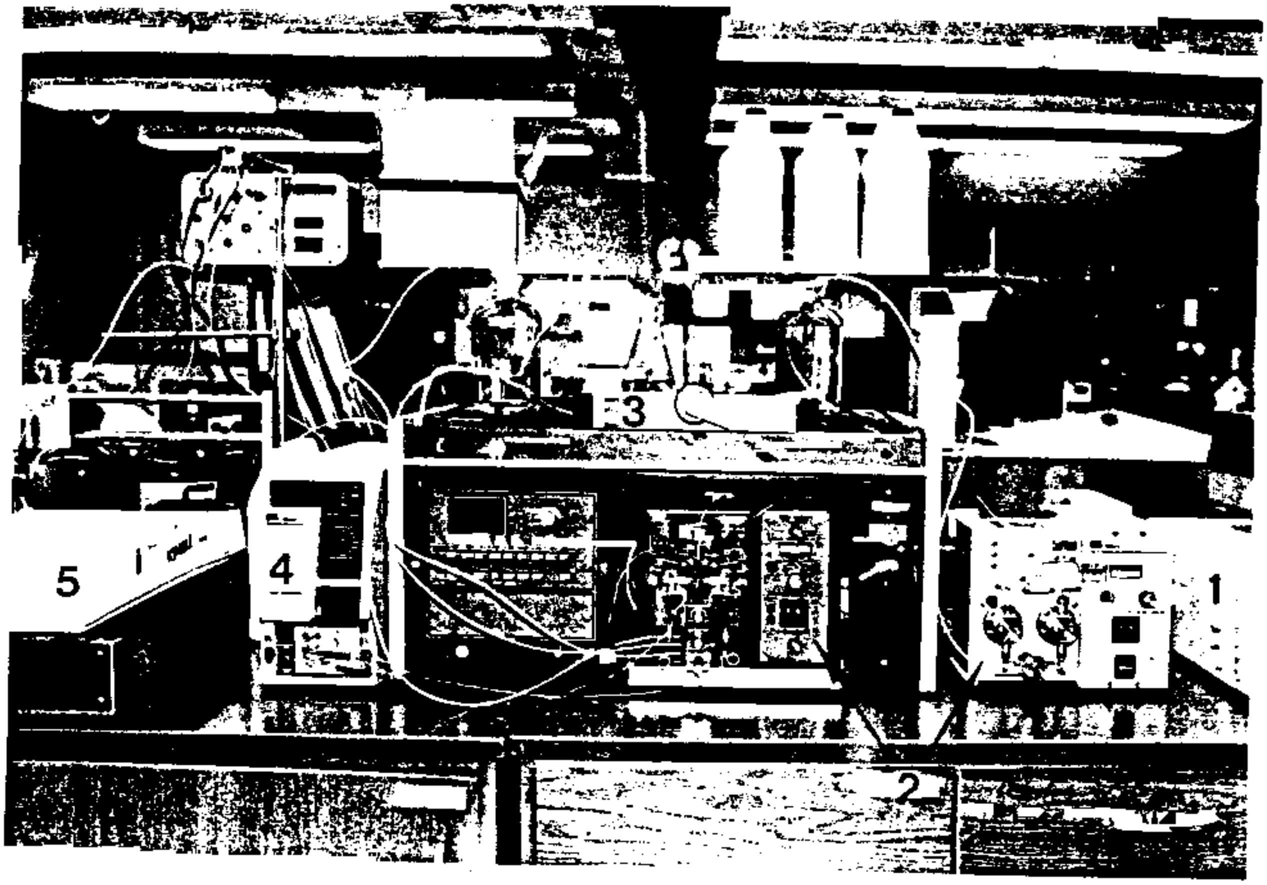


Figure 6. High performance liquid chromatography system for the separation and identification of arachidonic acid metabolites in normal and dust-exposed alveolar mecrophages. Components include system controller (#1), pumps (#2), separating column (#3), U.V. detector (#4) and fraction collector (#5).

APPLICATION OF RESEARCH RESULTS

A more comprehensive understanding of the effects of coal dust on AA metabolism in AM could be of benefit in the development of approaches to the prevention, detection and cure of CWP. First, if metabolites of AA are found to be involved in the progressive fibrosis of CWP, pharmacological manipulation of altered AA metabolism may be feasible. Second, if the characteristics of AA metabolism can be determined during the development of CWP, various stages of the disease process could be linked to specific alterations in AA metabolism. In this manner, not only could the progress of the disease be followed but it may be possible to define the earliest and most critical stages of the disease process. Finally, if AA metabolism is found to be more profoundly altered in certain individuals than in others, it may be possible to define those individuals who have an increase susceptibility to the disease. Similarly, if the degree of alteration in AA metabolism in AM can be correlated with different ranks or types of dusts, then those dusts could be specifically targeted in programs of exposure assessment and prevention. The practical application of our research results, however, depends on further exploration of the link between dust exposure, alterations in AA metabolism in AM and alterations in AM function which lead to the establishment of the disease process.

TECHNOLOGY TRANSFER.

The technology developed in this project is not yet refined for clinical or industrial application.

CONTINUING WORK

Studies are now in progress to 1) further define similarities and differences in dust-induced alterations in AA metabolism in AM exposed to coal dust *in vitro* and *in vivo*. These studies will have applications in the design of our future studies in sub-human primates and man. 2) Assess the effect of pharmacological intervention, via biological antioxidants, surfactants and specific agonists and antagonists of the metabolism of AA on the dust-induced reaction in AM exposed *in vitro*. These studies will help determine which type of agent may be utilizable in studies with animals exposed to dust in inhalation chambers. 3) To determine the effects of freshly-milled dust vs "stale" dust on AA metabolism in AM from rats exposed to dust in the inhalation chamber. These studies will further define the role of organic free radicals in the AM response to exposure and will help define the appropriate experimental design to future studies. 4) To develop experimental designs and methodology for studying the effect of *in vitro* dust exposure on AA metabolism in the subhuman primate and human AM. These studies will further define species differences in AM response to dust exposure and will begin to address the role of AA metabolites in the pathophysiology of AM from the most relevant species, man.

INTERACTIONS

This project has benefitted substantially from interaction with other investigators in the several institutions of the Generic Technology Center for Respirable Dust (GTCRD), as well as NIOSH and the BOM. Formal and informal meetings, site visits and interpersonal communications on a regular basis have led to the following specific and continuing interactions:

1. Coordination in methodology and use of lavage samples as well as an exchange of ideas among investigators at the M. S. Hershey Medical Center (with Drs. Bartlett and Bhavanandan).

2. Procurement animals exposed to dust in inhalation chambers (with Dr. Stanley).

3. Procurement of AM from subhuman primate (with Drs. White and Drozdowicz).

4. Information related to the presence of organic free radicals in dust samples (with Dr. Dalal).

5. Procurement and characterization of standardized dust samples (with Drs. Hagg and Duman).

We feel that the multi-center, interdisciplinary approach adapted in the establishment of the GTCRD has been of great benefit to furthering the goals of the funding organizations.

BIBLIOGRAPHY

1. Demers LM, Rose MP and Bartlett GL: The effects of coal mine dust particles on the metabolism of arachidonic acid by alveolar macrophages. In: Respirable Dust in the Mineral Industries:: Health effects, characterization and control. Eds. R.L. Frantz and R.V. Ramani, Pennsylvania State University Press, pp 135-141, 1988.

2. Demers LM, Edelson RA, Rose MP and Superdock DT: The metabolism of arachidonic acid by pulmonary alveolar macrophages exposed to coal mine dust. Prostaglandins (Submitted), 1988.

3. Kuhn DC, Stanley CF and Demers LM: The effect of in vivo coal dust exposure on arachidonic acid metabolism in the rat alveolar macrophage. Amer. Rev. of Resp. Disease (Submitted), 1988.

PS11/USBM 4210

Biochemical Alterations in Mammalian Respiratory Tract Mucus Caused by Coal Mine Dust

Bhavanandan, V. P.

INTRODUCTION

It is clear that coal will continue to be a major source of energy for many more decades. Thus the understanding and prevention of coal dust toxicity is imperative. Effective primary prevention is of extreme importance to minimize exposure of coal mine workers to respirable dust and thereby eliminate or reduce the risk of coal worker's pneumoconiosis (CWP). Engineering control technologies and work practices designed to reduce occupational exposure are two areas which can be expected to continue to improve. However, these measures alone are unlikely to reduce the risk of CWP to zero. To further reduce the incidence, secondary prevention measures are of equal importance. It is also essential that the cause of the disease and mechanism by which it develops be better understood.

From a survey of the available literature it is clear that there is a serious lack of information on the effects of coal dust on the mucociliary clearance mechanism in the tracheobronchial tract. Therefore, the purpose of this project is to understand the natural mechanism of defense in humans against inspired coal dust (initial studies will be in an animal model) and to determine in what manner this mechanism is impaired under conditions of repeated exposure to dust as in the case of coal miners. The basic biochemical research described will eventually lead to improved secondary prevention measures, help in the early diagnosis of the disease and in identifying workers at higher risk. Overall, these studies will contribute to the attainment of the goal of the Bureau of mines to benefit coal mine workers by improving general health and reducing economic costs that are a consequence of the occupational lung disease - CWP.

BACKGROUND AND RATIONALE

The respiratory tract and the lung are in direct and continuous contact with the environment. The lung has large areas of delicate, gossamer-thin membrane (in the several hundred million alveoli) that allow rapid exchange of oxygen and carbon dioxide but are vulnerable to inhaled pollutants. Human adults, depending on their size and physical activity, are estimated to inhale between 10 and 20 M^3 of air daily. This inhaled air contains large quantities of various inorganic and organic particulate matter and noxious gases. Despite this continuous bombardment with airborne, potentially deleterious, material the lungs are remarkably clean and sterile. The respiratory system can be considered to consist of three major (nasopharyngeal, tracheobronchial and pulmonary) compartments and each of these has a role in maintaining the sterility of the lung.

The nasopharyngeal compartment, in addition to temperature and humidity adjustment of the inspired air, filters out some of the particulate matter (mostly coarse particles). It is thought that the tonsils and adenoids may also play an important defense role in this compartment. The second line of defense is the tracheobronchial airways which has the major responsibility for trapping and clearing the inhaled particulate and gaseous pollutants *via* the mucociliary transport system. The last line of defense is the pulmonary macrophage system. Thus dust escaping the first two lines of defense and arriving in the pulmonary region (below the terminal bronchioles) are engulfed by macrophages and carried back to the ciliated airway epithelium for clearance or transported *via* the lymphatic drainage system to regional lymph nodes and blood circulation. It is apparent from the occurrence of various respiratory diseases caused by airborne pollutants that these composite defense mechanisms are not invulnerable. In the case of CWP, a small fraction of inhaled coal dust escapes all the defenses, remains in the lung and is responsible for cellular damage and associated disease. The long-term aim of the proposed research is to find means of reducing the amounts of respirable dust that reaches the alveoli of coal miner's lung.

The major portion of inhaled dust is cleared by the mucociliary escalator system in the tracheobronchial tract and to a lesser extent in the nasopharyngeal tract. Therefore, this project focuses on understanding the effect of chronic exposure to coal dust on the functioning of the mucociliary clearance mechanism. A fundamental question to be answered by this research is; whether exposure to coal dust alters mucus secretion and if so, what is the mechanism?

The mucociliary transport system requires two components. One, the whip-like upward beating cilia which helps to overcome gravitational forces. Two, an adequate supply of "normal" mucus secretions, about 100 ml of which is produced by an adult every day. This secretion provides a heavy blanket of mucus over the airway epithelium and acts as a trap to entangle particulate matter and to probably adsorb (or dissolve) gaseous pollutants. Further, the mucus provides the matrix by which the ciliary motion can move trapped material upward to the pharynx where it is normally swallowed or expectorated. In the respiratory system, as well as in other parts of the animal, mucus provides lubrication, osmotic pressure control and protection against dehydration, physical, chemical or microbial injuries. For example, the gastric mucus protects the cells lining the stomach from attack by the secreted hydrochloric acid and proteolytic enzymes. The British scientist, Sir Francis Avery Jones, commented, "mucus is one of Nature's perfections in protection, but even Nature has not anticipated all the noxious influences of Western civilization which can reduce the protective powers of the mucus lining".

Respiratory mucus secretion is made up of about 95% water and 5% solids. Of the solids, the major component is mucin which is responsible for the viscoelastic properties and the protective functions of the secretion. Other minor components are proteins, serum glycoproteins, lipids and inorganic salts. The effective functioning of the respiratory tract mucus is dependent on its optimal physical properties (viscosity, elasticity, surface tension) which in turn is dependent on its chemical composition. Alterations in the concentration, composition or structure of the mucin would result in alterations in the physical properties and thereby loss of biological functions. Accordingly, if the viscosity of the mucus is too low, it will not serve as an effective entrapment vehicle; conversely if the viscosity is too high, removal by the ciliary movement would be hindered.

Recently, it has been hypothesized that one of the functions of the mucus layers lining the respiratory tract is the scavenging of highly reactive oxygen-derived species; thereby providing antioxidant protection to the underlying mucosal epithelial cells. This function may be very important in preventing the development of CWP in view of the findings of Dalal *et al.* that freshly produced coal dust is rich in highly reactive free radicals. Further, oxygen-derived radicals such as superoxide (O_2^-) and hydroxyl radical (.OH) are produced within all aerobic cells and have many damaging effects. It is very likely that significant quantities of these radicals are produced by cells of the respiratory tract on exposure to coal dust. Thus, a deficiency of mucus production in the respiratory tract of coal mine workers could reduce a major line of defense against the highly toxic free radicals leading to cell damage and CWP. Alternatively, the fragmentation of mucin molecules by the free radicals in coal dust would result in the loss of the viscous properties of mucus produced in the respiratory tract of coal mine workers.

Some studies have been carried out to examine the influence of pollutants such as ammonia vapour, sulfur dioxide, cigarette smoke, O-chlorobenzilidine malonitrile (a riot control agent) and asbestos on mucus production in animals. However, there is virtually no information on the effect of exposure to coal dust on mucus secretion by the tracheobronchial system. This information will be extremely valuable in improving the efficacy of the mucociliary clearance of the coal dust deposited in the respiratory system of coal mine workers. The hypothesis to be tested is that the continued exposure of the tracheobronchial epithelium to coal dust leads to impairment in the mucus production; this defect could be either in the quantity or the quality of the mucin glycoprotein synthesized. A variety of coal dust preparations will be tested to determine whether certain preparations (for example, freshly ground dust) are more detrimental than others.

SCOPE OF WORK AND EXPERIMENTAL PLAN

1. Animal Model: We are using rats (specific pathogen-free) so that we can have a continuous supply of tracheal explants, lung lavage samples and also subject them to coal dust exposures under carefully controlled conditions. Parallel studies are also being carried out in monkeys. The choice of rats as the experimental animal has an advantage in that it is also being used in studies on coal dust - lung interactions by Dr. Bartlett and Demers at this Medical Center (subcontracts #4204 and #4209), and we would be able to closely coordinate our efforts. In future extensions, a comparison of mucus produced by tracheal epithelium explants obtained from post mortem of accident victims and from coal miners succumbing to CWP would be conducted for testing the relevance of the findings on animals to humans.

2. Dust Samples: These are obtained through the Director of The Generic Technology Center for Respirable Dust. The Directors of the center and other investigators involved the study of respirable coal dust - lung interactions are consulted as to the most appropriate samples to be tested.

3. Tracheal Explant Cultures: Because we would like to maintain as close a correspondence to the *in vivo* situation as possible, we are initially carrying out studies on intact tracheal explant cultures rather than on epithelial cells in primary culture. Tracheas are removed aseptically from rats and cultured under sterile conditions. The culture medium is changed every two days and it is possible to maintain viable cultures for up to three weeks. The tracheal cells are checked by bright field and phase contrast microscopy at every medium change. The ciliary movement is a good indication of viability and experiments are terminated once ciliary movement has ceased. The medium is checked routinely for microbial contamination by incubating aliquots with appropriate broths.

4. Isotopic labeling of mucins produced by tracheal explants: [^{3}H]Glucosamine and [^{14}C] leucine are added to cultures for the metabolic labeling of the carbohydrate and protein portions of the mucin glycoproteins. In some experiments $^{35}SO_4$ is employed concurrently with [^{3}H]glucosamine. Tracheal mucin glycoproteins are sulfated, therefore $^{35}SO_4$ is a convenient precursor for routine labeling of mucins as it is cheap and is a high energy β-emitter.

5. Collection and fractionation of tracheal secretions: After removal of the spent medium, the tissue is gently washed with additional warm medium to remove any secretions still adhering to the explant. The medium plus washings are dialyzed to remove unincorporated radioactive precursors and low molecular weight metabolites.

Aliquots (1 ml) of the dialyzed medium is treated with testicular hyaluronidase and bovine submaxillary mucin (1 mg) is added as carrier, followed by 15 ml of cold 2.8 N perchloric acid containing 2% phosphotungstic acid. After incubation in an ice bath for 30 min. the precipitate is collected by centrifugation, washed twice by reprecipitation, dissolved in 1 M NaOH or Protosol and radioactivity determined by scintillation counting. The above treatment precipitates mucins and other glycoconjugates quantitatively. For more accurate estimation of mucin the hyaluronidase digest is subjected to gel filtration of Sepharose 4B and radioactivity in the void volume peak estimated.

6. Nature of the mucin secreted by rat trachea with or without coal dust exposure: Both physical and chemical properties were compared. Exclusion column chromatography on supports such as Sepharose CL-4B, Bio Gel A5M, Sephacryl S-1000 in the absence or presence of denaturing (urea, guanidine HCl, detergents) and reducing (β-mercaptoethanol, dithiothreitol) agents yield information on molecular size distribution, aggregation and subunit structure. Examination by density gradient centrifugation in CsBr (± 4 M Guanidine HCl) provides information regarding covalent and or non-covalent association of lipids with mucins.

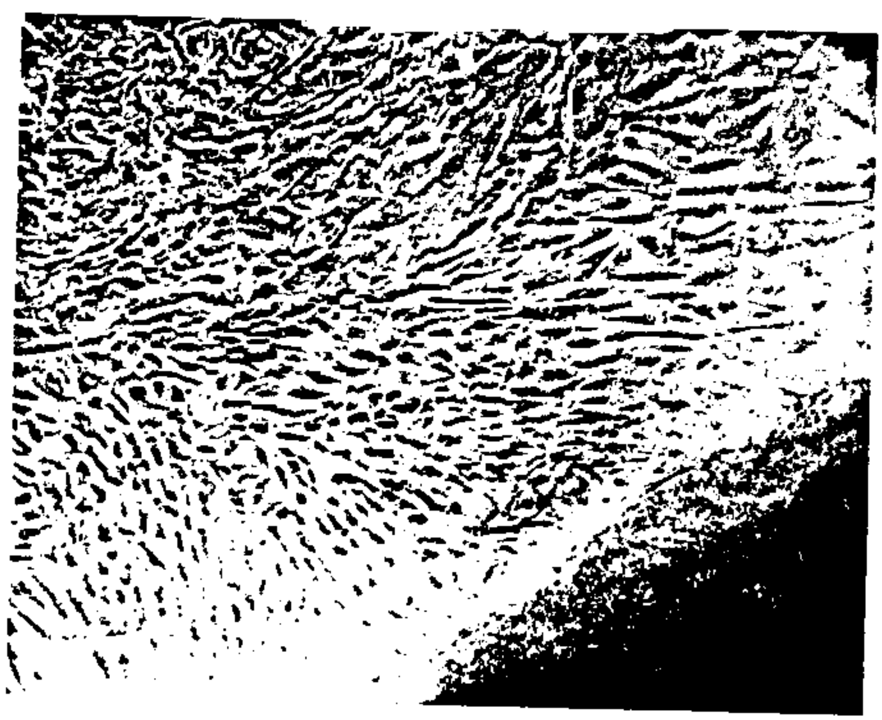
EXPERIMENTAL RESULTS

First, we determined the optimum conditions for rat tracheal explant organ cultures. Three different culture media (Eagles 199, CMRL 1060 and a 1:1 mixture of 199 and DMEM) all containing antibiotics and 10% fetal calf serum were evaluated. Scored petri dishes were used to facilitate attachment of the explants. Three to four days after plating, the explants produced outgrowths containing fibroblasts and epithelial cells some of which were ciliated. We tested the explant cultures for mucin production by culturing them in the presence of [^{3}H]glucosamine and in some experiments also $^{35}SO_4$. The isotopically labeled glycoconjugates secreted into the media were analyzed by dialysis, gel filtration and treatment with enzymes (hyaluronidase, chondroitinase). Based on the observation of growth characteristics and the labeling experiments it was concluded that CMRL 1060 is the best media for culturing rat tracheal explants. Medium 199 by itself was not capable of sustaining the growth of the explants and the 199:DMEM mixture was satisfactory but not as good as CMRL.

We then attempted to selectively precipitate the mucin glycoprotein from the dialyzed culture media by addition of cold 2.8 N perchloric acid and 2% phosphotungstic acid as described in the literature, but found this method unsuitable because it was not possible to re-solubilize the precipitated glycoconjugates (water, Tris buffer and 6 M urea were tested). Sodium hydroxide (1 M) dissolved the precipitate but this treatment will degrade the mucin and therefore the product cannot be used for structural investigation. Polyanionic material in the dialyzed media was precipitated with cetyl pyridinium chloride and the precipitate fractionally eluted with NaCl of increasing concentration. The labeled material solubilized with 0.2 and 0.4 M NaCl was recovered by dialysis and analyzed for sialic acid, hexosamine and susceptibility to hyaluronidase. The results indicated that very little sialoglycoprotein was present in the 0.2 M NaCl fraction and the 0.4 M fraction was entirely hyaluronic acid. We then attempted purification of the mucin by ion exchange chromatography on DEAE-Sepharose using a NaCl gradient for elution which yielded four major peaks. The first peak is presumably a mixture of sialoglycoprotein and some hyaluronic acid.

Labeled rat tracheal glycoconjugates were produced by culturing explants in the presence of [^{3}H]glycosamine. The non-dialysable labeled glycoconjugates were used as the starting material for the purification of mucin. A procedure for purifying the mucin synthesized by explants of rat trachea was worked out based on the results of a large number of preliminary experiments. Briefly, the spent culture medium containing the secreted mucin is dialyzed, concentrated and chromatographed on a column of Sepharose CL-4B in 50 mM Tris-HCl, pH 8.0 containing 6M urea. The material eluting at the void volume is recovered, treated with testicular hyaluronidase and rechromatographed on the same column. The glycoconjugates which still elutes at the void volume and consisting mostly of the mucin glycoprotein is further purified by ion exchange chromatography on DEAE-Bio Gel using a NaCl gradient. Examination of the purified mucin by CsBr density gradient centrifugation showed a single

A



B

C

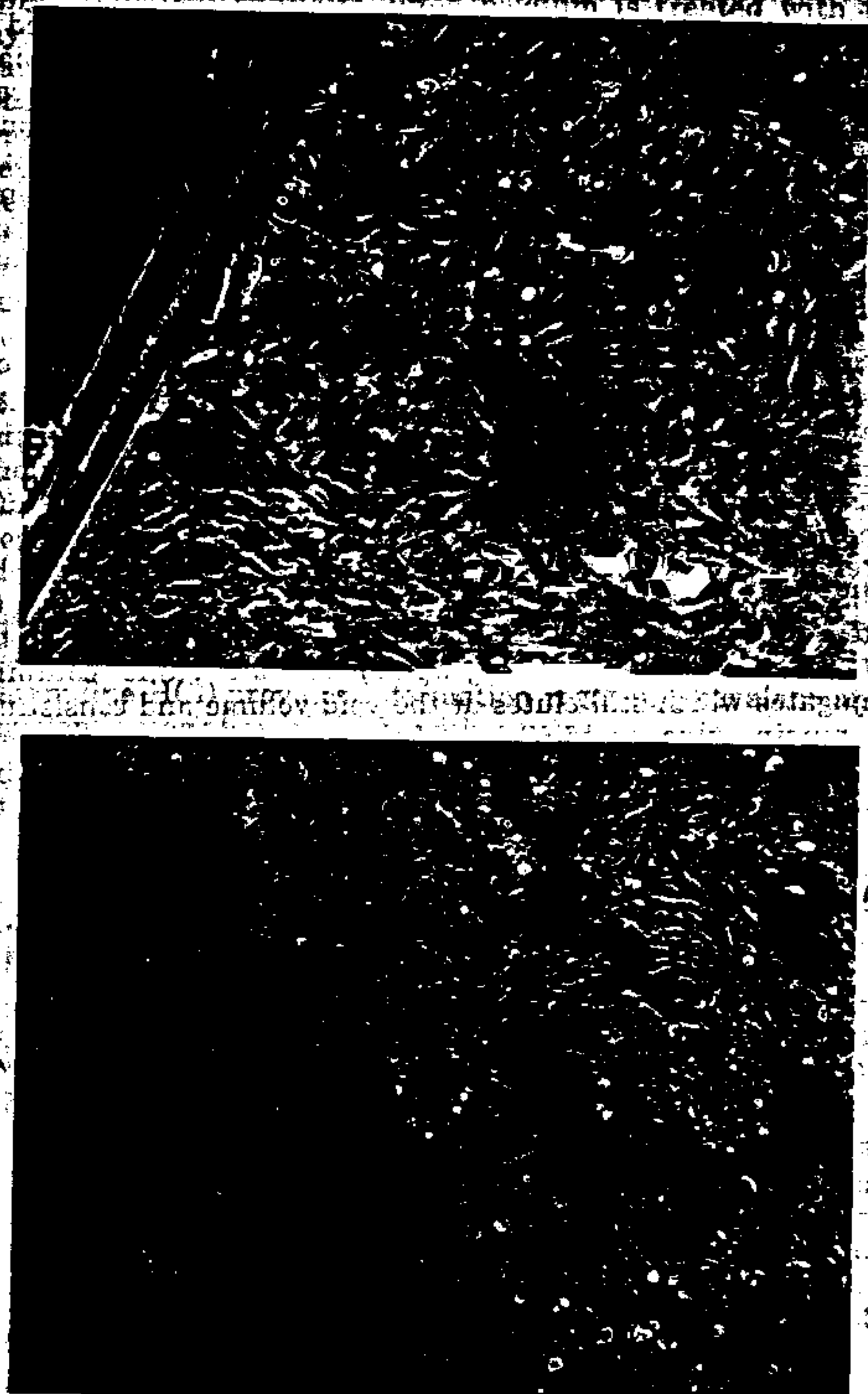


Figure: Photographs of rat tracheal explant cultures which were not treated (panel A) or exposed to coal dust at 100 µg (panel B) and 500 µg (panel C) per ml media. The dust appears to be concentrated in areas of the dish devoid of explants or outgrowth of cells, probably as a result of the mucociliary action.

peak of density 1.43 g/ml indicating a high carbohydrate content. About 50% of the tritium label was released as sialic acid on treatment with *V. cholerae* sialidase, the balance was in galactosamine (37%) and glucosamine (13%).

To examine the effect of coal dust on mucin production, we used eight dishes each containing half a rat trachea cut lengthwise. The explants were cultured for 48 hours in media containing 10 μCi of [^{3}H]glucosamine and 1 μCi of [^{14}C]leucine per ml before and after coal dust exposure. Four dishes containing halves of four trachea were treated with media containing 100 μg coal dust per ml every 2 days for 2 weeks, and the tracheas in the other four dishes were treated similarly but without coal dust. The distribution of radioactivity in the non-dialysable macromolecules in the pooled spent media is as below

	Before Treatment		After 2 weeks culturing in media with dust	without dust
	[dmp x 10^{-7}]			
[^{3}H]GlcH$_2$	3.2	3.2	2.2 (100%)	1.2 (54%)
[^{14}C]Leu	10.5	10.9	9.4 (100%)	5.8 (62%)

The results indicate that treatment with coal dust for two weeks decreased production of protein (^{14}C-leucine incorporation) by about 40% and of glycoprotein (^{3}H-glucosamine incorporation) by about 50%.

Further *in vitro* experiments were carried out to verify the effect of respirable coal dust (PSOC 867). As before, each rat trachea was cut lengthwise and one-half used as control and the other subjected to coal dust exposure. The explants once established wee cultured in the presence of either [^{3}H]glucosamine or [^{14}C]leucine before and after 2 weeks coal dust exposure (100 μg dust per ml every 2 days). The distribution of radioactivity in the non-dialysable glycoproteins secreted by the trachea was determined by our established procedure. At the end of the experiment the protein content of the tracheal explants were determined and the results are expressed as per mg protein in the Table below.

[^{3}H]GlcNH$_2$		[^{14}C]Leucine	
(dpm x 10^{-5}/mg protein)			
Control	Treated	Control	Treated
10.8	7.2 (67%)	0.61	0.32 (52%)
18.5	9.7 (52%)	1.10	0.50 (45%)

The trend noted above has now been found reproducible in three independent experiments. In the next experiment, we analyzed the effect on coal dust treatment on hyaluronidase-resistant acid-precipitable fraction consisting mainly of mucin. The results presented below indicate that treatment of rat tracheal explants with coal dust results in specific decrease of the mucin secreted.

Distribution of Precipitable Mucin Secreted by Control and Coal Dust Treated Rat Trachea

	Before treatment			After 2 weeks	
			(dpm x 10^{-4})	w/o dust	with dust
[^{3}H]GlcNH$_2$	2.0	2.0		1.6	0.82 (51%)
[^{14}C]Leucine	0.25	0.25		0.27	0.10 (37%)

To examine the effect of *in vivo* coal dust exposure: on mucin production rats were maintained in an inhalation chamber for two weeks. Six rats were exposed to a coal dust atmosphere for two weeks while a batch of six control rats were maintained in an adjoining chamber but in coal dust free atmosphere. At the end of the exposure period the rats were transported from Morgantown to Hershey and sacrificed the following day. The tracheas were removed aseptically and explant cultures established as previously. The viable explants were cultured for 48 hours in media containing 1 μCi of either [^{3}H]glucosamine or [^{3}H]leucine per ml. The media from the cultures were analyzed for non-dialysable glycoproteins and protein by our established procedure. The results presented below indicate a reduction in the production of protein (^{3}H-leucine incorporation) and glycoprotein (^{3}H-glucosamine incorporation). Therefore it appears that the effect of *in vivo* dust exposure on glycoprotein production by rat trachea is similar to that noted in *in vitro* experiments.

	Control rats		Rats exposed to coal dust for 2 weeks
Non-dialvsable		dpm x 10^{-5}/ml media	
[^{3}H]GlcNH$_2$	15.5		13.6 (88%)
[^{3}H]Leucine	8.0		6.0 (75%)

CONTINUING WORK/FUTURE PLANS

If as expected from our hypothesis, exposure to coal mine dust results in alterations of the quantity and/or quality of respiratory secretions, then the next major step would be to design studies to determine in which step(s) - biosynthesis, secretion, ciliary activity - the problem exists. One possible scenerio is that coal dust exposure inhibits one or more of the enzymes (glycosyltransferases) involved in the biosynthesis of mucin resulting in a decrease in the amount of mucus secreted. To check this possibility, the levels of some of the key enzymes in the synthetic pathway should be determined in control and dust-exposed tracheal epithelial cells. Alternatively, some of the degradative enzymes could be activated by constituents of the dust leading to increased breakdown of the macromolecular and therefore a loss in the physical properties, such as viscosity, of the secretions. This can be tested by measuring the levels of proteases and glycosidases in control and dust-exposed tissues. Changes in the physical properties of mucus could also be caused by alterations in components (other than mucin glycoprotein) in the secretion, for example, minor non-mucin glycoproteins, proteins, surfactant lipids *etc.* These possibilities should be tested by measuring the level of these components in the secretion by established sensitive techniques.

Once the defect has been identified, then we will seek means to correct the problem and devise ways of accentuating the normal mucociliary clearance mechanism to prevent or minimize the pulmonary deposition of coal dust in coal mine workers. As an example, if the defect is enzymatic then a search for appropriate stimulators or inhibitors of the particular enzyme which is inhibited or stimulated will be warranted.

PSU12/USBM 4211

Interaction of Coal Mine Dusts and Nonhuman Primate Lungs

White, W. J.; Drozdowicz, C. K.; Bowman, T.; Childe, S..

Introduction

The overall objective of research on the interaction of coal mine dusts and lung tissue has been to develop methods by which severe Coal Worker's Pneumoconiosis (CWP) can be prevented. Such a goal can only be met if this disease and the factors which alter its course are thoroughly understood. All available evidence suggests there is a direct relationship between the inhalation of coal mine dust and the development of the disease. Thus, present methods of control of the problem have focused primarily on decreasing exposure to the dust. Such efforts will in all likelihood never be 100% effective and thus improved methods for detecting and treating this disease need to be developed. The findings of this study have the potential for impacting significantly on our understanding of coal workers' pneumoconiosis with implicit benefits in its diagnosis and treatment.

This research project is complimentary to ongoing studies of cells found in the lungs responsible for entrapping coal dust particles which participate in the development of this disease. Currently, lung tissue of small laboratory rodents has been used to gain insight into how these cells function and interact in the disease process. Obtaining similar cells from individuals afflicted with CWP and those not afflicted is difficult and presents an unacceptable risk to the patients given our current level of understanding of this disease. This project has focused on the development of an animal model that is anatomically and physiologically similar to man which can serve as a source of those lung constituents under investigation. In addition, these biological constituents can be obtained in a non-destructive manner from the animals with little risk to their health or well being. Nonhuman primates have proven to be a logical choice for this purpose. The techniques developed thus far as well as the characterization of a pulmonary macrophages from these animals will allow studies necessary for the understanding of pneumoconiosis that would have been virtually impossible with the use of small laboratory rodents.

Rationale

The effects of chronic exposure to coal mine dusts on lung tissue have been well documented, however, the detailed mechanisms are not fully understood. Under normal environmental conditions, the respiratory system is continually exposed to particulate material carried in the air. These particles are either filtered out by the nose or trapped by mucus produced by cells in the lungs and carried out by cilia lining the airways. Smaller particles such as bacteria are eliminated by scavenger cells called macrophages. These cells line air sacs called alveoli which enable oxygen to be transferred into the bloodstream. The alveolar macrophages can digest biological material such as bacteria, thereby preventing damage to the lung tissue. Inhaled coal mine dusts are smaller than most particulates and bacteria found in the air and therefore make their way to the terminal portions of the respiratory tree. In the alveoli, macrophages ingest the dust particles and carry them into the surrounding lung tissue where they accumulate. Macrophages cannot digest coal dust particles, resulting in foci of dust-laden cells around the small airways leading to the alveoli. The body's response to these deposits of dust-engorged cells is the formation of fibrous connective tissue in or near their sites of deposition. The processes by which this reaction occurs are unclear but appear to be associated with the activation of cells called fibroblasts (cells capable of generating fibrous connective tissue). Fibrosis is a normal response to injured tissue, providing a temporary framework on which new tissue can grow. Work using macrophages obtained from other sites in the body of small laboratory rodents suggests that this activation may be through the release by macrophages of chemical messengers which have the ability to stimulate or inhibit the complex process of laying down fibrous connective tissue. The whole process of developing this tissue is relatively complex and its development may be influenced at many different stages. It is unclear whether the macrophages cause fibroblasts which are already present in the lung tissue to divide and form fibrous scar tissue or whether the macrophages release chemicals that cause the migration from other areas of such cells to their sites of accumulation. Normally, the degree of fibrosis is self-limited and thus a high proportion of miners exposed to coal mine dusts do not experience any compromise in pulmonary function.

For reasons not well understood, a proportion of miners exposed to coal mine dusts develop a severe manifestation of this process called progressive massive fibrosis. In such cases, much of the lung tissue is replaced by fibrous connective tissue, which limits the elasticity of the lung and begins to compromise its ability to expand and transfer air to the alveoli. The alteration in the lung's normal defense mechanism suggests some potential for genetic pre-disposition or an alteration in macrophage function.

It appears, then, that the most direct approach to understanding the development of this disease process and in finding ways to interdict it must hinge upon an understanding of macrophage function especially as it relates to the control of fibroblast activity. From the limited evidence available, the process of phagocytosis of dust particles and subsequent pulmonary fibrosis is not unique to man as very mild forms of related diseases have occasionally been reported in domestic animals that are exposed to a dust-laden environment. Thus, the study of macrophages from animals can provide a mechanism for understanding their function in man. While laboratory rodents have been traditionally used as a source of these macrophages due to their availability, small size, and low cost, the use of these species has placed some inherent limitations on the types of studies that can be conducted. In addition to the implicit question of the functional similarity of the cells derived from these animals to man, there are also limitations placed on these studies due to the low yield of macrophages from these animals, the need to euthanatize the animal in order to collect the cells, and the inability to study the same animal serially over an extended period of time following exposure of the lung tissue in vivo to coal dust.

An animal of reasonable size with rather close anatomical and physiological similarity to man would enable the utilization of broncholavage techniques to obtain in a non-invasive manner pulmonary macrophages in sufficient quantity for in vitro laboratory assessment. Their use would not only allow comparison to data already accumulated in rodents in order to provide greater confidence in the extrapolation of conclusions derived in these species to the function of human macrophages but would also provide a mechanism for performing certain crucial in vivo exposure studies with serial sampling from the same animal that would be difficult or impossible to do in smaller rodent species.

The goal of this project has been to explore and characterize the nonhuman primate as a suitable animal model for the assessment of macrophage function by developing techniques for collection of pulmonary cells in a non-destructive fashion. In addition, preliminary studies have been initiated for in vivo exposure through installation of coal mine dust into primate lungs and serial collection following exposure from the same animal.

Scope of Work

The main focus of this project has been limited to short term studies because of the expense and supply of nonhuman primates and to avoid unnecessary injury to these animals. The research thus far has been divided into 2 main areas: 1) determine the effects of coal mine dusts on alveolar macrophages in vitro and 2) provide materials collected by bronchoalveolar lavage to investigators at the Hershey Medical Center who are studying different avenues of the disease mechanisms involved in the development of coal workers' pneumoconiosis.

Experimental Methods

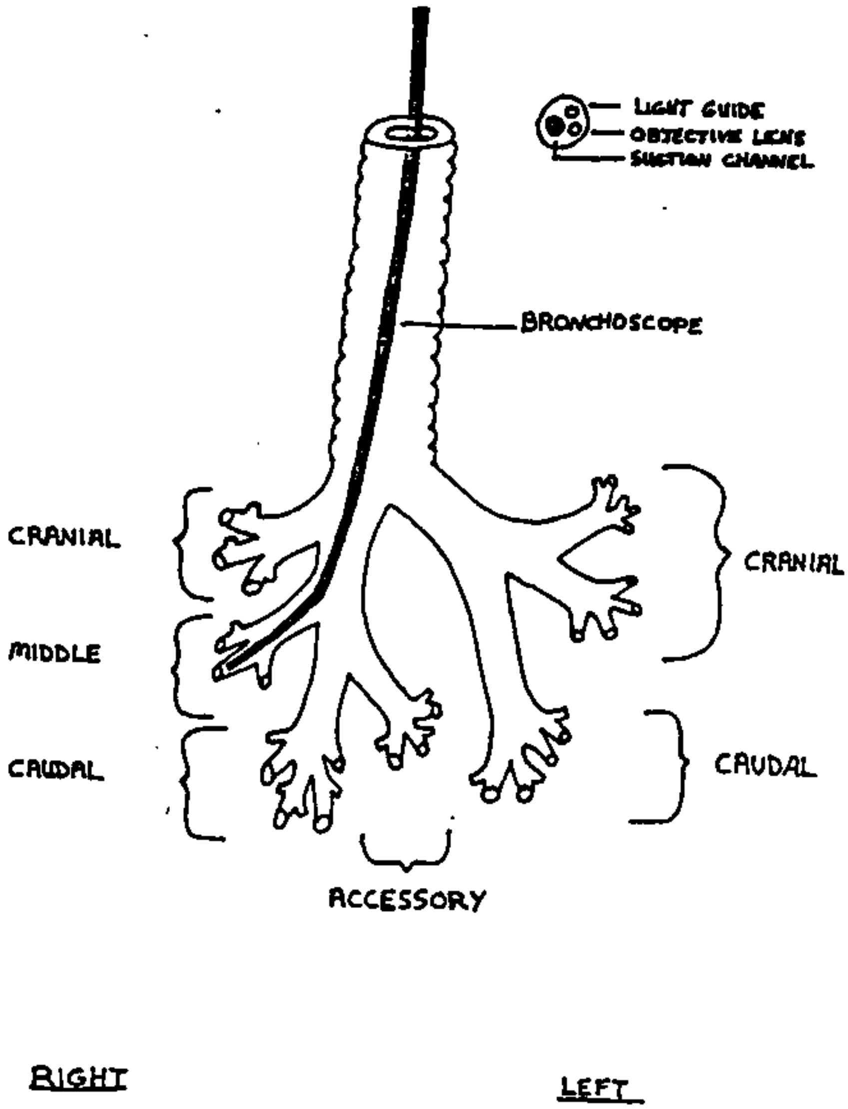
Pulmonary Lavage: While bronchoalveolar lavage is a common diagnostic technique used in human medicine, the method of repeatable sampling of pulmonary constituents in nonhuman primates has not been well documented. Therefore, the initial phase of the investigation focused on the development of lavage techniques in nonhuman primates using pediatric bronchoscopic equipment. Refining the technique included determining the proper anesthetic regimen needed to provide adequate anesthesia without compromising post-procedural recovery. In addition, the critical amount of collecting media used during the lavage procedure had to be determined. During the first year of the investigation, successful broncholavage techniques were established to collect pulmonary macrophages and other materials in a reproducible fashion from lungs fields in nonhuman primates (Figures 1 & 2). In this section of the study a number of variables were explored including reproducibility of positioning of the bronchoscopic device, evaluation of the collecting media and the assessment of post-collection prophylaxis against secondary bacterial infection.

Kinetics of Macrophage Response to Dust Exposure: The assays to assess macrophage function and the production of macrophage products were developed by Dr. Gerald Bartlett in the Department of Pathology at

Bronchoalveolar lavage with the fiberoptic bronchoscope using an anesthetized nonhuman primate.

The Milton S. Hershey Medical Center. Initially, these assays were performed in conjunction with Dr. Bartlett's laboratory. At present, an additional laboratory with its own technical personnel and equipment has been established to expedite the amount of work accomplished.

It is assumed that macrophages possess the ability to stimulate the proliferation of fibroblasts and in turn promote collagen synthesis. Collagen, the main component of scar tissue, is the biological product of stimulated macrophages. Macrophages are activated by a variety of stimuli, including particulates such as coal mine dusts. These events can be reproduced in an in vitro system, which provides the opportunity to study those mediators produced by macrophages when exposed to coal mine dusts.

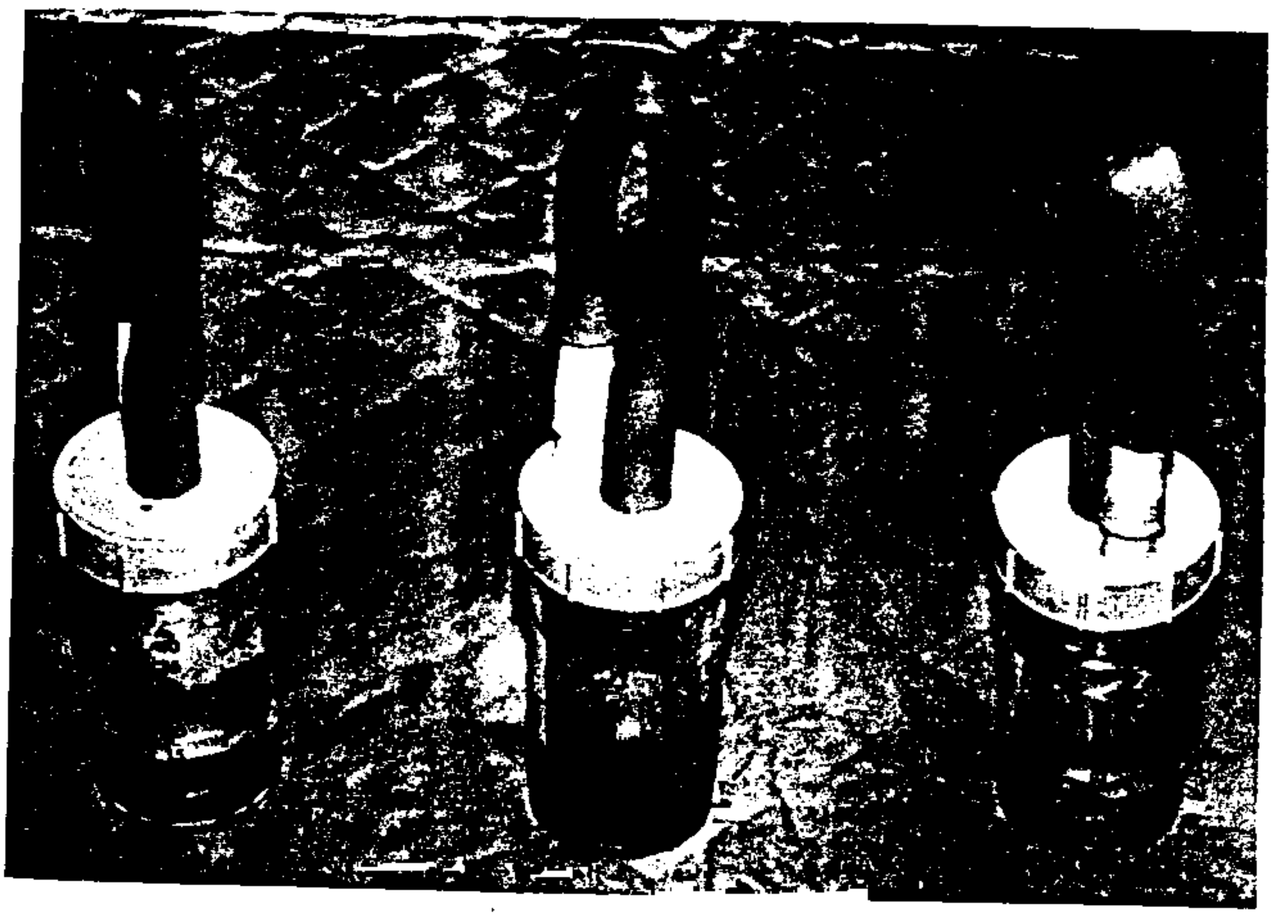


Schematic of the location of bronchoscope following introduction into the bronchial tree.

Pulmonary macrophages recovered from a bronchoalveolar lavage are placed in culture containing those nutrients essential for maintaining the cells outside the body (Figures 3 & 4). These macrophages are then exposed to defined quantities and types of coal mine dusts. The culture media is sampled following a defined incubation period to examine the amount of interleukin 1 (IL-1) activity. This factor has a variety of bioregulatory activities, including stimulation of fibroblast proliferation and stimulation of the enzyme collagenase by fibroblasts. However, its defining function is its ability to render thymocytes responsive to the T-cell mitogens, PHA or ConA. Thymocytes (T-cells) are one of the major cellular components of the mammalian immune system. The presence of IL-1 in macrophage supernatant media is assessed by the ability of supernates to stimulate proliferation of thymocytes in the presence of PHA. In addition, stimulation of fibroblast growth by macrophage products is assessed.

These assays will also be used for pulmonary macrophages exposed to coal mine dust while still within the nonhuman primate lungs. The above in vitro systems are in the preliminary phase of the investigation, therefore a definitive conclusion from the results at this point in time cannot be made. However, the initial data does suggest there is an increase in the production of macrophage mediators following stimulation with coal mine dust.

Professional Interactions: The most productive aspect of this project has been the cooperative interaction between investigators at the Hershey Medical Center through the use of the nonhuman primate colony funded by the Generic Mineral Technology Center for Respirable Dust. In addition to utilizing the nonhuman primates for this project, the colony is available for use to other investigators who can benefit from the materials collected by lavage. The materials collected from the bronchoalveolar lavage have been used to study the abnormal prostaglandin pattern by pulmonary cells (Dr. Demers), the effect of dust exposure on pulmonary mucus production (Dr. Bhavanandan) and comparison of alveolar macrophages in guinea pigs to nonhuman primates (Dr. Bartlett).



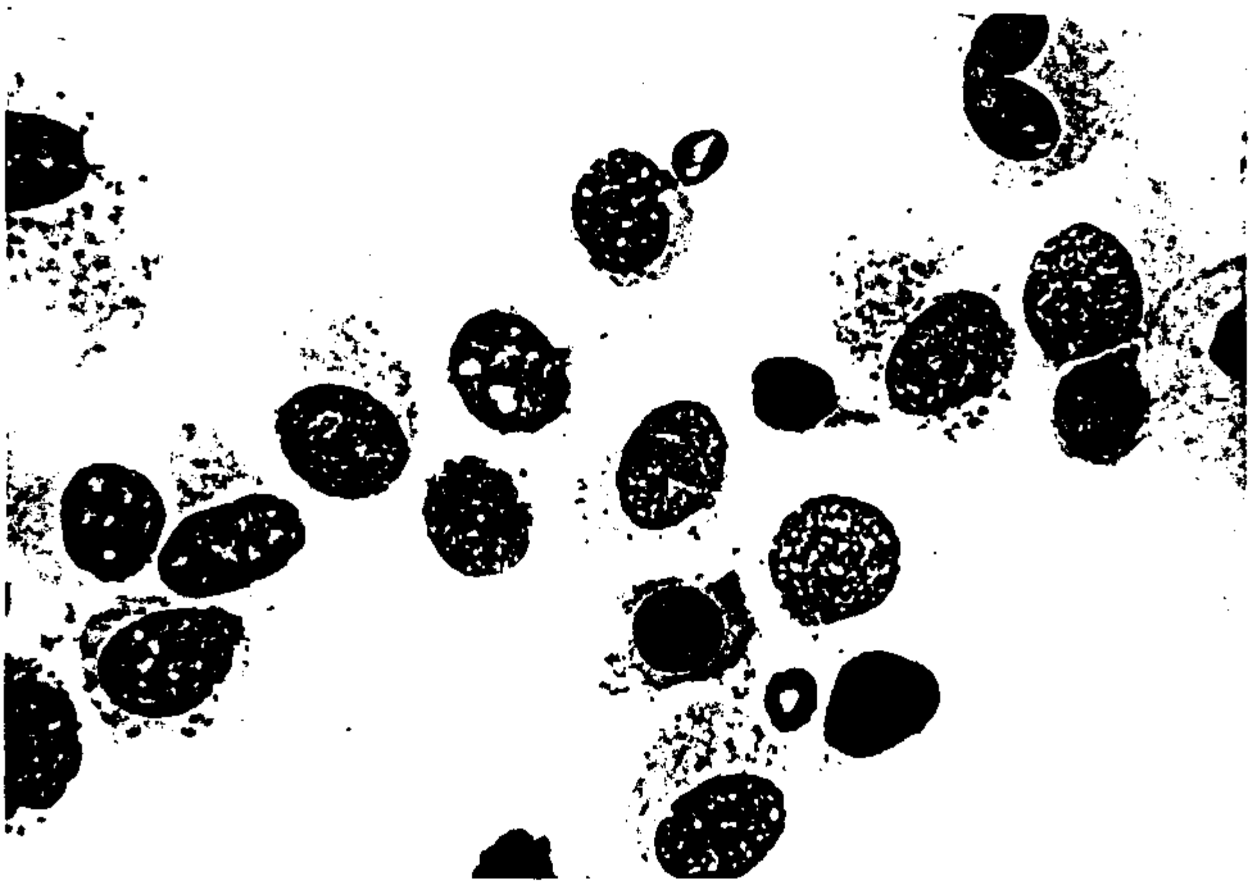
Collection vials containing sterile saline and lung constituents following bronchoalveolar lavage.

Conclusions

The general conclusion of this research study thus far is that the nonhuman primate is an excellent model for examining the effect of coal mine dust on the alveolar macrophage and other pulmonary defense mechanisms. The preliminary data suggests that coal mine dust does stimulate the production of biological mediators which are known to promote changes within the lungs. The animals in this investigation are an important tool in examining the effects of chronic exposure to coal mine dust in situ and will provide a source of information that can be expanded to man.

Applications of Research Results

The nonhuman primate is an animal model which is applicable to the investigation of the biological mechanisms responsible for coal workers' pneumoconiosis. It provides a non-invasive source of materials which can be obtained on a continual basis. In addition, the nonhuman primate is a promising animal model for the investigation of the effect of coal mine dust both in vitro and in vivo.



Photograph of macrophages collected during a routine bronchoalveolar lavage.

Continuing Work

The major task during the final year of funding is to complete the studies of macrophage function using the culture systems. In addition, continuing work is focused on converting the *in vitro* use of coal mine dust to exposing nonhuman primates to conditions similar to those experienced by the coal miners. The facilities at The West Virginia University provide an excellent opportunity for performing *in vivo* studies using nonhuman primates. The limitations of this investigation are only those related to time. It is unfortunate that this facet of the project is in its infancy, just now in its second year of funding.

Tech Transfer

Several useful discussions with personnel from other research institutes involved with the Generic Mineral Technology Center for Respirable Dust have resulted from this work. The investigators involved with the utilization of the nonhuman primate colony have offered the use of these animals to other researchers within the Center to promote and expand the information that may be gained from this animal model. A paper will be submitted for publication by the end of this calendar year and the results of this study will be presented at a national symposium this October.

WV5/USBM 5405

Pulumonary Inhalation Toxicity of Respirable Coal Mine Dust: A Morphometric Study

Lantz, C.;**Stanley**, C.; **Dalal**, N.; **Dey**, R.; **Abrons**, H.; **Pavlovic**, A.

INTRODUCTION/RATIONALE

The overall objective of this project has been to quantitatively assess the effects of inhalation of respirable coal mine dusts on pulmonary structure. The overall working hypothesis has been the following. A relationship exists between the physical and chemical makeup of the inhaled dusts and the alterations in lung structure caused by dust inhalation. Therefore, by controlling and knowing the physical and chemical makeup of the inhaled dusts, the important factors which lead to pulmonary injury following inhalation of coal mine dusts can be determined.

Inhalation exposure of experimental animals is the most difficult route of exposure. It is much easier to expose cells in vitro and although important information can be obtained from these types of exposure, the cells are usually in tissue culture alone and cannot react to the cell to cell interactions which would occur in the whole animal. Intratracheal instillation of dusts is also easier than inhalation, but the location and amount of dusts deposited in the lung following instillation is much different from that following inhalation. Therefore although the most difficult, inhalation is the most meaningful route of exposure for experimental animals and for humans. The establishment and maintenance of an inhalation facility is imperative for the determination of the causative agents in pulmonary diseases. Once established, as has been done at WVU, an inhalation facility can be used to test hypotheses as to the causative agents in and the cell types which react to inhaled dusts. The causative agents can be tested by alteration of the physical and chemical makeup of the dusts and the reacting cell types can be determined by supplying exposed animals to a number of experimental groups who will examine different cell types or pulmonary tissue and determine the changes brought about by inhalation of the dusts.

SCOPE OF WORK

This research is performed to correlate dust characteristics with alterations in the lung following inhalation and to indicate the causative agents involved in the pulmonary injury. Implicit within this plan is the development of an animal exposure facility, the selection of dusts, and the evaluation of lung alterations.

Animal Exposure Facility

An animal inhalation exposure facility has been developed at WVU. The facility includes two Hazelton 2000 chambers, each with a volume of about 64 ft^3 and capable of housing 144 small animals (Fig. 1). Both chambers receive air (15 scfm) which has been filtered and conditioned to 70°F and 50% relative humidity. Environmental conditions are monitored and controlled by a Zenith microcomputer (Fig. 2).

Animals are selected at random and placed in either the control chamber, which receives only the conditioned air, or the exposure chamber which receives coal mine dust in addition to conditioned air. Stale dust is aerosolized using a TSI 9310 fluidized bed aerosol generator while fresh dust is made and aerosolized in a Fluid Energy Processing and Equipment Model 0101-C6P Jet-O-Mizer mill. Dust concentrations in the exposure chamber are monitored with cascade impactors.

Table 1

Effect of Silica Exposure on Hamster Lung

Parameter	Control	Time After Silica Exposure		
		1 Week	4 Weeks	12 Weeks
Total Lung Volume (cm^3)	4.99 ± 0.19	4.36 ± 0.17	4.79 ± 0.16	5.84 ± 0.30^A
Large Airways (cm^3)	0.46 ± 0.05	0.30 ± 0.02	0.49 ± 0.07	0.39 ± 0.05
Large Blood Vessels (cm^3)	0.39 ± 0.03	0.36 ± 0.03	0.49 ± 0.03	0.44 ± 0.05
Distal Lung (cm^3)	4.14 ± 0.18	3.70 ± 0.16	3.81 ± 0.20	5.01 ± 0.25^A
Distal Lung Airspace (cm^3)	3.60 ± 0.13	3.14 ± 0.15	3.25 ± 0.19	4.15 ± 0.20^A
Alveolar Septa (cm^3)	0.54 ± 0.07	0.56 ± 0.04	0.56 ± 0.03	0.86 ± 0.09^A
Alveolar Mean Linear Intercept (μm)	55.5 ± 2.6	55.1 ± 2.5	57.3 ± 2.3	50.6 ± 2.9
Septal Thickness (μm)	1.99 ± 0.15	2.45 ± 0.15^B	2.47 ± 0.07^B	2.55 ± 0.19^B

Values are mean ± SEM
A = significantly different from all other groups ($P < 0.05$)
B = significantly different from control ($P < 0.05$)

Typical testing includes exposing Long-Evans rats to 5 μm dusts at a 30 mg/m^3 concentration, 16 hrs/day, 7 days/wk, for two weeks.

The exposure facility is available to researchers at Penn State, WVU, and NIOSH.

Selection of Dusts

Three general types of dusts are to be utilized: silica, coal mine dusts, and fresh versus stale dusts.

Silica is a known fibrogenic agent when inhaled alone and has also been postulated as an important causative agent in coal workers' pneumoconiosis. Although efforts have been made to elucidate the mechanism of pathogenesis of silicosis, the events which lead to the deposition of collagen and fibrosis in the lung following silica exposure are not completely understood. Several investigators have attempted to describe the tissue and cellular responses following silica exposure either following intratracheal instillation or inhalation. However, these studies have used relatively high doses and have only been concerned with qualitative evaluation of the morphological alterations. One goal of this research is to describe, in quantitative terms, the structural alterations in the lung following inhalation of silica (Min-U-Sil 10).

Coal mine dusts need to be well characterized to meet the goals of this research. Two types of coal mine dusts are to be used in this study. One type is supplied by the Pittsburgh Research Center of the U.S. Bureau of Mines and designated as 20/20 dust from the Pittsburgh bituminous seam. The second type is obtained from Dr. Richard Hogg at Penn State University and is designated as standard dust #1192. Both types of dusts are processed through a Donaldson classifier to ensure that about 70% of the dust is below 5 microns in size and 100% is below 10 microns. A goal of this research is to correlate lung alterations with the exposure concentrations and exposure durations of these dusts in the animal exposure facility.

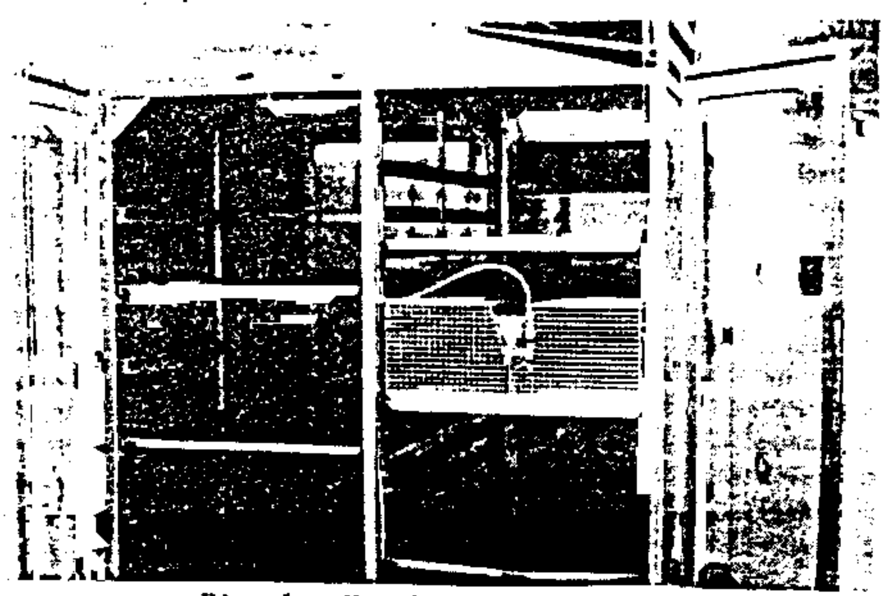


Fig. 1 : Hazelton 2000 Chamber with One of Six Cages Installed

Mine workers with the highest risk of developing pneumoconiosis are those who are exposed to freshly ground coal mine dusts. The possibility exists therefore that production of the dust causes changes in the dust which renders it more toxic than older, "stale" dust. Preliminary data support this hypothesis; namely, exposure of red blood cells to freshly produced dusts causes more cell lysis than does older dusts. Because in the red blood cell experiments the effects of "fresh" dust are time dependent, the experimental protocol will call for comparison of animals exposed to freshly produced dusts with animals exposed to the same dust which has been allowed to "age" for at least several hours.

There could be many types of chamical and/or physical changes that distinguish fresh from stale dusts. In 1980 Russian scientists Artemov and Resnik suggested that the discrepancy may be related to the excessive amount of short-lived free radicals present in freshly generated coal mine dust. Because of their short life, such free radicals would be absent in the "stale" coal dust used in most animal experiments. To test this hypothesis we have undertaken a systematic study of the generation, reactivity with oxygen and biological significance of free radicals in coal dust.

Electron spin resonance (ESR) is used as a technique for the direct detection of radical production and kinetics of decay. ESR signals from the newly generated radicals decrease with time on exposure to oxygen or when stored in biological buffers at a rapid rate. In vitro biological tests suggest that the reaction between the newly generated radicals and oxygen plays a significant role in the sample's cytotoxicity.

Techniques to Evaluate Lung Alterations

After the animals are exposed to selected dusts in the animal exposure facility, their excised lungs are examined predominantly by morphometrical techniques although electron spin resonance and x-ray diffraction techniques are also being used.

All animals are anesthetized by a single i.p. injection (0.6 ml/100 g body weight) of 1.0% aqueous Brevital sodium (Lilly). After exposure of the trachea, a catheter is inserted between the second and third tracheal cartilaginous rings. The catheter is connected to a three way valve allowing maintenance of a patent airway. At this time the anterior abdominal wall is opened and the diaphragm is punctured permitting collapse of the lung against atmospheric pressure and flow of fixative (1/2 strength Karnovsky's fluid containing .01% picric acid in 0.1 M phosphate buffer, pH 7.4) into the lungs is initiated. This fixative was selected since it has been shown to be satisfactory for light and electron microscopy. Lungs are inflated against a constant pressure of 20 cm H_2O for 1 hr. at which time the trachea is ligated and lungs, heart and other components of the mediastinum are removed, immersed in fixative and stored at 4°C overnight. Total lung volume (via fluid displacement) and weights of right (apical, middle, caudal and infracradiac lobes) and left (left lobe) lungs of each animal are recorded.

After fixation, each lobe is dissected free and sliced along the axis of the major intrapulmonary airway from the hilus to the periphery. Slices are taken from each lobe for routine light microscopy (LM) (paraffin embedment and staining of 5 μm sections, taken at 1 mm intervals, with hematoxylin and eosin). Slices from right caudal and left lung lobes of each animal are used for high resolution light microscopy (HRLM). These are gently minced into 1 mm^3 pieces, rinsed in phosphate buffer as above, postfixed in OsO_4 for 1 h, dehydrated in graded ethanol solutions, passed through propylene oxide and embedded in Epon-Araldite. Semithin sections (1 μm) of Epon-Araldite embedded material are cut with glass knives and stained with toluidine blue for HRLM. Randomization is assured at the lung lobe level since approximately 100 pieces from individual lobes are mixed in vials of fixative prior to removal of 10 pieces for HRLM.

Morphometric Procedures

Standard point counting techniques as described for the lung are used. Point counting of all light microscopic material is performed directly from glass slides using a drawing tube attachment which superimposes an image of the square lattice over the image of the tissue section. Analysis of stained, paraffin embedded sections from each lobe of each lung is performed using a grid overlay of 100 points with an interpoint distance (as determined by stage micrometer) of 0.2 mm. The number of points overlying structures of interest is used to estimate volume densities (V_V)for large blood vessels and airways as well as distal lung (respiratory bronchiole, alveolar ducts, sacs and alveoli) in 10 fields/animal. The second level of analysis is HRLM material. Slides are viewed at 625X and a grid overlay of 100 total points with interpoint distance of 20 μm is used. Points over air space and alveolar septal tissue are used to estimate V_V of each. Surface density of alveolar epithelium is estimated by counting intercepts of test lines with the epithelial surface.

Arithmetic mean barrier thickness of alveolar septa is calculated by dividing the volume density of septal compartment by the epithelial surface densities. Alveolar mean linear intercept length is calculated from the volume density of distal lung airspace and surface density of alveolar epithelial cells.

CONCLUSIONS

The goals of this research are to examine the effects of inhaled silica, coal mine dusts, and fresh versus stale dusts on the lungs of animals. Testing of stale inhaled silica dust has been performed, testing of coal mine dusts is presently being done, and the evaluation of fresh versus stale dusts is planned for the immediate future.

Qualitative evaluation of light micrographs from animals exposed to silica show responses typical of toxic dust exposures. Examination of tissue demonstrated cellular accumulations in the alveolar spaces and apparent thickening of the alveolar septa. These changes were present in animals at 1, 4 and 12 weeks following the termination of the two week exposure to silica.

Light microscopic morphometric data are presented in Table 1. Values for volumes are presented as absolute values so that any change in various tissue compartment volumes could be detected. Although control animals were examined at all three time points following the end of exposure, no significant differences were seen between any of the controls and therefore all control animal values were placed in a single group.

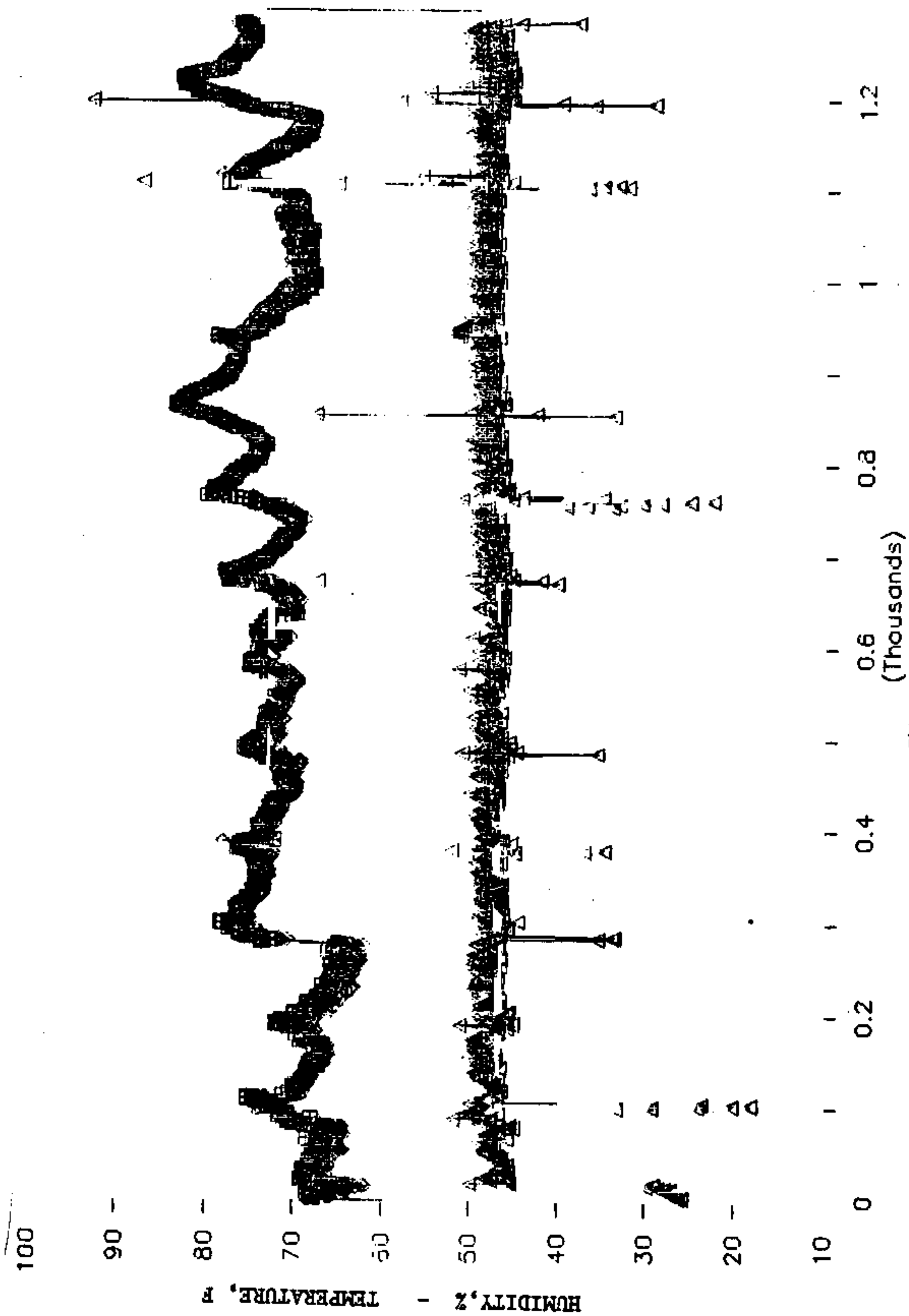


Fig. 2 : **Inhalation Exposure #2**

(3/15/88 – 3/30/88)

Twelve weeks following silica exposure significant increase in total lung volume was seen versus all other groups. When the total lung volume was divided into its constitutive parts it was determined that the increase in lung volume was caused by increases in both the distal lung airspace and alveolar septal volume (Table 1).

In order to determine if the changes in volume of distal lung compartments represents septal thickening and/or emphysema, alveolar mean linear intercept (the average distance between alveolar septal walls) and the septal thickness were calculated. No significant differences were seen in alveolar mean linear intercept. Alveolar septa were thicker in the 12 week group but significant increases in this parameter over controls were also seen in the 1 and 4 week postexposure groups.

Data presented in this light microscopic study support and extend the findings of qualitative evaluation of pulmonary tissue following silica exposure. Wehner, et al., reported that inhalation of silica lead to increases in lung volume as early as four months postexposure. They did not however present data as to the exact cause and site of the increase in lung volume. Our study has also found a similar increase in lung volume in silica exposed animals at 12 weeks postexposure but by using morphometric techniques it was determined that the increase is due to changes in both the distal lung airspace and septal volumes.

Alteration in these volumes may be expected if, as is well documented, silica exposure leads to fibrosis and also to emphysema. However, this conclusion is not substantiated by our data. If emphysema were present in the silica exposed animals, alveolar mean linear intercept values should increase. No significant differences were seen in this parameter at 12 weeks postexposure. In addition, if increases in septal lung volume is due only to increases in the septal thickness, then increases should only be present in the 12 week group and not in all groups of exposed animals. Since tissue volume and air space have increased without an increase in alveolar size one interpretation of the data is that the number of alveoli has increased in the silica exposed group 12 weeks after the end of the exposure. Similar increases in alveolar number in response to toxic inhalants has been reported previously by Hyde, et al.

Increases in septal thickness at all time points following the termination of exposure may be an indication of either interstitial edema, interstitial cellular accumulation and/or fibrosis. The exact nature of the septal response and the cells involved in the response are currently under investigation by performing morphometric examination at the electron microscopic levels. Data obtained at that level of investigation should enhance the understanding of the cellular and tissue responses following silica inhalation.

CONTINUING WORK

Work is continuing to make the inhalation facility generally available to the researchers in the Generic Mineral Technology Center for Respirable Dust. The facility has provided exposed animals to Penn State researchers (Bhavandndan, Demurs), WVU (Cilento), and NIOSH (Castranova, Wallace). Planned exposures are for Bartlett (Penn State) and Sneckenberger (WVU).

Exposures using stale coal mine dusts (BOM 20/20) have been made, and animal tissues are being analyzed at 1, 4, and 12 week periods post-exposure.

Fresh coal dust generation equipment has been tested, and animal exposures are planned in the immediate future.

TECHNOLOGY TRANSFER

Many publications and individual interactions have resulted from this research. Three co-authored publications on inhalation technology, two on morphometric analysis, and one on free radical formation have resulted from this effort. Five master's level students in mechanical engineering, industrial engineering, and physics, and one Ph.D. student in chemistry have been supported.

WV8/USBM 5407

Airway Reactivity in Coal Miners

Abrons, H.; **Petsonk**, E. L.; Daniloff, E.; Niggemyer, M.

INTRODUCTION

The effects of coal mine dust on the human lung have been studied extensively. Several conditions, particularly coal workers' pneumoconiosis (CWP), have been widely accepted as caused by underground coal mine dust exposure. CWP is a condition resulting from foci of dust accumulation in the lung, and often produces nodular shadows on chest radiographs. Changes in the mechanical properties of the lung can be identified in the presence of CWP, but disabling lung impairment is unusual in the absence of the advanced form (progressive massive fibrosis). Since CWP is a distinct disorder, there is no doubt regarding its relationship to coal mine dust exposure. Several other disorders have been related to coal mine dust exposure, including chronic cough and sputum production (chronic bronchitis), emphysema, and decreases in lung function. When found in an individual miner the relationship of mine exposures and severity of impairment is more controversial, since these conditions are also associated with exposure to other inhaled materials, particularly tobacco smoke.

Decreased lung function related to coal mine dust exposure, after accounting for tobacco smoking, has been documented in several large groups of miners followed prospectively for over ten years. Recent analysis has suggested that a significant minority of miners develop severe lung dysfunction when exposed to historically high dust levels. Regulations have been promulgated mandating reduced exposure to respirable mine dust, and it is unlikely that the functional losses seen in the past will continue. However, since these regulations were directed at reducing the incidence of CWP, it is not certain that miners will also be protected from declines in lung function. Controversy remains concerning why, among apparently similarly exposed miners, only some will develop severe lung impairments. Different authorities propose cigarette smoking, constitutional factors (e.g. airway hyperreactivity), or variation in dust exposures alone, as explanations for the disparate responses.

RATIONALE

The exact mechanism(s) for development of lung damage in coal miners, and their relationship to symptoms remain unclear. Recent investigations have suggested that, prior to the development of identifiable physiologic lung dysfunction, inflammatory changes can be identified in the lung cells of exposed individuals. These inflammatory changes may be manifest by symptoms, such as cough and sputum production, or by changes in the lungs' acute responses to inhaled materials. Interest has focused on acute ventilatory responses of the lung, termed "airway reactivity", to inhaled nonspecific irritants, such as dust. Several investigations have suggested that the presence or development of airway hyperreactivity may be important in the pathogenesis of chronic, irreversible lung disease in the general population, and in dusty occupations including coal miners. In a recent review of occupational airways diseases, an internationally recognized researcher suggested that "There is good reason to examine long term decline in airway function in relation to acute airway reactions to all occupational exposures." (Becklake, MR Chronic Airflow Limitation: Its Relationship to Work in Dusty Occupations, Chest 88:608-617, 1985). The goal of this project is to define this relationship in coal miners and non-mining controls.

The project has been investigating the relationship between airway reactivity and long term changes in symptoms and lung function in current underground coal miners and controls. Major hypotheses being tested are: 1) The presence of airway hyperreactivity in underground coal miners is related to coal mine dust exposure, and 2) Irreversible loss of lung function in underground coal miners is related to the degree of airway reactivity. The influence of tobacco smoking and coal mine dust exposure on lung function will also be evaluated. Upon completion of the final two years of this five year investigation we will determine if prolonged coal mine dust exposure leads to increased airway reactivity, and whether airway reactivity testing can predict the development of symptoms and decreasing ventilatory capacity in coal miners, after the effects of smoking and dust exposures are taken into account.

SCOPE OF WORK

Since human subjects are involved in the project, approval of the Institutional Review Board of West Virginia University was required and received. All potential volunteers received a complete explanation and signed an approved consent form.

The design of the project entailed identification of a cohort of volunteer underground coal miners and a comparable group of non-mining controls recruited from local industries without known respiratory hazards. The baseline evaluation consisted of a symptom questionnaire, occupational and smoking histories, spirometry, and a brief airway reactivity test. Participants are followed with a brief questionnaire and spirometry every six months. Dust exposures in the mining group are estimated based on data collected by the mine operators and the Mine Safety and Health Administration, as well as an industrial hygiene survey to be performed under the auspices of the project. After five years of follow-up, the complete questionnaire and airway reactivity testing will be repeated.

The methods selected for the project were modifications of tested and accepted techniques for epidemiologic investigations. Symptoms and demographic information were obtained using a self-administered modification of the British Medical Research Council Respiratory Symptom Questionnaire. A complete occupational and smoking history was also included. Spirometry is performed using techniques and equipment

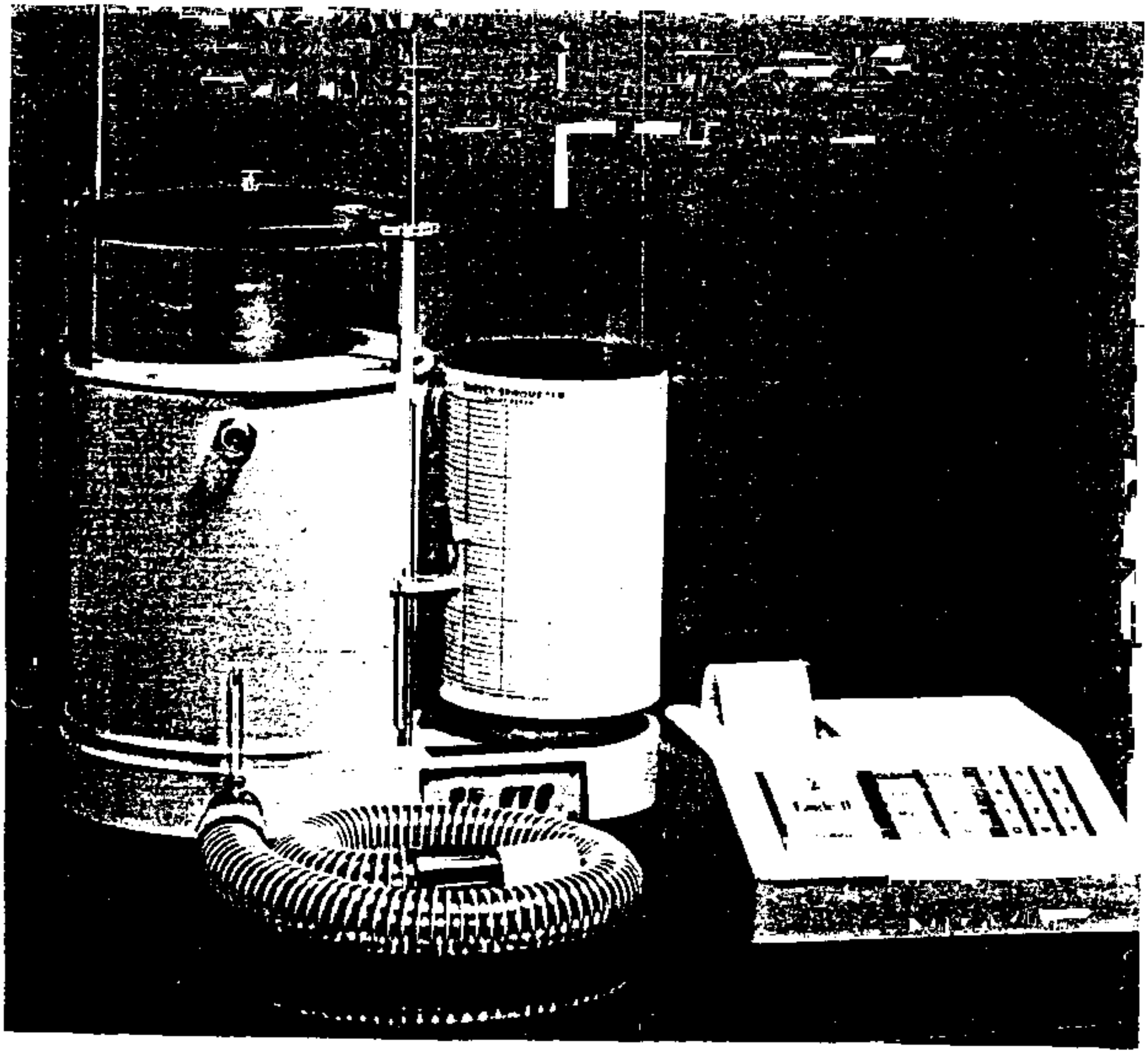


Figure 1. Spirometry equipment used in Airway Reactivity Project.

recommended by the American Thoracic Society. An accurate and reproducible measure of an individual's airway responsiveness can be obtained using a pharmacologic provocational agent such as methacholine. The airway reactivity test selected was a modification of a published technique used in other similar investigations. Dust sampling will be performed using standard gravimetric techniques with the addition of mineralogic analyses.

The goals of the project were related to the appropriate methodological and statistical design considerations in order to determine a sample size. It was apparent that detection of important differences in lung functional declines related to airway reactivity would require a minimum of three years of follow-up of a minimum of 128 subjects in both the mining and control groups, for a total of 256 participants with complete data. To allow for attrition due to transfers and disability, as well as incomplete follow-up, the project was designed to enroll up to 500 subjects and assure follow-up for 5 years.

A total of 478 volunteers were enrolled in the cohort. From this number must be excluded individuals who 1) had abnormal lung function at the baseline evaluation, 2) were unable to adequately perform the tests, and 3) withdrew prior to completion of the initial testing. At this writing, 419 subjects have complete and interpretable results, and an additional 26 are potentially interpretable after completion or clarification of some results.

AIRWAY REACTIVITY IN COAL MINERS

ANALYSIS OF BASELINE DATA

Table 1 Comparison between selected variables for miner and control groups.

	MINERS	CONTROLS
Number of Subjects (complete data)	200	228
Mean age (years)	38	41
Mean height (inches)	70.2	69.8
Mean education (years)	13	13
% current smokers	32	25
% non-smokers	44	45
Mean % P FEV1	107	104
% reactive to methacholine	25	29
Mean % P FEV1 of reactors	102	100

CONCLUSIONS

A preliminary inspection of the baseline results has been performed. Analysis of longitudinal results will be deferred until a minimum of three years of follow-up is completed on all study groups. Initial symptom and lung function data has suggested several hypotheses. The frequency of symptoms in non-mining controls was consistently greater in persons with airway hyperreactivity. In miners, this does not appear to be the case and exposure status may be a greater determinant of symptoms. Tobacco smoking is also a significant predictor of respiratory symptoms. Regarding lung function, miners show a significantly higher level of lung function than the controls, likely indicating a selection process prior to employment. Both miners and control groups show significantly lower lung function in the presence of increased airway reactivity. Although analysis of the baseline data revealed no apparent interaction between reactivity and exposure status, this could become manifest as long term follow-up is continued. As expected, smoking status was related to a significantly reduced lung function. Interestingly, the magnitude of the smoking effect on baseline lung function was smaller than that found with increased airway reactivity.

The prevalence of increased airway reactivity is inversely correlated with duration of work at the mine face. No miner in the group with the longest tenure at the mine face was noted to have airway hyperreactivity. Although this may simply represent selection bias, it also suggests that the development of increased reactivity may be a mechanism for selection out of the work force. Follow-up examinations will indicate whether increasing coal mine dust exposure correlates with increasing levels of airway reactivity.

APPLICATIONS OF RESEARCH RESULTS

Results to date are preliminary in nature, and more substantive conclusions await the analysis of longitudinal changes. It is also important to keep in mind that miners and controls are volunteers, and self-selection processes may be different between the two groups. Longitudinal data is less likely to be influenced by this effect, and only tentative observations are offered at this time.

In the analysis of the baseline spirometry data, airway hyperreactivity is associated with consistently lower lung function. This effect did not appear greater in the mining group than in the controls. Decreased baseline airway caliber can affect the measurement of airway reactivity. However, all individuals with abnormal lung function were excluded from the analysis. Thus, the reduced lung function seen in subjects with hypperreactivity is unlikely to be explained by baseline airway caliber.

Reactivity was a reasonable predictor of increased symptoms in the controls; this finding was not consistently seen in the miners. Mining status alone was a significant predictor of increased respiratory symptoms. The use of airway reactivity testing to exclude miners from working in higher dust exposed job categories is not justified on the basis of these preliminary results.

CONTINUING WORK

The project team is actively continuing follow-up testing of all groups. Energetic encouragement and motivation of project participants, including letters and telephone calls, is ongoing. To date, over 1462 subject test sessions have been completed. Files encompassing over 1.2 megabytes of data have been assembled and verified, including questionnaire responses, occupational and smoking histories, spirometry and reactivity tests, and dust data. Computer programs are operational for assembling and addressing individual participant test reports with interpretations, motivational letters, and scheduling of follow-up testing. Project team meetings have focused on intensive evaluation of baseline data, and a work plan for continued analysis and interpretation of results has been established.

Major emphasis will be given this year to a large industrial hygiene survey of participating miners. This will allow a closer comparison of the response variables and current exposure measures, including mineralogic analyses.

NORMAL

```
            AIRWAY REACTIVITY PROJECT - SPIROMETRY RESULTS CHART
            ----------------------------------------------------

            BELOW NORMAL <--------NORMAL--------> ABOVE AVERAGE
DATE          -70%-------80%-------90%-------100%------110%-----

03/23/86
                                                    111%  *
                                              101%  X

11/11/86
                                                106%  *
                                            98%  X

05/18/87
                                                   109%  *
                                               103%  X

11/18/87
                                                   109%  *
                                             100%  X

05/23/88
                                                  108%  *
                                              102%  X

            ----------------------------------------------------
'*' INDICATES FEV1 RESULT, 'X' INDICATES FVC RESULT
```

ACCELERATED DECLINE

```
            AIRWAY REACTIVITY PROJECT - SPIROMETRY RESULTS CHART
            ----------------------------------------------------

            BELOW NORMAL <--------NORMAL--------> ABOVE AVERAGE
DATE          -70%-------80%-------90%-------100%------110%-----

03/27/86
                                                             120%  *
                                                   110%  X

11/12/86
                                                        116%  *
                                                107%  X

05/20/87
                                                    112%  *
                                                106%  X

11/18/87
                                                   110%  *
                                                107%  X

05/26/88
                                                 109%  *
                                             102%  X

            ----------------------------------------------------
'*' INDICATES FEV1 RESULT, 'X' INDICATES FVC RESULT
```

Figure 2. Typical spirometry reports to volunteers: Change in lung function over time.

TECHNOLOGY TRANSFER

The investigators are in continuing contact with other researchers in the field. Preliminary results have been presented at the Generic Technology Center Conferences, as well as in poster form at the 1988 national meeting of the American Thoracic Society. The latter abstract was published in April 1988. Further reports will be forthcoming as data analysis proceeds. However, the project's major results will require analysis of the completed five year longitudinal follow-up.

WV9/USBM 5408

Effects of Respirable Dust on Release of Superoxide From Pulmonary Alveolar Macrophages

Cilento, E. V.; **Lantz**, R. C.; DiGregorio, K.

INTRODUCTION

The major objective of this project is to develop a better understanding for the role superoxide release (O2-) by pulmonary alveolar macrophages (PAM) plays in the basic functions this cell provides for protecting the lungs against inhaled dusts and bacteria. Specifically, it is not understood whether certain dusts (or constituents of dusts), inhaled over a period of time, can alter the ability of this cell-type to remove foreign material from the lung. Also, it is not known whether dysfunction of PAM occurs which may result in an underproduction or an overproduction of superoxide; either of which may be harmful to normal lung tissue. In this project a novel technique has been developed to quantify superoxide release by single PAM. This has permitted study of the effects of different dusts, concentrations of dust, and time of exposure on O2- release by PAM.

A multifaceted approach has been used in this research project, which encompasses the following: (1) study of superoxide release by single PAM isolated in culture, when contacted directly with different concentrations of dusts suspended in the medium; (2) study of superoxide release by PAM after *in vivo* exposure to dusts in inhalation chambers for known periods of time (in conjunction with WV 05); (3) development of a mathematical model to describe the kinetics of superoxide release by single cells; and (4) development of computer analysis methods to improve image detail that potentially can provide further insight into intracellular events occurring during O2- release. This also may ultimately provide a rapid, quantitative clinical assay to assess antimicrobial functions related to O2- production by PAM.

RATIONALE

PAM are free cells found in the lungs which protect the lungs by removing foreign debris and bacteria. This is accomplished, in part, by the process of phagoctyosis, whereby foreign matter is engulfed and internalized into a vesicle known as a primary phagosome. Phagocytosis involves not only ingestion but also the chemical breakdown of inhaled dusts and the killing of microbes. Bacterial killing is partially due to the respiratory burst, which is a metabolic response of the cell to foreign substances that results in the production of highly reactive antimicrobial agents by the partial reduction of oxygen. Detoxification is accomplished by the actions of the oxidizing agents produced during the respiratory burst.

Superoxide undergoes either spontaneous or enzyme-catalyzed dismutation reactions to form hydrogen peroxide (H_2O_2) and subsequently hydroxyl radical ($OH^{\cdot}$) and singlet oxygen ($O_2{}^1$) (Figure 1). However, while these oxygen metabolites aid in the killing of microbes they also may destroy endogenous tissue. Superoxide has been linked to the aging process and to many diseases including emphysema, diabetes, and cancer.

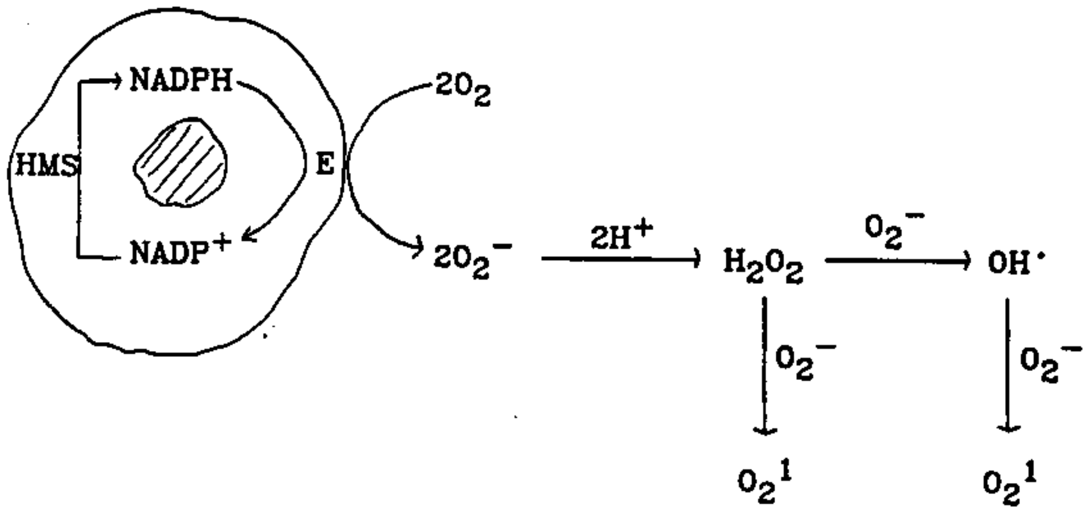


Figure 1. Schematic of PAM showing O2- production and the subsequent dismutation of O2- to H_2O_2 and formation of OH and O_2; E =NADPH oxidase; HMS=hexose monophosphate shunt.

Thus, understanding the production of superoxide is extremely important since an abnormally low production could result in damage by inhaled dusts and bacteria while an abnormally high production could result in damage to the lung tissue by the phagocytes themselves.

Inhalation of respirable sized mineral dusts, such as respirable quartz (silica), coal mine dusts (CMD), and asbestos, may result in various pulmonary disorders. PAM are thought to play an important role since evidence suggests that the first step in fibrogenesis is an interaction of dust particles with PAM. In vivo exposure of animals to mineral dusts generally results in increased numbers of PAM and often in increased respiratory burst activity. Superoxide release, migratory patterns, phagocytic behavior, and secretory potential of PAM, therefore, have been implicated to be pivotal events in the pathogenesis of pulmonary diseases. In addition to resident PAM, an influx of PAM into the lung or production of new macrophages generally occurs in response to fibrogenic dust inhalation. Further, PAM attract fibroblasts by secreting chemoattractants and enzymes. These cells, which normally synthesize proteins and collagen during repair of tissue, also may contribute to the fibrogenic responses. Thus, PAM may be involved in pulmonary disorders through failure or partial loss of their defensive capability, or indirectly, through release of other mediators.

While O2- release, and other biochemical indicators of PAM activity have been extensively studied using spectrometric methods on whole populations of cells in culture the results remain conflicting, and many of the mechanisms involved remain unknown. In vitro exposure of PAM to fibrogenic dusts, such as quartz, often results in cell death and subsequent release of lytic enzymes. In general, cell death (or red blood cell lysis) has been used as an indicator of the toxic effects of dusts on PAM. However, inflammatory mediators are thought to be released only from living cells rather than those killed during initial contact. Thus, damaged macrophages still capable of carrying on cell functions, may be more important to the process of the host response to mineral dusts. For this reason, effects which occur due to sublethal dosing are gaining prominence in studies of fibrogenesis.

In summary, pulmonary alveolar macrophages remove foreign particles and microbes by phagocytosis and by the detoxifying and digestive actions of various enzymes. In this process, oxygen is reduced to superoxide which undergoes various reactions to produce other oxygen metabolites that destroy the bacteria and other foreign microbes; but they may also damage lung tissue. Superoxide production is heterogeneous and highly complex and many of the mechanisms of activation, initiation, and termination of superoxide production as well as the kinetics involved in the production and measurement of superoxide remain to be elucidated. The purpose of this research is to develop a better understanding for the health effects associated with inhalation of airborne mine dusts; especially the role PAM play in removing dusts from the lung.

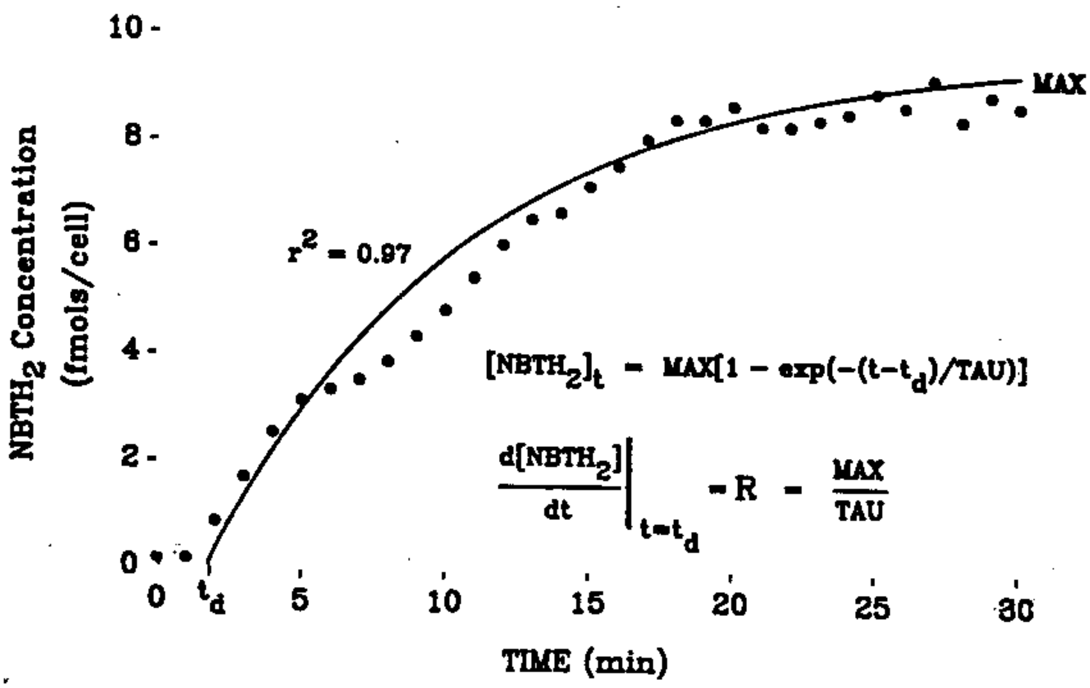


Figure 2. O2- produced versus time measured for a single PAM. The curve is the regression fit to the log linearized form of the eqn.

SCOPE OF WORK

The research being performed under this project has been designed to ensure coordination with results being obtained by other investigators in this Center studying the health effects of inhaled dusts on other functions performed by PAM. The study has been divided into three areas: (1) effects of in vitro exposure; (2) effects of in vivo exposure; and (3) theoretical model development.

Experimental Studies

The experimental protocols used to analyze PAM for superoxide release (Figure 2) were developed and extensively tested during years 01 and 02 of this project (years 02 and 03 of the Center). All dusts used have been obtained from the dust bank maintained by the Center.

In Vitro Experiments. The effects of acute in vitro exposure to respirable quartz and kaolin on superoxide release were tested using either a high or low dust concentration as well as control dishes containing no dust (Figure 3). The low dose of quartz decreased the maximum amount of O2- produced (Max) 38% compared to control while the high dose did not. The maximum rate of diformazan production, R, decreased 31% and 24% for the low dose and high dose when compared to control. In vitro exposure of PAM to a low dose of sonicated CMD suspensions resulted in increased O2- production. In contrast, the low or high dose of kaolin (non-fibrogenic dust) did not significantly change either Max or R. These results suggested that O2- production may be a better indicator of PAM dysfunction than cell death, which gives comparable results for quartz and kaolin and that O2- release may be an important indicator of pathogenicity and PAM dysfunction. The effects of mineral dusts in the presence of surfactant (tween 80) coating similar to that found in the lung also were examined. No changes in O2-production were observed following in vitro exposure of quartz, kaolin, or CMD in the presence of this surfactant. These results suggested that lung surfactant may alter the acute toxicity of these dusts.

After attachment to the culture dish, PAM can not be restimulated. However, our recent findings show that O2- production from adherent PAM, incubated with serum, was possible (Figure 4). Serum alone did not stimulate adherent PAM indicating serum is necessary but not sufficient for stimulation. This result supports suggestions that in vivo serum may condition PAM to produce O2-.

In Vivo experiments. The effects of in vivo exposure of animals to respirable quartz (20 mg/m3, 16 hrs/day, 5 days/wk of MIN-U-SIL 10, 95% <5 um) was tested by housing animals (2-4 weeks) in the WVU inhalation facilities (WV 05). Control (no quartz) animals also were kept in identical inhalation chambers for 2-4 weeks. Following exposure, animals were removed from the inhalation chambers and housed in WVU animal-care facilities for 3, 10, or 31 days post-exposure. This approach permitted analysis of the effects of length of in vivo exposure and post-exposure time on PAM analyzed for O2- release. In vivo exposure of all animals to respirable quartz increased Max 36% and R 29% compared to control animals. PAM from exposed animals showed an increased O2- production for up to 10 days after exposure followed by a decrease back to control levels by 31 days (Figure 5). Interestingly, the 3 day group results suggested that there was activation and/or recruitment of PAM into the lung. This finding is being studied further by analyzing cells immediately after a very brief exposure.

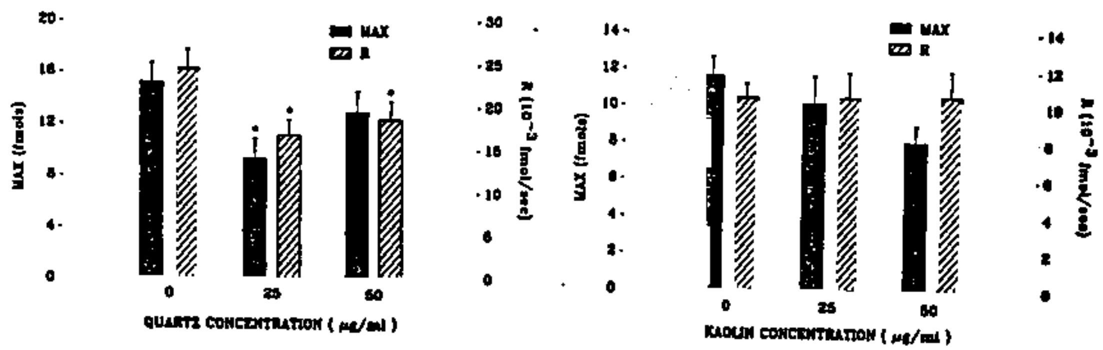


Figure 3. Max and R for different concentrations of kaolin and quartz obtained for in vitro exposure of PAM.

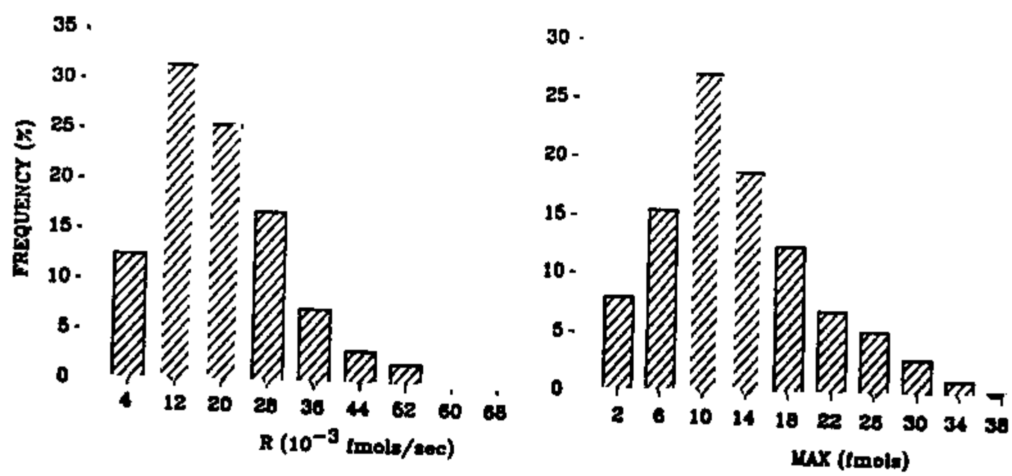


Figure 4. Relative frequency distribution (%) for R and Max obtained from 336 control PAM from 54 animals.

Also, several more in vivo exposures have been performed this year using CMD but the analysis has not been completed yet, although it is clear that CMD has been phagocytosed by the cells.

Theoretical Model Development

A kinetic model was developed to describe the production of superoxide by single PAM. Model predictions were compared to experimental results obtained from single rat PAM. The O2- was quantified by measuring the reduction of nitroblue tetrazolium (NBT) to diformazan precipitate ($NBTH_2$) from video-recorded images of individual cells (Figure 2). The kinetic model considered three reactions: (1) the production of extracellular O2- from the reduction of oxygen by NADPH oxidase using intracellular NADPH as the substrate, (2) the subsequent dismutation of O2- to form H_2O_2, and (3) the reaction of O2- and NBT. NBT specificity of O2- was analyzed by comparing results in the presence and absence of superoxide dismutase (SOD) which catalyzes the dismutation of O2- to H_2O_2.

Measured PAM heterogeneity (Figure 6) was accounted for by varying the concentration of intracellular NADPH, its rate of depletion, and the concentration of intracellular NADPH oxidase in the kinetic model. Model predictions (Figure 7) compared favorably with experimental results except when SOD was present. This discrepancy may be due to diffusional limitations since NBT is a relatively small molecule (818 D) compared to SOD (34 kD). In addition, the cell surface is both ruffled and negatively charged, which may introduce steric hindrances and/or electrostatic effects since SOD is also negatively charged.

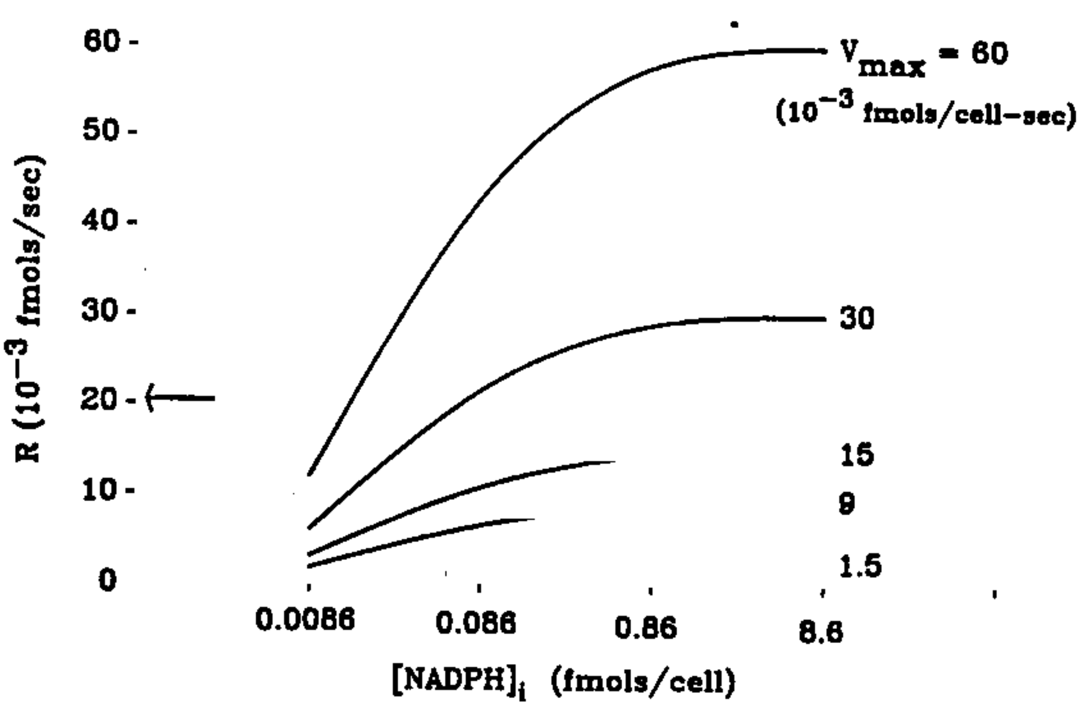


Figure 5. Model predictions for R from single cells versus its initial intraceullar NADPH concentration for different values of V_{max}.

CONCLUSIONS

A general conclusion of this research thus far is that a sensitive, quantitative assay to study individual PAM function related to O2- release has been developed which shows that respirable dusts do effect O2- release by PAM. This approach has the potential to provide information not possible using whole-cell cultures and to critically assess: (1) the effects of *in vitro* and *in vivo* exposure to mineral dusts on PAM function; and (2) the role O2- production by PAM plays in protecting the lung from inhaled dusts and bacteria.

Several conclusions have been obtained from the experiments and theoretical results of this project. Superoxide release may play an important role in silicosis and other respiratory diseases. In vitro assays on large numbers of cells in culture using hemolysis of red blood cells or release of enzymes from PAM following dust exposure have been used to analyze cytotoxicity. In such systems, kaolin has been found to have an activity comparable to quartz on a mass basis. However, in vivo, quartz is highly fibrogenic resulting in silicosis while kaolin is not. Therefore, the assay results do not correlate with the in vivo effects of quartz and kaolin. In this study, in vitro exposure to kaolin did not significantly effect PAM compared to control. These results correlate more closely with in vivo exposure effects and help support the usefulness of this quantitative superoxide assay in evaluating the effects of respirable dusts on PAM. It has been hypothesized that the difference between assay results and in vivo data may be due to dust interaction with pulmonary surfactant in the lung. The results obtained in this research support this hypothesis but further studies are needed.

Interestingly, in vivo exposure to quartz resulted in increased O2-production rather than the decrease observed in vitro. This difference may be due to a change in cellular function from the in vivo to the in vitro environment. However, the in vitro results also may be due to the initial (acute) response to quartz produced immediately after contacting the cells with dusts. In contrast, the in vivo responses seen resulted from a longer contact time since animals were exposed 2-4 weeks followed by a post-exposure period before analysis. Thus, it may be possible that quartz causes an initial injury to PAM resulting in decreased O2- production followed by recruitment or activation of PAM having increased production capabilities. This is supported by the fact that PAM analyzed 3 days post-exposure exhibited a wider range than the control or 10 and 31 day post-exposure groups. Specifically, perhaps two populations of PAM are present: (1) cells injured by initial or long-term dust contact, resulting in decreased O2- production and lytic enzyme release; and (2) recruited or activated PAM which exhibit increased superoxide production. In conclusion, studies to examine this further as well as the effects of in vitro and in vivo exposure of PAM to respirable coal mine dusts are currently in progress.

APPLICATIONS OF RESEARCH RESULTS

The combined research and development results obtained in this project thus far provide the basis for elucidating a better understanding of PAM function related to the phagocytosis of inhaled dusts. The collaborative efforts and coordinated activities possible in the Center provide a strong synergistic effect that would not otherwise be possible.

(1) The in vitro results provide the basis for quantifying the acute effects of dust-cell contact (or constituents of dusts) on O2- release by PAM. Importantly, the addition of serum to

the culture medium permits use of this single cell technique to study re- stimulation of the same cell by different soluble dusts after adherence of the cell to the culture dish.

(2) The in vivo results provide the basis for critically examining the effects of long-term exposure to airborne dusts on superoxide release by PAM.

(3) Continued refinement and development of the methodology to measure other cellular indicators of function (or dysfunction) will provide a means to assess and improve present understanding of the phagocytosis process in health and disease.

(4) PAM are complicated cells that have many important functions. Continued collaboration and comparison of our results with ongoing research being done by other medical investigators in the Center, studying the effects of dusts on other functions performed by PAM, will ultimately lead to a much improved understanding of PAM in health and disease. This ultimately should lead to improved clinical therapies for treatment of pulmonary disorders.

(5) The theoretical kinetic model developed to explain the kinetics involved in O2- release predicts the considerable heterogeneity observed in production by PAM. Model development to incorporate external diffusional and steric hindrances, and other intracellular pathways involved in O2- release are continuing. This will provide further insight into the antimicrobial functions provided by PAM as well as the role PAM heterogeneity might play in protecting the lungs.

CONTINUING WORK

Based on the results and conclusions obtained to date, continuing work is focused on several specific objectives. Experimental work is designed to critically examine the effects of repeated exposure to different dusts (or concentrations of dusts) on the ability of the same cell to produce and release superoxide. The ability to re-stimulate the same cells in vitro now provides the basis to examine these effects. Concomitantly, the ability to maintain animals for long periods of time in the WVU inhalation chambers (in collaboration with WV 05) will permit evaluation of the effects of chronic exposure to dusts (and concentrations) on the ability of PAM to remove inhaled microbes from the lung. Theoretical work is underway to refine and evolve the kinetic model to be able to examine the effects of diffusional and steric hindrances on release of O2- by PAM.

Very importantly, continued collaboration among the investigators in the Center studying different PAM functions is exciting and has the potential to provide a significant improvement into present understanding of PAM function. This collaboration is becoming more established and is a key focus of this project as the Center continues into 1988.

TECH TRANSFER

A number of publications as well as many useful collaborative discussions with colleagues in the Center have resulted from this work. One refereed paper, two symposium papers, one M.S. thesis, one Ph.D. dissertation, and five national presentations have resulted from the study to date. One paper presented this year at the FASEB meeting was the winner of the Dr. Harold Lamport Award given by the Biomedical Engineering Society. Four papers are presently under peer-review and one thesis is continuing. The continued research is expected to involve more dissertations and refereed publications.

WV14A/USBM 5413

Development of New Early Detection Methods for Black Lung: Tracheal Acoustic Impedance of Lung Air Passages

Sneckenberger, J. E.

INTRODUCTION

An important advancement toward the prevention of coal workers pneumoconiosis (CWP) in our country's miner population would be the early detection of airway disorders in lungs. Early CWP lung dysfunction is associated with changes in the physical functioning of the peripheral air passages of the lung. These remote lung airways, however, account for less than 15% of the lung's total airflow resistance. Thus, since most of the conventional clinic methods used to assess lung dysfunction do so by measuring lung airway resistance, there is need for an alternate method to better detect the initial beginnings of CWP so that the disabling forms of CWP can be prevented in the miner population.

A recently developed acoustic impedance measurement technique exists that holds considerable promise for assessing small air flow alterations in the peripheral airways of lungs. The dynamical condition of these remote lung airway passages is contained in the spectral measurement of the tracheal acoustic impedance for the lung. This lung acoustic impedance data provides statistical insights of the lung's dysfunction. It is further expected that effective lung modeling will enable this measured acoustic impedance information to be related to actual structural lung mechanics such as airway wall absorption and compliance.

RATIONAL

Acoustic measurement techniques have recently been applied in several non-lung situations where the structure of the system to be analyzed could not be easily observed. Acoustic wave reflections has been analyzed to infer core information about geophysical layers below the earth surface. Similarly, acoustic pulse signals have been utilized to learn about the geometry of the vocal tract during speech science experiments. Previous investigators have also used acoustics to study the lung. J.J. Fredberg, et.al. in their 1984 publication "Reproducibility and Accuracy of Airway Area by Acoustic Reflection" report on their measurement of upper airway structure using short acoustic pulses. K. Jayaraman and D. Frazer reported at a 1987 JASA

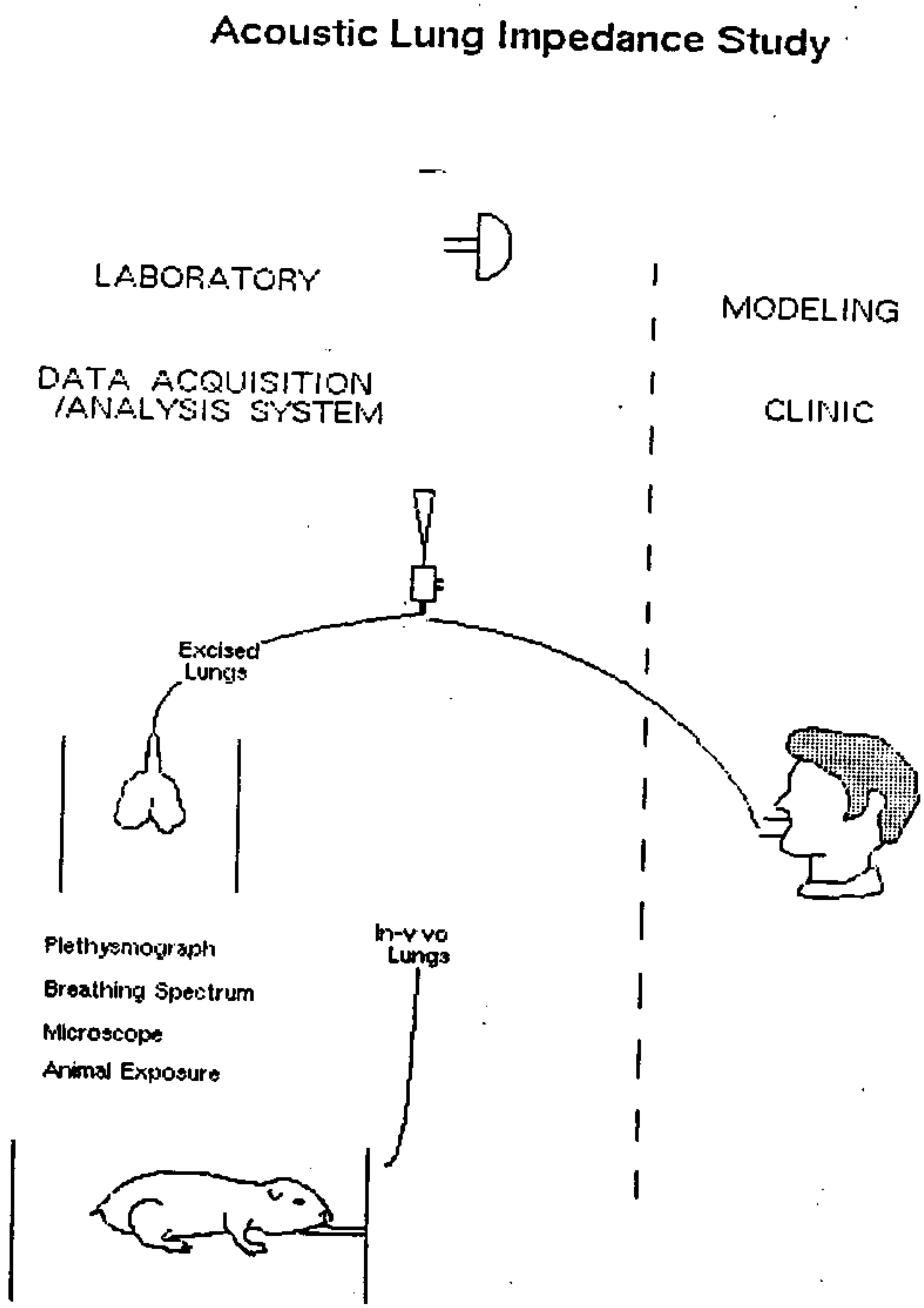
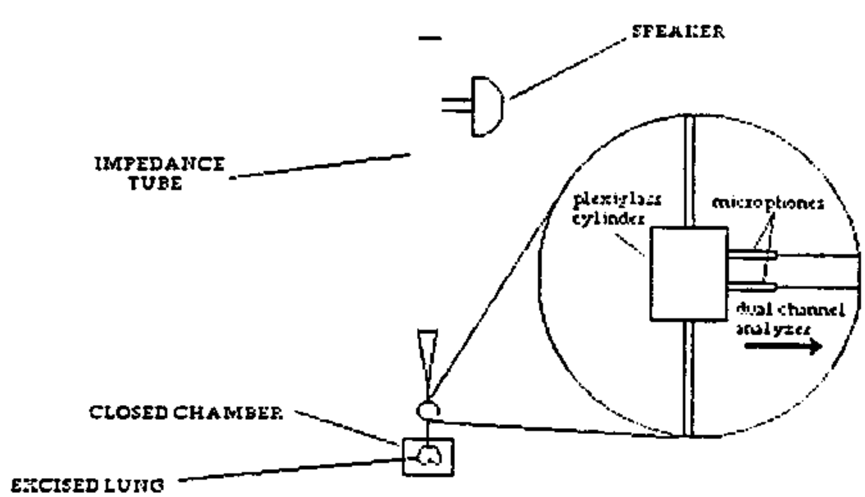


Figure 1. Schematic of Project Laboratory/Clinic Activities.

Meeting their measurement of broadband (100 to 6400 Hz) acoustic reflections to study the lung impedance of rats at various transpulmonary pressures. R. Peslin and J.J. Fredberg, who together have recently coauthored an extensive manuscript titled "Oscillation Mechanics of the Respiratory System" as Chapter 11 in the 1988 Handbook

TRACHEAL ACOUSTIC IMPEDANCE
OF LUNG PASSAGES



$$Z_L = \left(\frac{H_L - H_0}{H_L - H_C}\right) \Big/ \left(\frac{H_E - H_0}{H_E - H_C}\right)$$

Figure 2. Schematic of Acoustic Impedance Facility.

of Physiology state in regard to clinical applications that the acoustic measurement technique "is a potentially powerful method for exploring the respiratory system. Together with modeling and parameter estimation it should prove valuable in detecting and interpreting abnormalities in disease. However, little has been done in that direction." This project is directed exactly in that direction.

SCOPE OF WORK

The three main focuses for this project are shown schematically in Figure 1. Two of these three focuses involve laboratory studies: excised lung studies and invivo lung studies, both with animals. The third focus involves human lung studies in the clinic. The animal laboratory studies involve facilities to expose animals to lung disease and to measure lung quality; breathing pattern and capacity, microscopic assessment, as well as acoustic impedance (See Figure 2). In addition, a computer-based system to provide comprehensive data acquisiton and analysis is one of two associated focuses for this project. The other associated focus is the theoretical modeling of lung mechanics (See Figure 3).

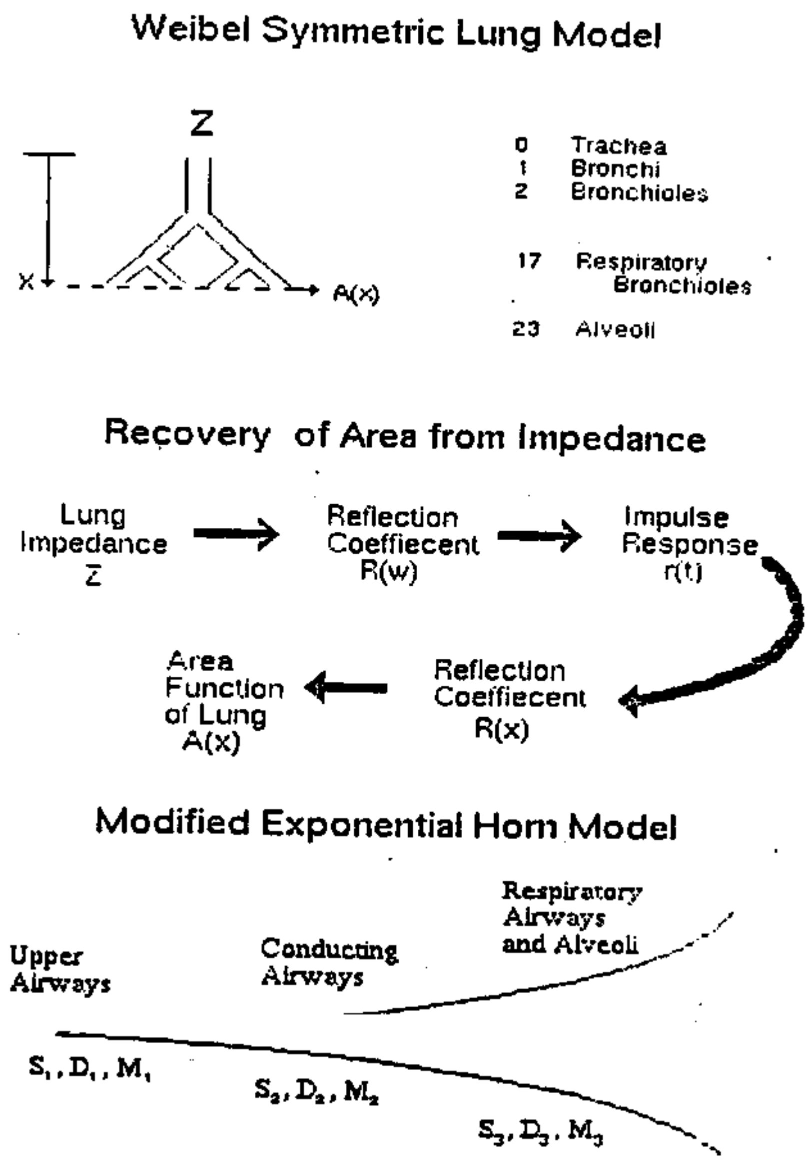


Figure 3. Schematic of Lung Mechanics Modeling.

The project efforts for the first year of this research involved the development of animal laboratory facilities and their initial use to determine the sensitivity of the acoustic impedance method. There were two specific objectives: to improve the inhalation chamber's control of silica concentration and to implement a common data acquisition/analysis system. Additional project objectives during last year were focused on development of both animal invivo and human clinical acoustic impedance facilities.

This year's project effort has as its two main objectives the completion of animal laboratory assessment of this acoustic impedance method and the finalization of a conceptual clinical acoustic impedance facility. In addition, a more detailed model of lung mechanics will be sought.

The focus of next year's proposed project will have as its primary objective the achievement of a clinical acousticla impedance facility that will have conducted initial human participant testing to document the facilty's capabilities. Another interest will be to extend the lung mechanics modeling based on this initial clinical testing. The projected objective of the project's fourth year will be to apply this clinically proven method to the assessment of lung drug treatment.

Theoretical Studies

A physical model of the lung and trachea is being developed using a flexible tube attached to a flexible absorptive exponential horn to give some physical meaning to experimentally measured differences. Each component of this model has mass, damping, and stiffness elements that can be varied to give this tube-horn assembly a similar theoretical impedance as the experimentally obtained acoustic impedance of animals. Using this modeling technique, the physical changes in these lung airway wall parameters during inspiration and experation can be determined. Thus, physical dysfunction changes in the lung associated with silicosis can be assessed.

Experimental Studies

The acoustic impedances of twelve rat lungs were measured at frequencies between 100 and 6400 Hz. Rats were divided into a silica exposed group (N=5), a sham exposure group (N=4), and a control group (N=3). The silica exposed group were injected intratracheally with silica solution, while the sham group received saline. Between four and six weeks after the injections, all lungs were excised and degassed. Lungs were suspended in a pressure chamber, with the trachea canula attached to the end of a tapered impedance tube. The pressure in the chamber was varied between -30 cm H20 and 6 cm H20 to simulate deflation and inflation. With pressure being held constant, the impedance tube was excited with random noise. A dual channel analyzer calculated H12(f), the transfer function between the two microphones. This function was used to calculate the lung's impedance at that pressure. The impedance spectra of the silica group were markedly different from the impedance spectra of the control and sham groups. The impedance magnitude spectra of a typical control or sham rat had three local maxima, occuring at approximately 1000, 2000, and 4000 Hz. The typical impedance magnitude of the silica group had a single local maximum, usually occuring between 3000 to 4000 Hz. This fact seems to confirm that this method can detect lung disease. Further research will indicate whether this method will be able to detect the onset of coal worker's pneumoconiosis.

CONCLUSIONS

The development of necessary animal laboratory capabilities accounted for an unexpectedly large amount of involvement during the initial year of the project. It became essential that research personnel for this project (primarily only one graduate research assistant initially) be knowledgeable about not only the equipment and procedures for the acoustic impedance measurement, but also the quality-of-life facilities (breathing spectrum and plethysmograph). In addition, it was necessary that project personnel become trained in both conducting animal exposures and lung extractions. This multidimensional facility involvement situation was eventually managed by adding two undergraduate research assistants to the project team.

The four main first year results were 1) an improved silica concentration control system was developed for the animal inhalation chamber to induce a more assured CWP-type lung exposure in individual animals, 2) a data acquisition/analysis computer system was specified that provides for common data collections from animal silica exposure to acoustic impedance measurement, for later comprehensive statistical analysis, 3) an 18 animal study conducted was visually observed to show substantial acoustic impedance measurement sensitivity in detecting the progressive development and nondevelopment of lung dysfunction over a three-week period for silica and saline tracheally-injected rats respectively, and 4) the modeling of respiratory mechanics has progressed to include compliant and massive walls for an exponential-type lung airway network structure.

Theoretical Results

An area function recovery program has been implemented. The program determines the equivalent area from acoustic impedance measurements. Satisfactory results have been obtained when applied to the impedances derived from a straight tube and a straight tube connected to an exponential horn.

The Ware-Aki algorithm, which mathematically recreates the lung cross-sectional airway area as a function of sound-propagated distances in the lung, has been made operational on an MS-DOS computer. Experimental acoustic impedance data from the animal (guinea pig) study of April 1987 has been initially analyzed using this algorithm method. This experimental/computational technique was able to detect the progression of this known bronchoconstriction phenomena following the animal's death. The cross-sectional area versus distance function consistently decreased with time. Since the method yielded satisfactory results in this guinea pig bronchial tube constriction case, the algorithm is now being applied to the acoustic impedance study of August 1987 of excised lungs from control rats as well as from saline and silica injected rats to attempt to note any spectral frequency differences. Initial T-test statistical comparisons of the various acoustic impedances have revealed significant relative spectrum differences for 95% confidence levels.

Experimental Results

T-tests were performed on impedance magnitudes for frequencies between 100 and 6400 Hz for the three test groups: control, silica exposed, and saline exposed. Two pressures were analyzed, deflation at 2 cm of water and inflation at -2 cm of water. Comparisons between the control and saline groups show that at only one point does the T-test yield differences that are over 95% significant at a frequency where coherence is acceptable: at approximately 4000 Hz at DEF 02. The saline and control lungs then are essentially the same.

Comparisons between the control and silica groups show that the differences are more pronounced in the INF N02 graphs. At approximately 1000, 2000 and 5000 Hz, significant differences occur with at least a 95% level of confidence. Differences at these frequencies are not apparent in the DEF 02 graph, yet statistically significant differences do occur.

Comparisons between the saline and silica groups show that for both inflation and deflation, significant differences occur at 1000, 2000, 2500, and 4000 Hz.

To summarize, the control and saline groups were essentially the same, while the silica group was consistently different, with the differences more pronounced during inflation.

CONTINUING WORK

The continuing laboratory work for the remainder of the second year of the project will primarily involve completion of the planned invivo facility experiments. These important animal tests will utilize the common data analysis system and the statistical computer analysis programs to quantitatively document the ability of the tracheal two-microphone method to detect abnormal features in lungs. The importance of developing a theoretical model for respiratory mechanics will result in attention to measuring the best acoustic impedance spectrum possible. An operational clinical acoustic impedance facility will be conceived for normal and diseased human participants.

The proposed third year's work plan will accomplish the initial clinical application of the acoustic impedance method. This application study will attempt to translate the method from the animal laboratory to the clinical world. Clinical participants with both normal lungs and severe CWP lungs will be studied. Lung function will be diagnosed using chest x-rays as well as flow-volume curves measured by spirometry. It is conceived that a minor lung drug treatment study will note the time progress of a certain performance. The greater expected need for adaptive noise cancellation of corrupting unwanted human sounds will be met with measurement system modifications. Extended lung mechanics modeling is envisioned to accomodate laboratory toxicity evaluations.

TECH TRANSFER

The completion of a substantial animal invivo study that yields a comprehensive statistical statement about the acoustic impedance method's suitable degree of sensitivity for early CWP-type lung dysfunction is an expected result during the project's second year. Based on this laboratory work, a third year endeavor is expected to result in a similar successful statement about the method's clinical ability. Further clinical study with drug treatment patients will result in the method being adopted as a broad diagnostic tool for various lung function problems. All of this acoustic impedance spectrum data will be frequency analyzed using an inverse scattering algorithm to infer cross-sectional area and wall functions for the lung airway network as a function of distance into the lung. This will be a result of national significance.

WV14B/USBM 5413

Topographical Laser Holography to Infer Pulmonary Function for the Early Detection of Black Lung

Stanley, C. F.; Fraser, D. G.; Pathak, M.

Introduction

Coal workers pneumoconiosis (CWP) results from the accumulation of coal dust in the lung. The primary lesions of simple CWP are coal macules which are usually clustered in the small airways in the region of the terminal and respiratory bronchioles. These macules, measuring up to 5 mm in diameter, are normally distributed evenly between the apex and the base of the lung. As the macules enlarge during the progression of CWP, the bronchial smooth muscle mass is reduced in the respiratory bronchiole and the bronchiole dilates. The increase in bronchiole diameter results in the development of focal emphysema. In the past it has been difficult to detect diseases such as CWP since their effects are initially confined to the peripheral airways of the lung. This is a problem because the resistance of the peripheral airways accounts for only 10 to 15% of the total airway resistance, and large changes in the peripheral resistance of the lung must occur before CWP would be expected to have a significant change in airway resistance. As a result, most conventional methods for measuring airway function are not well suited for detecting diseases like CWP.

The object of this research is to examine a promising new method for detecting small alterations in the mechanical properties of the peripheral airways of the lung. This method involves measuring small regional changes in lung mechanics in the periphery of the lung by looking at the outside surface of the lung. The method examines the lung pleura using laser holographic techniques and will be able to precisely measure subtle regional differences in lung expansion from the lobar to alveolar level. By studying the mechanics of the lung pleura in this manner, it is possible to predict mechanical changes which have occurred in the small airways of the lung due to diseases like CWP. In this investigation the laser method will also be used to examine regional differences in the expansion of the thorax of live animals.

The initial investigation as described here develops the holographic techniques to detect slight variations of the surface of excised rat lungs as the lungs are acoustically excited via the trachea.

Holographic Interferometry

In holographic interferometry, the three dimensional image of an object from two different states, which have been recorded in the hologram, are compared interferometrically. If the displacement of the object is different in the two states, bright and dark fringes proportional to the displacement are seen during the hologram reconstruction process. Therefore displacements as small as a few microns can be detected.

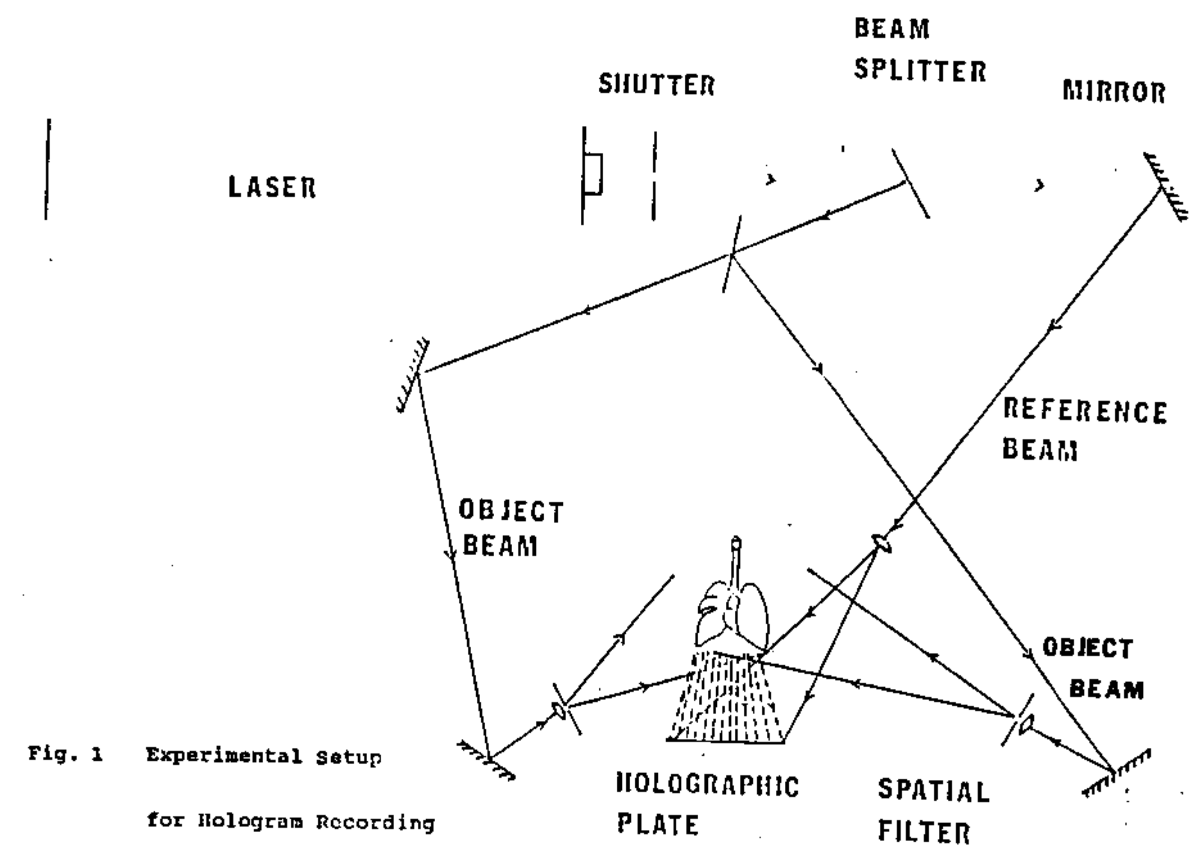


Figure 1. Experimental Setup for Hologram Recording.

The procedure can be explained with the help of Figure 1. The laser beam is split by a partial mirror called the beamsplitter. A reflective coating on this mirror divides the beam amplitude and generates two beams of varying amplitudes but the same wavelength. One of these beams, called the object beam, is expanded to illuminate the object uniformly.

Each point on the object reflects light to all the points on the holographic plate. This property of diffusely reflecting objects makes it possible to see the hologram in the smallest piece of the holographic plate as it has received light from all the points of the object. The other beam is directed at an angle to illuminate the holographic plate. This beam is not altered in any way and it is called the reference beam. It preserves all the necessary characteristics, e.g., phase, amplitude, coherence, of the original beam.

The object beam reflected from each point of the object onto each point of the holographic plate interferes with the reference beam. The reference beam is undisturbed while the object beam characteristics have changed due to its reflection from the object.

The object characteristics such as reflectance, transmittance and absorption of light, along with surface contour, change the amplitude and phase of the reflected object beam. So there exists a phase difference between the light reflected from each object point onto the plate. These object beams interfere with each other as well as with the reference beams, creating a complex interference pattern in the emulsion. A diffusely reflecting, irregularly shaped object like the lung modulates the object beam such that there is always some amount of phase difference present.

An interference pattern thus created contains an image of the object and is referred to as a hologram. If the object is displaced a certain distance and then a second exposure is taken, which creates another hologram, the second hologram has different phase information recorded in it. (The displacement of the object changed the path length thus creating a phase difference.) These two holograms interfere and create dark and bright contours that represent lines of equal displacement and are referred to as the interference fringes. All those contiguous points on the object that have moved by the same amount will be connected by one dark or bright fringe. Thus these fringes represent contours of equal displacement.

If an object vibrates during an exposure especially if the exposure time exceeds the period of vibrations, then the hologram will record the waves scattered by this object in all of the states through which it consecutively passes. This technique, termed time-averaged holographic interferometry, is based upon the use of long exposures to record the vibratory motion of an object. Although the vibration fringes are not seen in real time, they show better contrast than obtainable with any other method. Time-averaged holographic interferometry was thus chosen for this preliminary investigation of the vibrations induced in the excised rat lungs.

Experimental Techniques

The components used in this research consisted of the holographic unit, an acoustic excitation device and excised animal lungs. All work was performed in Room G-19, Engineering Sciences Building, West Virginia University.

Figure 2 is a photograph of the current lab facility that is used for these experiments. The equipment includes: 1) an Argon ion laser, 2) mechanical shutter, 3) circular variable beamsplitter, 4) two spatial filters, 5) two front surface reflecting mirrors, 6) holographic plateholder, 7) an acoustic excitation device, 8) honeycomb holographic table, and 9) miscellaneous surrporting equipment, e.g., function generator, oscilloscope, B&K sound level meter, and laser power meter.

1. The sound level intensity is measured by B&K sound level meter type 2204 (microphone UA 0196 and an Octave filter type 1613) at the opening of the special needle. The noise level in the room is also measured.

The noise level in the room was kept low by turning off all the unnecessary equipment. The reading for the noise level is subtracted from the sound intensity level at the needle to get the true value of sound intensity that is being transmitted into the lung.

2. A Long Evans male hooded rat is anesthetized by a single intraperitoneal injection (0.6 ml/100 gm body weight). The anesthetic used is sodium pentobarbital (Abbott labs.).

3. One centimeter of the trachea is exposed and a small incision made between the second and third cartilaginous trachea rings.

4. The anterior abdominal wall is opened and the diaphragm punctured to permit the lung to collapse against atmospheric pressure.

5. The dorsal aorta is cut and the rat is allowed to bleed till the heart action stops.

6. The lung is removed and stored in the refrigerator until used, typically less than one hour. Extreme care is taken not to puncture the surface of the lung when it is being removed. A punctured surface will have a different response to the forced acoustic vibrations.

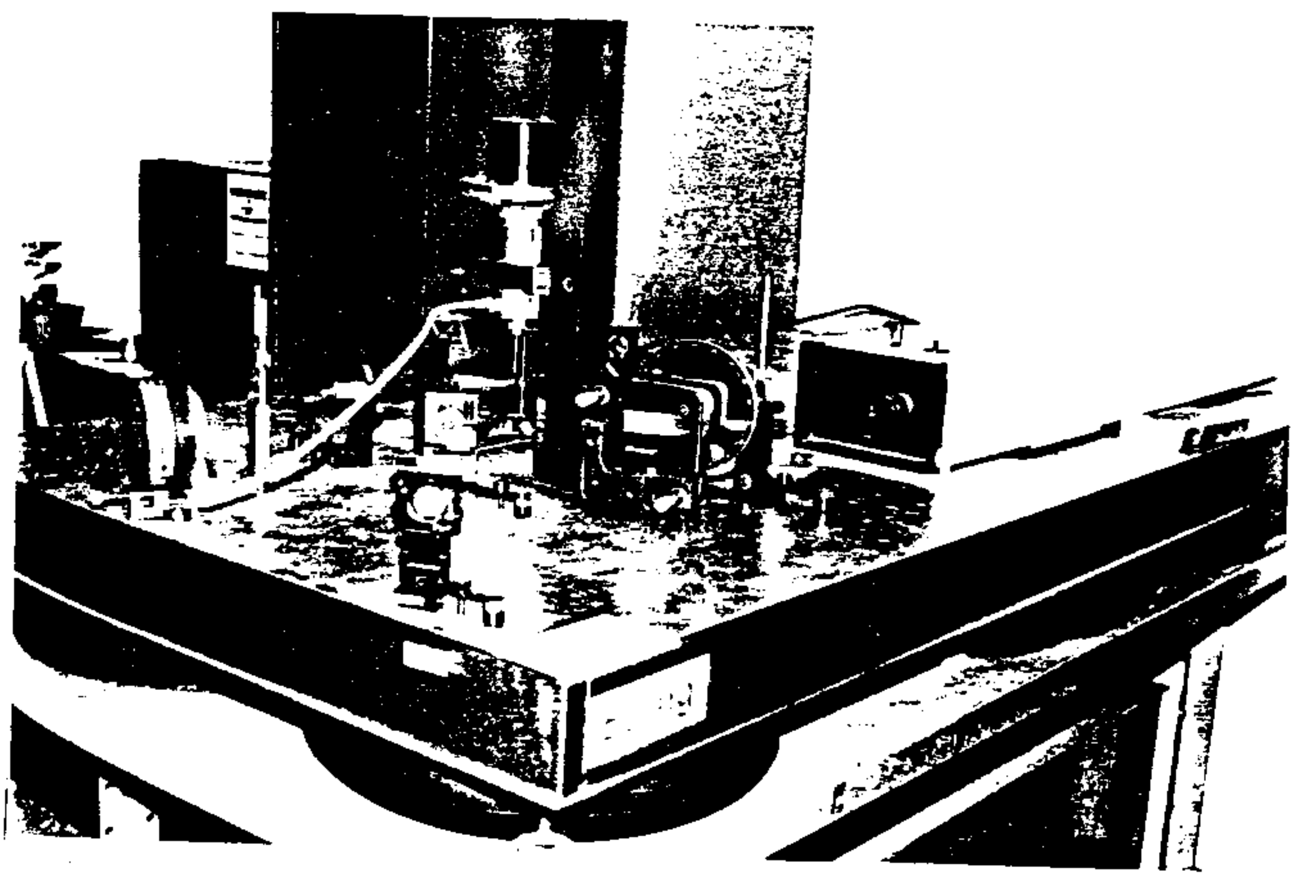


Figure 2. Laboratory Facility to Apply Holographic Interferometry to Excised Animal Lungs.

7. The excised lung is not degassed because, 1) the degassed lung has a smaller surface area, 2) in the preliminary experiments tissue damage was observed on the lung surface, and, 3) blood clotting is seen on the lung surface which changes the surface color producing poor contrast in the hologram. Additionally, the incident laser beam does degrade the lung tissue. This also reduces the contrast with the black interference fringes that cover the lung surface. Also, the intensity of the laser beam reflected from the lung surface is reduced which makes it difficult to record good holograms.

8. The lung surface is coated with a thinly sprayed layer of white paint. This increases the reflectivity of the lung surface and makes it possible to record a good hologram with a 3 msec exposure time.

9. The excised lung is attached to the impedance tube through the special needle and oriented such that both lobes of the lung are well illuminated.

10. The roomlights are turned off and the holographic plate is removed from its box and then lightly clamped in the plateholder.

11. The function generator is turned on to vibrate the lung at 800 Hz. Preliminary research in acoustic impedance has shown good lung response at about 800 Hz. The input vibration amplitude is increased by the power amplifier and monitored on the oscilloscope.

12. As soon as the shutter is opened, the laser beam illuminates the plate and the object for a duration of 3 msec.

13. The plate is then unclamped and developed.

14. After the processing is complete, the room lights are turned on and the dried plate is positioned in the plateholder again and only the reference beam is allowed to illuminate the plate. The three dimensional image of the lung covered with vibration fringes is viewed in the plate.

15. The beamsplitter is adjusted so as to reconstruct the image with maximum brightness and visibility.

16. A photograph of the image is taken on a black and white, Kodak Plus X, ASA 125, 35 mm film. These photographs are later analyzed for amplitude information of the object vibration.

Results

The rat lung is divided into right and left lobes. The right lobe is again divided into four segments which are referred to as the anterior, middle, posterior and post caval lobes. The left lobe is undivided. The internal structure of the lung consists of airways, and these airways branch into alveoli which are nothing but air sacs. These airsacs are the main communicator with the outside air for the respiration process. The acoustic vibrations introduced through the trachea travel throught these airways into the alveoli and cause them to inflate and deflate.

The effects of increased excitation amplitude at 800 Hz are shown in Figures 3 and 4. It can be easily seen that fringes are progressing from the trachea down to the bottom, i.e., inferior lobe, of the lung as the value of the amplitude is increased. Figure 3 shows the lung vibrating at the frequency of 800 Hz, 2 volts peak to peak amplitude measured from the oscilloscope and the sound level intensity of 53 dB. The zero order fringe is seen on the left lobe of the lung while on the right lobe fringe progression is very little. This can be due to the fact that the left lung is undivided while the right lung has four segments which have a different impedance to the same acoustic frequency.

It is also observed that the fringes are very dense at the point of junction between the trachea and the lung. This phenomenon is observed in all the holograms taken so far which suggests that there is a large amount of movement present at this junction. At this point, the trachea divides into two bronchi, one going to each lung, and it is at this point that the fringes are dense which can be due to the unequal distribution of the sound components directed into the trachea.

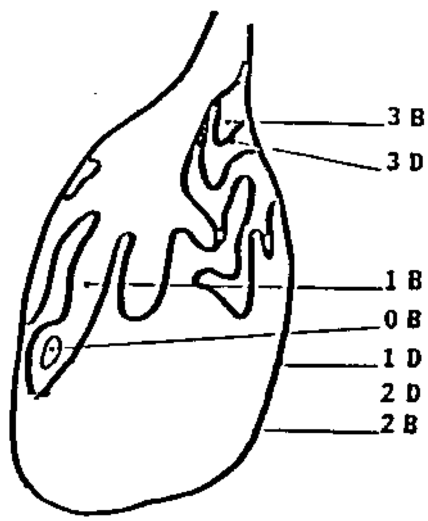


Figure 3. Fringe Pattern on the Lung Vibrating at 800 Hz, 53 dB.

Figure 4 is the hologram of the same lung vibrating at 800 Hz, 4 volts peak to peak amplitude and 72 dB sound intensity. The interval between the holograms of Figure 3 and Figure 4 was kept at one hour to find any difference in fringe patterns, e.g., due to tissue damage. The lung was kept in the buffer solution for this time to maintain the surface moistness. As can be seen, the left lung has similar fringes on its surface while the right lung is showing a large number of fringes as a result of increased amplitude. The zero order fringe is located in the upper righthand corner of the superior lobe. The middle lobe has but one fringe while the inferior lobe shows no fringe at all although a few dark spots are seen that are the beginnings of dark fringes. The fringes recorded in this hologram are relatively sharp compared to other holograms indicating that the lung is responding better at this amplitude.

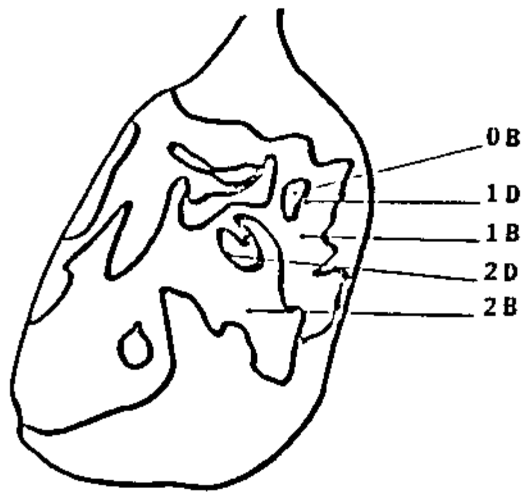


Figure 4. Fringe Pattern on the Lung Vibrating at 800 Hz, 72 dB.

Table 1 lists the calculated vibration amplitudes for different regions on the lung surfaces in Figures 3 and 4.

Continuing Work

The techniques developed have been successful in detecting lung surface movements with a high degree of accuracy. The technique is now being applied to compare vibration patterns of diseased and normal lungs.

Tech Transfer

A total of one symposium paper, one thesis, and three conference presentations have resulted from this study. One additional thesis is in preparation.

Table 1. Calculated Vibration Amplitudes on the Lung Surface

Figure	Dark Fringe Order	Amplitude d, cm
3	1	1.42×10^{-5}
	2	3.09×10^{-5}
	3	4.71×10^{-5}
4	1	1.34×10^{-5}
	2	3.13×10^{-5}

WV17/USBM 5423

The Role of Platelet Activating Factor in the Etiology of Coal or Silica Induced Pneumoconioses and the Effects of Fresh Cleavage Planes on This Response

VanDyke, K.; Castronova, V.

1. Introduction

Inhalation of dusts from coal mines causes lung diseases of miners. These diseases arise because normally protective systems which process and kill infecting organisms such as bacteria and viruses etc. react with particles like coal mine dust. These protective systems react with normal lung tissue which can be irritated and eventually destroyed if the irritation from inhaled particles stays over a long period of time, i.e., chronically irritated. This results in lung diseases such as emphysema or black lung. In emphysema, lung tissue is destroyed and the honeycomb tissue structures (where oxygen is normally exchanged into the blood) are converted into large air spaces which have markedly decreased surface area, therefore, decreasing oxygen uptake from the lung into the blood. In black lung disease the ability to move air into and out of the lung is decreased due to collapse of airways. In either disease, the patient suffers shortness of breath because normal breathing is not possible.

The destruction of normal lung tissue occurs because of chronic inflammation or irritation caused by the interaction of particles such as coal mine dust or silica (sand) with white cells in the lung. These white cells (neutrophils or macrophages), when they interact with particles, eat or engulf the particles (Fig 1 and 2). This causes chemical changes in the cells which release toxic oxygen substances and enzymes which degrade healthy tissues as well as histamine and various toxic lipid substances (Fig 3). The lipids can cause constriction (pinching off) of the airways in the lung so that ventilation of the lungs is decreased, i.e., there is a decrease in the flow of air into the lungs. One of these toxic lipid substances is called platelet activating factor (PAF). This substance is produced by both types of white cells and has important amplifying effects on these cells. In addition they cause other toxic lipid substances (leukotrienes and prostaglandins) to be produced which leads to further destruction of normal lung tissue which decreases lung function. The resultant degradation of normal lung tissue seems to be inevitable. However, if we had a detailed understanding of how and why chronic inflammation occurs, maybe we could short circuit the inflammatory sequence and reduce the incidence and severity of black lung disease. We think (based upon preliminary experiments) that this is clearly possible!

2. Rationale

The most obvious ploy to reduce the chronic inflammatory diseases - emphysema and black lung would be to reduce the number of inspired particles which interact with the white cells of the lung. However, this approach has not been totally successful, i.e., workers do inspire coal mine dust and silica. The next approach would be to study the detailed interaction of these particles with the white cells in hopes of blocking the sequence of reactions causing release of inflammatory mediators. Another method of blocking the chronic inflammation would be to shut off the production of toxic oxygen substances, degradative enzymes, or toxic lipids responsible for the destruction of lung tissue.

Figure 1. Human macrophage poised to engulf rod-like bacteria.

There are lung diseases which are similar to emphysema and black lung that have chronic inflammation as a probable cause. These are inhalation of dusts which contain endotoxin and exercise-induced asthma. In both of these inflammatory lung problems, the lipid, platelet activating factor (PAF), appears to be involved. In the exercise-induced asthma problem (which we measured in human volunteers), we have shown that upon ceasing exercise lung function decreased (bronchoconstriction) at a time when PAF levels in the blood increased. Others have shown that if anti-PAF drugs are given prior to the development of asthma, bronchoconstriction does not develop. In addition, we have shown that anti-PAF drugs were also effective post-exercise.

When endotoxin is inhaled, the decrease in lung function has been associated with an inflammatory reaction resulting from neutrophils and macrophages, concentrating in an area and releasing reactive secretions. Furthermore it has been demonstrated the inhalation of endotoxin results in release of PAF from lung macrophages.

Therefore, there is a rational basis for our studies that coal mine dust or silica particles in the respirable range (i.e., 5 microns or less) can activate the release of toxic oxygen species and PAF. This would cause the chronic inflammatory sequence in the lung, which in turn causes degradation of lung tissue and loss of function. Indeed, our preliminary studies with human macrophages indicate hyperactivation of cells from workers exposed to silica and fly ash.

Therefore, we will measure the release of PAF from lung macrophages and neutrophils which have been activated by coal mine dust and silica particles. We will measure effects of PAF on release of reactive products from macrophages and neutrophils. We will use specific anti-PAF drugs to protect or prevent the effects of PAF.

3. Scope of Work

A. We isolate the while cells causing inflammation in the lung (human neutrophils and animal macrophages). These are needed to study detailed inflammatory reactions to particles.

B. We measure the effect of PAF on neutrophils regarding oxygen consumption, chemiluminescence and membrane potential. When PAF activates neutrophils sodium goes into the cell

2. Human white cell (neutrophil) engulfing coal-dust related particles.

decreasing the negative charge of the cell. These changes cause oxygen to be used by the cell causing the cell to produce light or chemiluminescence which is dependent on oxygen reacting with certain enzymes (catalyzing) in the cell.

C. We will determine similar changes as in B with macrophages of the lung.

D. We will determine the effect of coal mine dust on the secretion of PAF from macrophages (regarding secretion of PAF). We believe PAF release from macrophages activates other inflammatory cells, i.e., neutrophils. This causes magnification of inflammation.

E. We will determine the effect of silica (ground sand) on secretion of PAF from macrophages. We think silica greatly increases secretion which are inflammatory.

F. We will try a variety of different amounts of silica and coal mine dust to determine a dose-response relationship regarding secretion of PAF.

Figure 3. Oxygen metabolite mediated cytotoxicity of human white cell (neutrophil). These reactions cause inflammation and degradation of normal lung tissue.

G. We will measure reactive substances produced on freshly ground silica (cleavage) and determine the relationship between time after cleavage surface activity. We will determine how long these reactive substances remain after grinding the silica.

H. We will determine the effects of silica cleavage, aging, free radical inhibitors and radical traps on the production of reactive substances on the silica surface. We believe cleavage causes production of unpaired electrons (free radicals). Electron spin resonance (ESR) measures free radicals and there should be a correlation between production of light (chemiluminescence) and ESR signal versus time of production.

I. We will determine the synergistic effect of coal plus silica on release of PAF from macrophages. We believe coal and silica particles will magnify the secretion of PAF from macrophages.

J. We will measure the effect of specific in inhibitors of PAF to see if we can block the inflammatory effect of particles or macrophages.

K. We will measure whether freshly cleaved silica will affect the production of oxygenated products such as superoxide, hydrogen peroxide and light production (dependent on oxidative reactions).

L. We will determine the effects of fresh cleavage planes of silica on the release of PAF from macrophages. We think newly cleaved silica will cause a greater production of PAF from macrophages.

4. Results and Conclusions

1. We isolated human neutrophils from whole blood by two different methods:
   a. dextran setting and centrifugal elutriation which yields a preparation of 93.0% $\pm$ 0.5 pure neutrophils
   b. using a density medium (mono-poly resolving media) and centrifugation which yields a preparation of 95.0% $\pm$ 1.1 pure neutrophils
2. We monitored the production of superoxide by measuring the reduction of cytochrome c. Addition of platelet activating factor (PAF) at 20^{-5}M to 10^7 cells yields relatively little superoxide: 13 nannomoles of superoxide/10^7 cells in 30 minutes.
3. We determined the hydrogen peroxide (H_2O_2) produced from human neutrophils by measuring the oxidation of scopoletin in the presence of horseradish peroxidase. Activation by 10^{-5}M PAF results in a substantial release of hydrogen peroxide: 623 $\pm$ 147 nannomoles/10^7 cells/minute.
4. Initial experiments demonstrate the generation of substantial amounts of chemiluminescence (CL) upon addition of 10^{-5}M PAF to human neutrophils with a peak generation 2 minutes after addition. PAF-induced CL exhibits a strong dependence on external sodium (Fig 4). PAF induced CL is effectively inhibited by PAF antagonists (Fig 5).

5. PAF induces a strong depolarization of human neutrophils. This depolarization precedes the generation of CL. As noted with CL, depolarization events are dependent on external sodium. Dose-response for the two parameters indicate a K1/2 of 2.5×10^{-6}M.
6. PAF causes rat alveolar macrophages to secrete only small amounts of superoxide. However, in combination with particles such as zymosan, PAF causes a significantly higher production of superoxide than the particle alone. This indicates the soluble stimulant PAF may act as a primer for particles on the alveolar macrophages (see Figure 6).

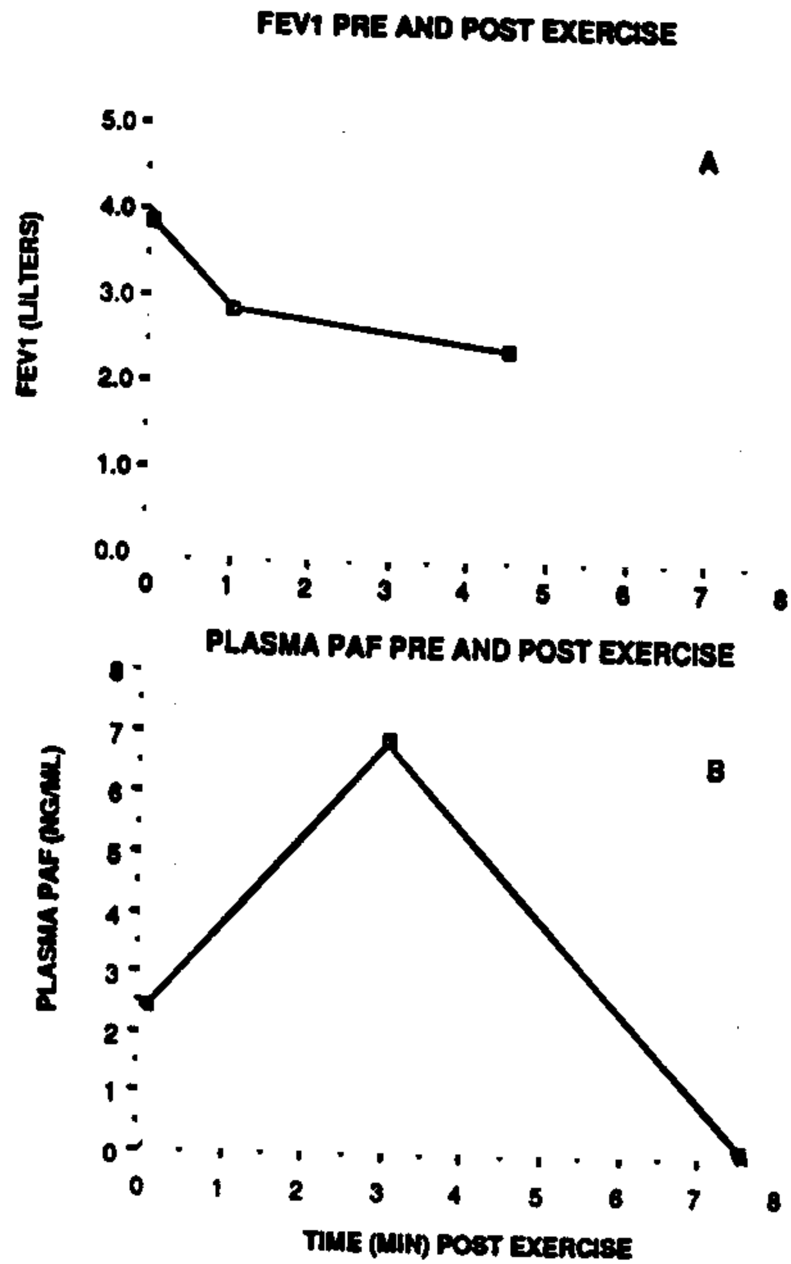


Figure 4. Response of volunteer to exercise-induced asthma. As asthma occurs, FEV decreases. At the same time, PAF level rises then decreases.

7. PAF causes rat alveolar macrophages to produce little or no increase in cellular oxidative metabolism as measured by the production of chemiluminescence. But when PAF is added with particles there is a significantly higher amount of chemiluminescence produced than with particles alone. Again PAF may be acting as a priming agent to the cell which then produces more oxidative metabolism when exposed to particles (see Figure 7).
8. When humans are stimulated to produce PAF, e.g., in producing bronchoconstriction (which is very similar to some pneumoconioses in bronchoconstrictor activity), lung function diminishes as the concentration of PAF in the blood produces more oxidative activity (see Figure 8). Drugs used to block or inhibit PAF receptor activity are much more effective in inhibiting oxidative activity once PAF levels have increased (see Figure 9). Recently, it has been shown by others that a bronchoconstriction condition can be prevented by administering anti-PAF drugs before the decrease in lung function. In other words, inhalation of anti-PAF drugs before the decrease in lung function can prevent the decrease in lung function. Our original proposal suggesting that drugs may be useful in this regard seems to be correct.
9. We have written a paper submitted to Platelet Activating Factor in Endotoxin and Immune Diseases entitled,

Figure 5. PAF causes human white cells (neutrophils) to produce light. The precursor compound, lyso PAF, reacts very slowly.

"Endotoxin-like Actions of Platelet Activating Factor on Ventilatory Function and Activation of Alveolar Macrophages: Parallelism between exercise-induced asthma and effects of endotoxin exposure" (see enclosed).

10. We have written an abstract on our findings to the VIIth International Pneumoconioses Conference on "Effects of Platelet Activating Factor on Various Physiological Parameters of Neutrophils, Alveolar Macrophages, and Alveolar Type II Cells" (see enclosed).

5. Application of Research Results

We believe that the results from this work may have a direct application to the treatment of black lung and silicosis in humans. The drugs which block the activity of PAF are being

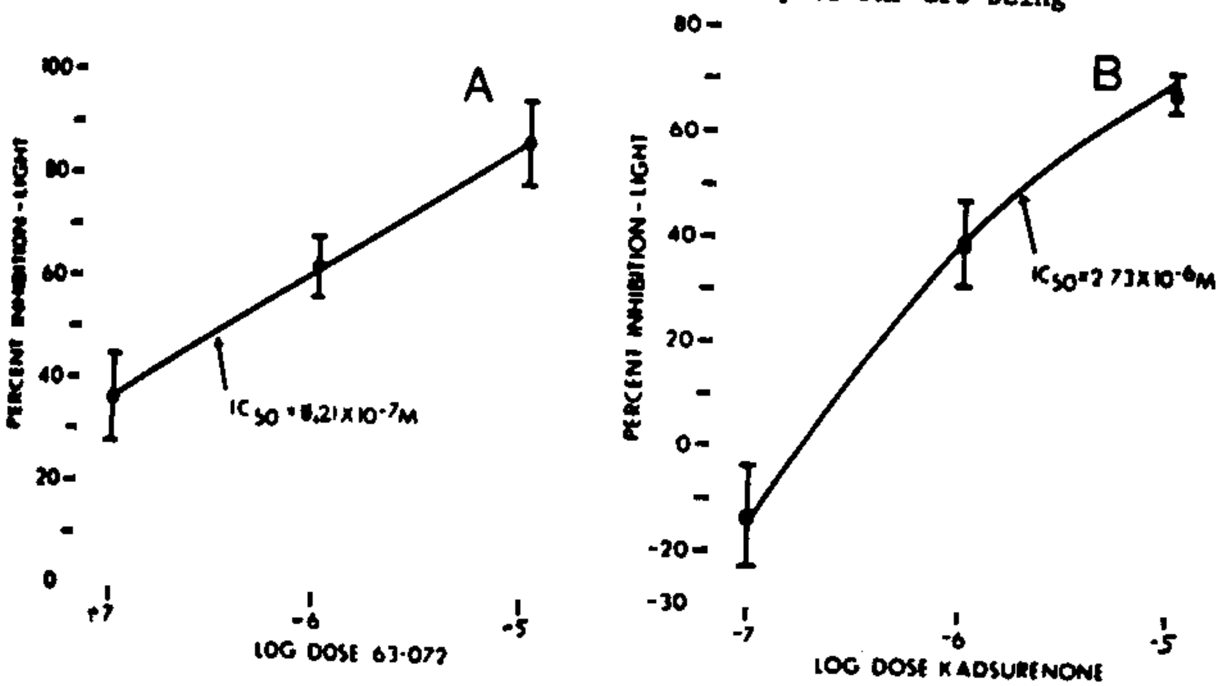


Figure 6A. Dose-response curves for inhibition of PAF-induced chemiluminescence by 63-072 (A) or kadsurenone (B). Granulocytes were stimulated with 1410-5 M PAF.

developed at the present time. They are effective in preventing asthma which is an inflammatory condition. PAF has been shown to be released from alveolar macrophages with stimulation by particles. Therefore, we will attempt to use a variety of PAF synthesis and receptor inhibitors to stop the harmful effects of PAF and, therefore, block or inhibit inflammation from particles.

In addition we will investigate the usefulness of a drug developed in China named tetrandrine. We have shown that this drug inhibits the inflammatory oxidative burst of macrophages without interferring with particle uptake. Therefore, in the presence of this drug the lung may be able to repair the damage caused by particles.

6. Continuing Work

Our project has been ongoing for about 5 months and we have a clear indication that PAF release is very important in particle interaction with white cells of the lung. We know we can block

PAF responses. It is a matter of selection of an inhibitor that is effective without toxicity to the body. We can limit the toxicity of the drugs by isolating the drug to the lung cavity. Possibly we could develop a inhalation-PAF derivative or possibly a tetrandrine-like drug.

We will measure the effects of freshly ground silica and coal dust on white cells of the lung.

7. Tech Transfer

This work has or will produce a variety of important technological benefits that might transfer to other projects. We believe that it will produce the first linkage between production of light, chemiluminescence, and production of free radicals as detected by electron spin resonance. The drugs we are testing have never been used in black lung disease or in particle-induced inflammatory conditions like fibrosis in the lung. Our preliminary studies indicate that these drugs will be effective. We think if permanent damage has not been done to the lung, we can arrest and possibly reverse damage that has been done to the

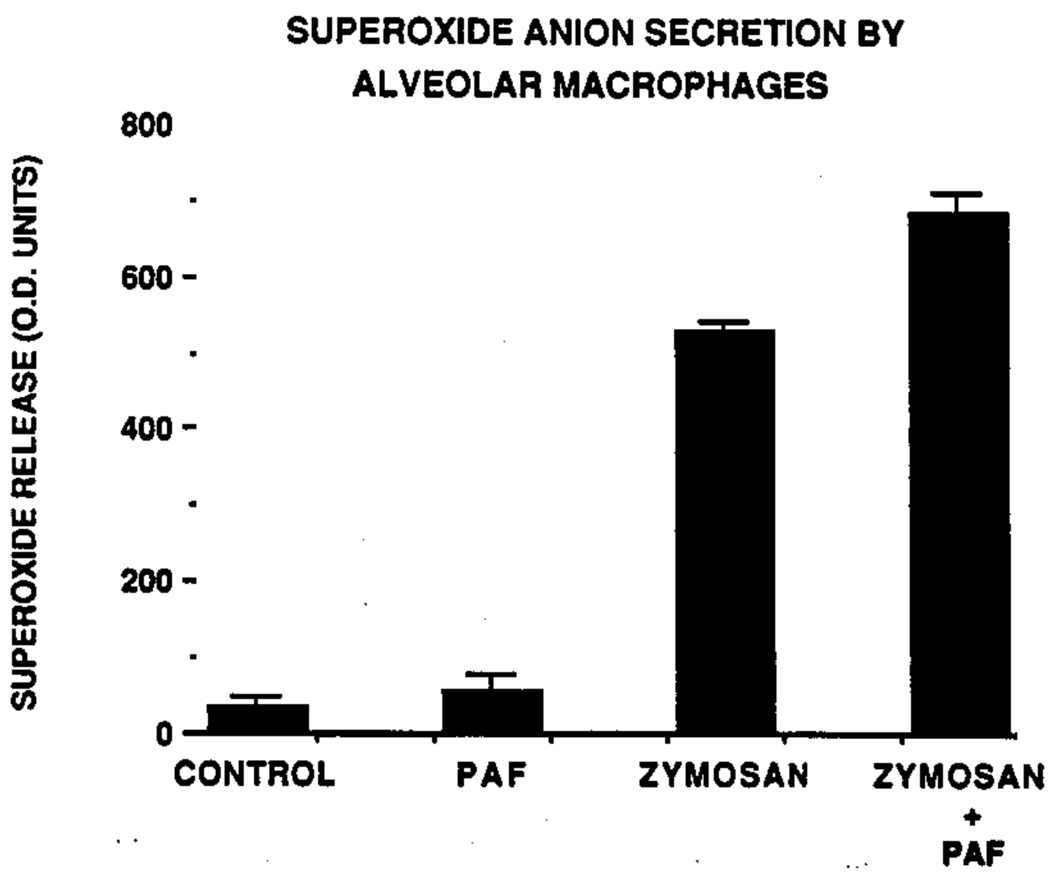


Figure 6B. Effects of PAF on superoxide anion release from rat alveolar macrophages. Superoxide secretion was monitored by measuring the reduction of cytochrome C. Cells were treated in vitro with 1.3x10 M PAF and/or 2 mg/ml zymosan. Values are means + standard errors for four different preparations.

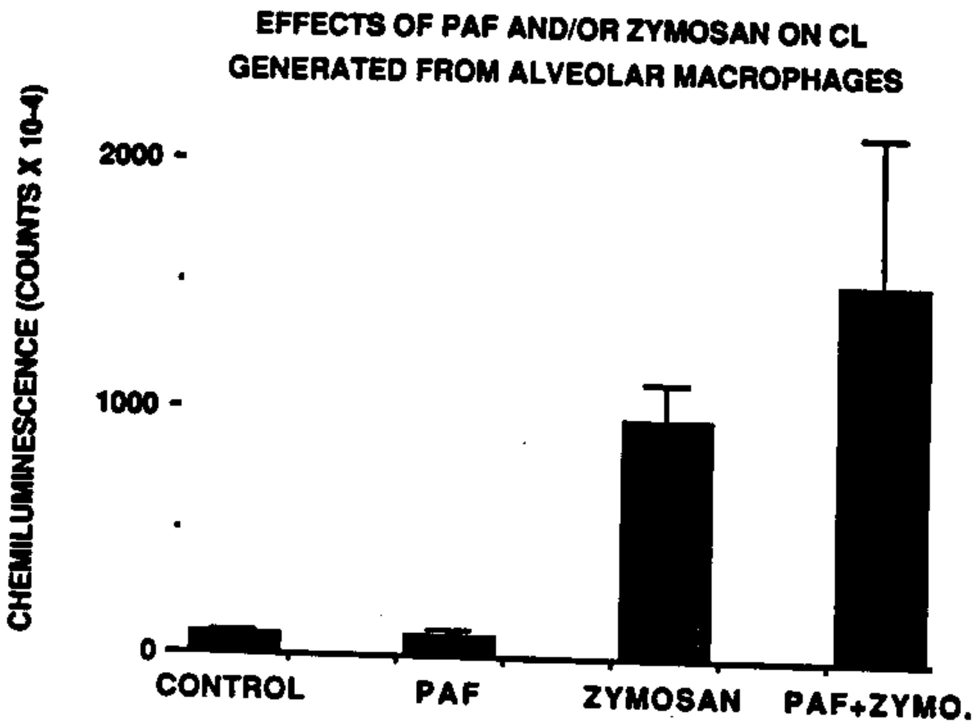


Figure 7A. Effects of PAF on chemiluminescence generated from rat alveolar macrophages. Chemiluminescence was measured in the presence of luminol (10 M). Cells were treated in vitro with or without 1.3x10 M PAF for 15 min prior to the addition of 1 mf/ml zymosan. Values are means + standard errors for three different preparations.

lung. Furthermore, these drugs may be effective for smoker's lung and respiratory distress syndrome as well as inflammatory conditions caused by viral infections.

We have interacted with the group at WVU measuring free radicals from coal and silica headed by Drs. Dalal and Vallyathan. Our project next year will fuse our project with their project.

Our group has interacted with the group in anatomy at WVU headed by Dr. Cilento who are measuring superoxide in single macrophages. Also, we have interacted with Drs. Bill Wallace and Meloy on coal dust surface analysis and Dr. Lee Lapp and Vince Castranova on human macrophages.

In our six months of funding, we have finished a full paper and an abstract for the upcoming meeting on pneumoconioses in Pittsburgh in late summer. It is entitled "Effects of Platelet Activating Factor on Various Physiological Parameters of Neutrophils, Alveolar Macrophages and Alveolar Type II Cells."

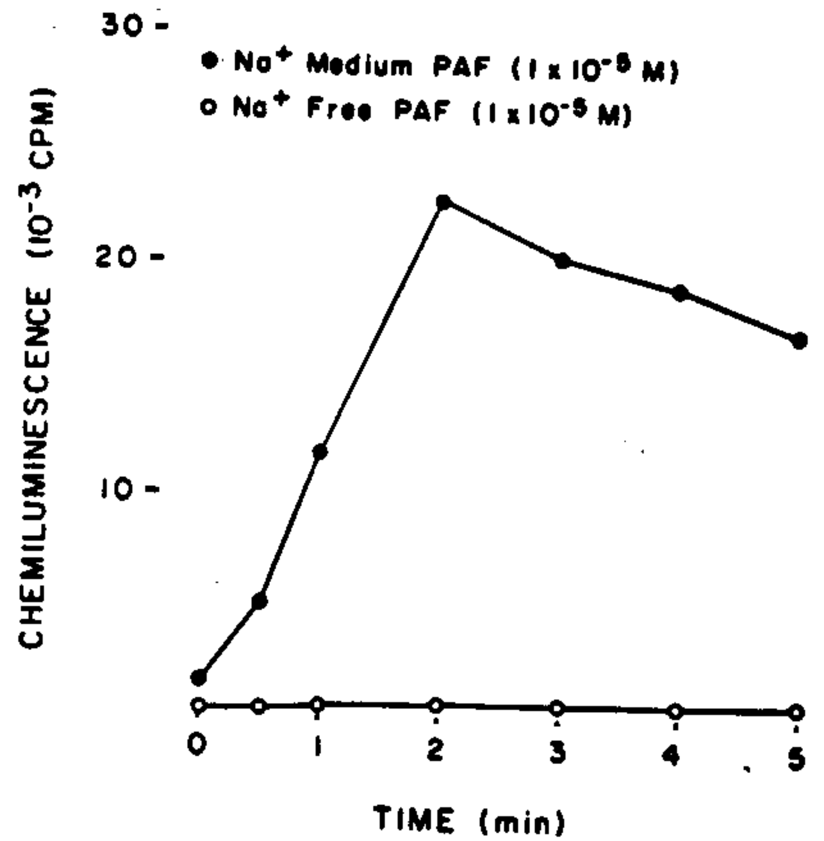


Figure 7B. Effects of PAF on chemiluminescence generated from rat alveolar macrophages. Chemiluminescence was measured in the presence of luminol (10M). Cells were treated in vitro with or without 1.3x10 M PAF for 14 min prior to the addition of 2 mg/ml zymosan. Values are means + standard errors for three different preparations.

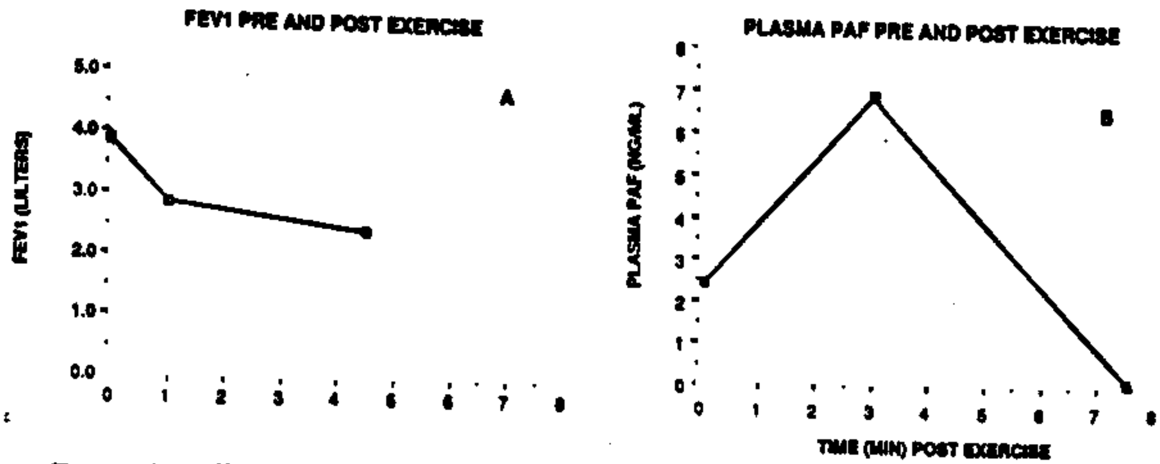
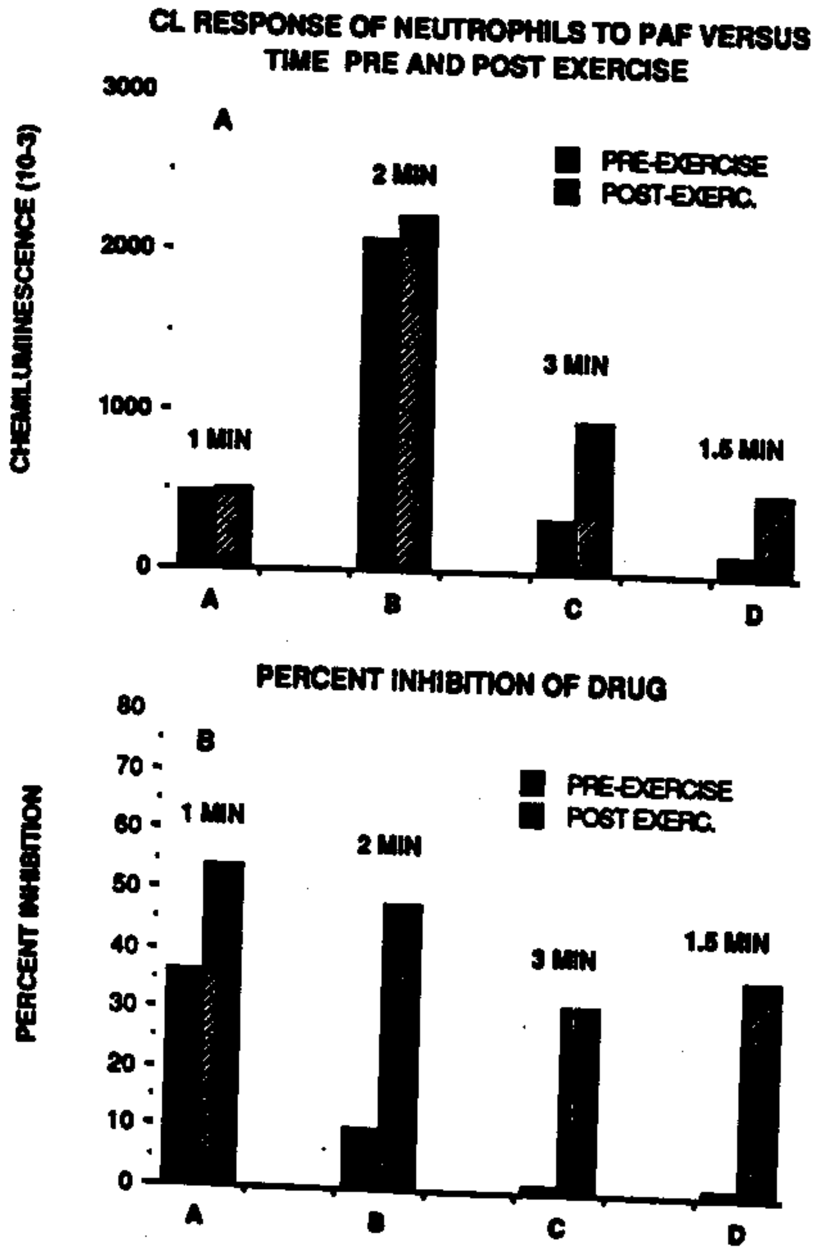


Figure 8. Effect of exercise on chemiluminescence generated by neutrophils taken from four volunteers (A-D). A) Chemilunimescence in response to in vitro treatment with 1410^{-6} M PAF was monitored with neutrophils collected before and after exercise; B) the effectiveness of 63-072 a PAF receptor antagonist, in inhibiting PAF-induced chemiluminescence generated by neutrophils collected before and after exercise. Timese post exercise are noted above the bars.



Effect of exercise on chemiluminescence generated by neutrophils taken from four volunteers (A-D). A) Chemiluminescence in response to in vitro treatment with 1410^{-6}M PAF was monitored with neutrophils collected before and after exercise B) the effectiveness of 63-072 a PAF receptor antagonist, in inhibiting PAF-induced chemiluminescence generated by neutrophils collected before and after exercise. Times post exercise are noted above the bars.

Table 1. Various druge which inhibit the action of PAF at the receptor (causes bronchoconstriction) at very low doses (10 M) or (10 M).

4.2
Characterization of Dust Particles

PSS/USBM 4203

Characterization of Dust Particles

Hogg, R.; Luckie, P.; Dumm, T. F.; Bunnaul, P.

INTRODUCTION

Coal is an extremely heterogeneous material. Even at respirable sizes, each particle may contain a variety of carbonaceous and mineral constituents. The relative amounts of these constituents and the nature of their distribution within the particle may vary from particle to particle. There may be systematic variations according to the particle size as well as variations among particles of the same size. The primary purpose of this project is to develop, evaluate and compare techniques for the determination of the chemical, physical and structural characteristics of respirable coal dust particles. Clearly, characterization is central to the problem of respirable dust in mines. The characteristics of the particles presumably determine their effects on miners' health. These characteristics are themselves determined by mining procedures, control systems, etc. In the context of this project, characterization is defined as the measurement of those features of the individual particles and of the assemblage of particles which determined the behavior of the dust in the mine environment, its response to control measures, and its behavior in the human pulmonary system. The list of such characteristics which could potentially be measured is obviously open-ended. An important aspect of our research is, therefore, to establish procedures for evaluating different classes of characteristics: Size/shape, chemical/mineralogical composition, etc., and to specify limitations, etc., on the kinds of analyses which can be performed.

It is also important to recognize that dust characteristics are not single-valued quantities. There are distributions of particle size and shape and also of each of the other chemical and physical characteristics. Our approach is to consider characterization at three distinct levels: the complete sample, the separate size intervals, and the individual particles within an interval. Adequate characterization of any dust sample should include information at each of these levels.

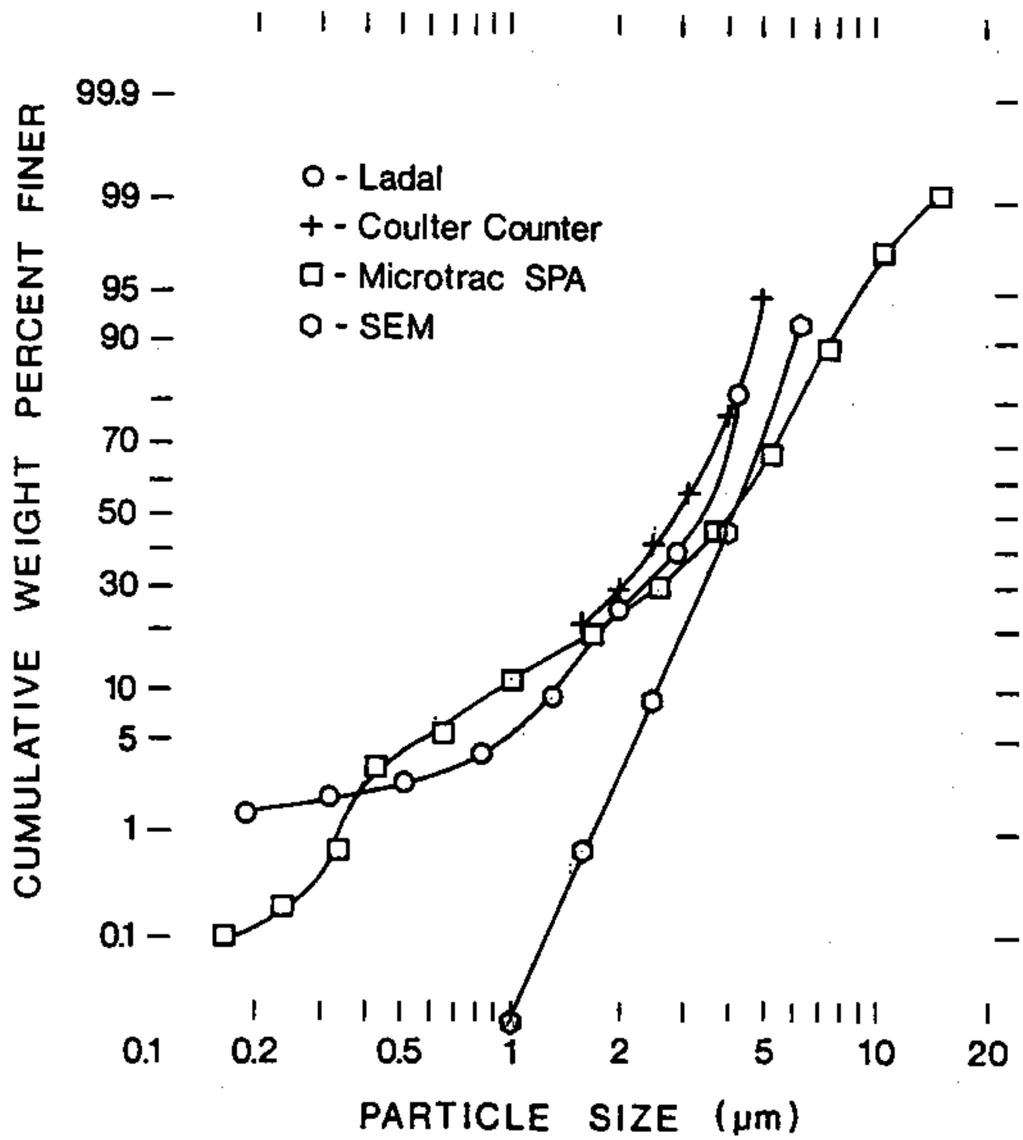


Figure 1. Particle size distributions for standard dust 1192M obtained using various techniques.

For example, the most reliable data on the free silica (quartz) content of a dust sample would come from an analysis of the entire sample (or randomly selected subsample). The distribution of quartz with respect to size can best be determined from classified subsamples. Evaluation of the extent to which quartz occurs as single, "free" particles as opposed to composites, would require investigation at the individual particle level.

An important aspect of this project has been the preparation and characterization of a series of standard respirable dust samples, which can be used to provide a common link among the various research programs in the Generic Technology Center for Respirable Dust.

RATIONALE

This project is concerned with the characterization of the chemical and physical attributes of respirable dusts. Important characteristics include the distributions of particle size and shape, the chemical and mineralogical composition of the dust and the relative distributions of these among the size classes and among the individual particles. In the case of coal dusts, the amounts and distributions of the various petrographic constituents would also be of interest.

The basic problems of characterizing respirable dusts arise primarily from the extremely fine size of the particles, the need for information on the distributions of the characteristics, and the fact that sample sizes are frequently very small, especially in the case of actual mine dusts. Particularly for such systems as these, it is important to recognize that, while analytical procedures will almost invariably provide data, the validity of such data should always be subject to considerable scrutiny. The major thrust of our research in this project lies in the adaption and evaluation of modified conventional characterization procedures to the study of particulates in the respirable size range.

Characterization is an essential feature of the integrated efforts of the Generic Technology Center for Respirable Dust. All of the research projects being conducted through the Center involve dust characterization to some extent. Consequently, a significant component of this project is to provide coordination of the various characterization efforts, consultation on characterization problems and (limited) testing services.

SCOPE

The primary objective of this project is to establish and evaluate practical and reliable techniques for the chemical, physical and structural characterization of respirable dust particles. The project is, to some extent, open-ended but the major emphasis to date has been on:

- Evaluation of existing particle characterization techniques and of their applicability to respirable dust systems.

- Development of sampling/characterization procedures which can provide reliable and useful information yet are sufficiently simple for direct application in mining environments.

- Preparation, characterization and distribution of a suite of standard respirable dusts which can be used to provide a common base for instrument calibration and the development of experimental procedures in engineering and biochemical research.

- Provision of technical service (coordination, consultation, testing) for the various research groups associated with the Center.

CONCLUSIONS

The Distribution of Particle Size is generally recognized to be of prime concern to the transport of dust particles in mines, and its deposition in the human pulmonary system. It is also likely that particle size may play a significant role in the cyto-toxic response of respirable dust. Procedures for particle size analysis on respirable dust from coal mines have been evaluated. Using respirable dusts dispersed in a laboratory dust chamber, size distributions measured using cascade impactors have been compared with the results of a variety of laboratory sizing methods performed on samples collected on filters placed side-by-side with the impactors. The laboratory techniques included centrifugal sedimentation, laser diffraction/scattering and automatic particle counting. The agreement among the various methods is illustrated in Figure 1 and was generally very good, with systematic differences which can be attributed to the different definitions of size used. Simple conversion factors have been obtained which can be used to transform the laboratory data to equivalent aerodynamic sizes.

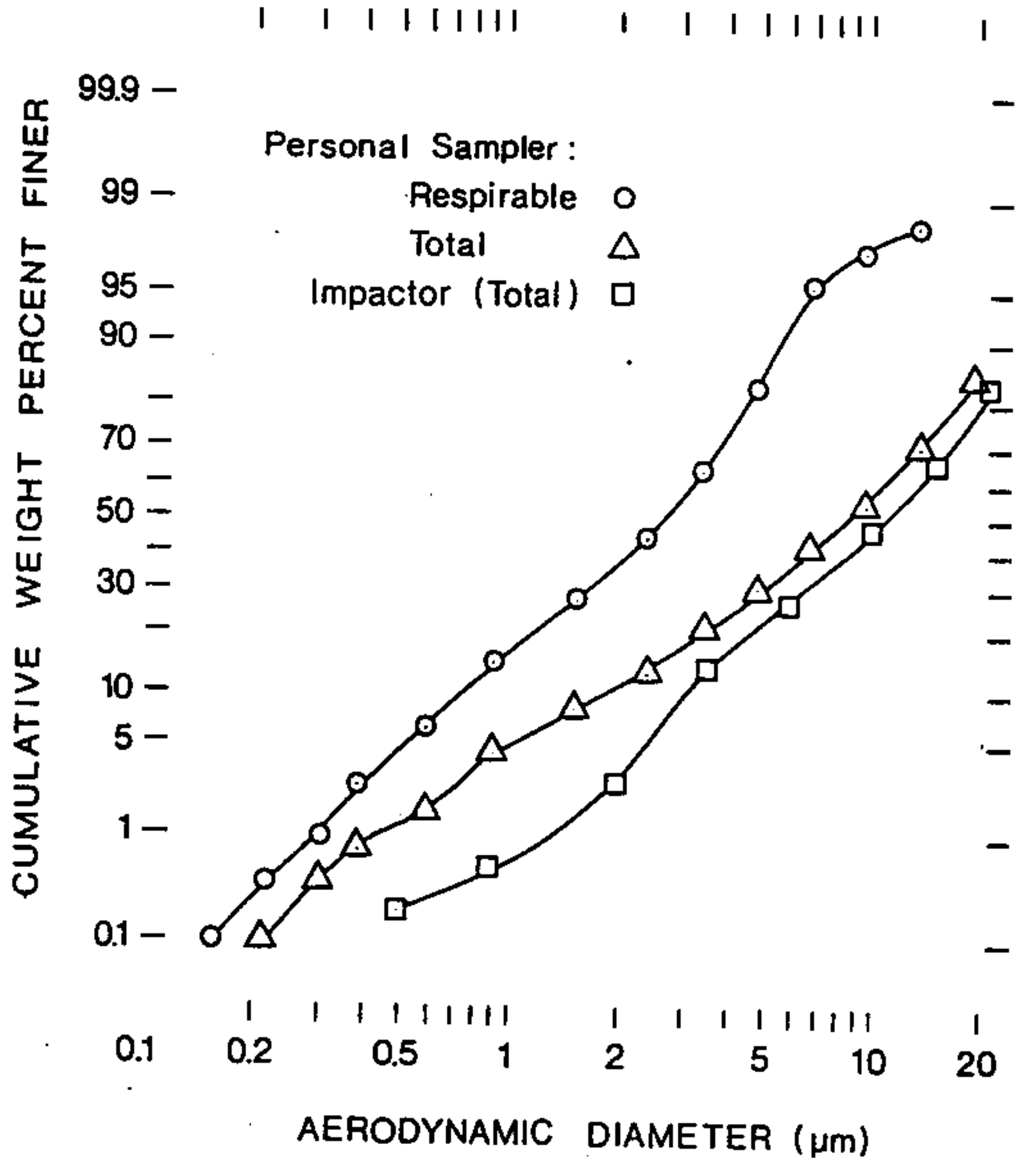


Figure 2. Distribution of aerodynamic diameter of mine dust collected using a modified personal sampler (respirable fraction and total dust) and an Andersen model 298 cascade impactor.

Similar comparisons have been made on samples collected in underground coal mines. An example is shown in Figure 2. Again, the results are in quite good agreement although small discrepancies were observed in some cases. These have been attributed to some degree of agglomeration in the airborne dust, leading to slightly coarser apparent distributions in the impactor samples.

The results of these investigations indicate that different laboratory sizing procedures used to analyze particles dispersed in liquid or in air, give consistent results provided proper allowance is made for the different definitions of size used and for the existence of detection limits for some techniques. Based on these results it is concluded that the Microtrac SPA is especially appropriate for the analysis of respirable dust. Samples of as little as 0.1 mg of dust can be analyzed quite accurately, the analysis is simple and rapid, and the lower detection limit at about 0.1 μm does not lead to significant errors. Centrifugal sedimentation would also be highly appropriate, perhaps even more so than the Microtrac since there are no detection limits involved. However, the large sample size required ~1g) render this technique impractical for routine analyses. Because of the fairly coarse detection limit (~0.8 μm) the Coulter Counter is not recommended for the analysis of respirable dust. Our results indicate that about 10% of the respirable component of mine dust is finer than this size. Scanning electron microscopy (SEM) is not generally suitable for particle size analysis on respirable dust, due to the problems associated with poor resolution of submicron particles and the need to count extremely large numbers of particles to obtain reasonable estimated of the numbers of large particles present. Microtrac SPA analyses of dust collected using modified personal samples or simple filters offers a useful and reliable alternative to *in-situ* analysis using impactors. Recognizing, however, that the SPA has a lower detection limit at about 0.1 μm, samples which are found to contain significant quantities in the 0.1 to 0.2 μm range should be subjected to further investigation using, for example, cascade impactors.

The Chemical/Mineralogical Composition of respirable dust is obviously an important factor and its determination must be a primary goal of any characterization scheme. Bulk analyses, by standard techniques, are readily applicable to respirable dust, but provide

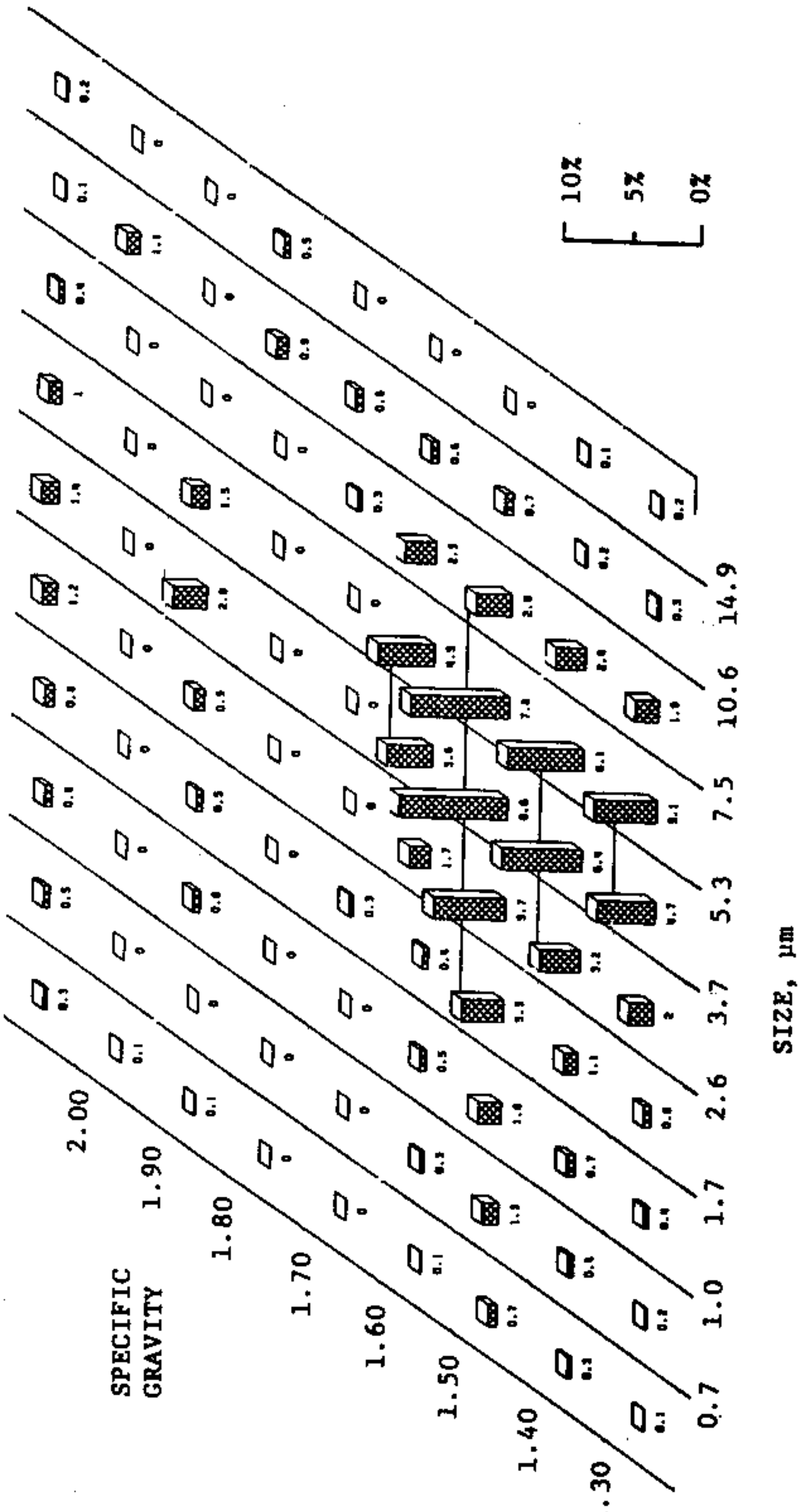


Figure 3. Size-specific gravity distribution of standard respirable dust PSOC 1361P as a percent of total coal.

information only on the average composition. A more complete description, including the distribution of composition by size, is often desirable. Gravity fractionation using heavy liquids is widely used for characterizing coals with respect to their potential for cleaning by gravity-based methods. We have developed procedures for extending these analyses into the respirable size range. The major problem was found to be to ensure complete dispersion of the particles in the heavy liquids. A procedure has been developed in which surfactants are used as dispersing agents, and solids concentration is minimized. Using centrifuges to increase separation rates and subsieve particle size analysis of the specific gravity functions, a complete size-gravity distribution can be obtained. Analyses have been performed on the standard respirable dust samples. A typical result is shown in Figure 3.

The results of this investigation indicate that the float-and-sink procedure can indeed be extended to ultrafine particles provided steps are taken to ensure complete dispersion of the particles in the heavy liquids and sufficient time is allowed for separations to reach completion. Micron-size particles of near-gravity material may require very long separation times (hours) even in high-speed centrifuges. Appropriate measures to ensure dispersion of the particles include the use of surfactants such as Aerosol-OT to reduce particle-particle attraction and very low solids concentration to minimize interparticle collisions. Since statistical constraints are easily satisfied for very fine particles, sample size can be determined on the basis of the minimum quantity needed for reliable weighing of the fractions etc.

Standard Respirable Dusts, with consistent, reproducible characteristics which simulate those of actual mine dust, should be of significant value in promoting coordinated research into dust characterization and mine monitoring, dust control, and the biomedical aspects of dust toxicology. The use of an opposed-jet, fluid-energy grinding system in closed circuit with a cross-flow, centrifugal air classifier for preparing bulk quantities of respirable-size dust has been investigated, and appropriate, standardized procedures have been established. By stage-crushing, screening, and fine-grinding with a Donaldson Acucut classifier/mini-grinder system, it is possible to produce bulk quantities of respirable dust at relatively high rates.

Using minor modifications to the system, broader or narrower size distributions can be prepared within the respirable range.

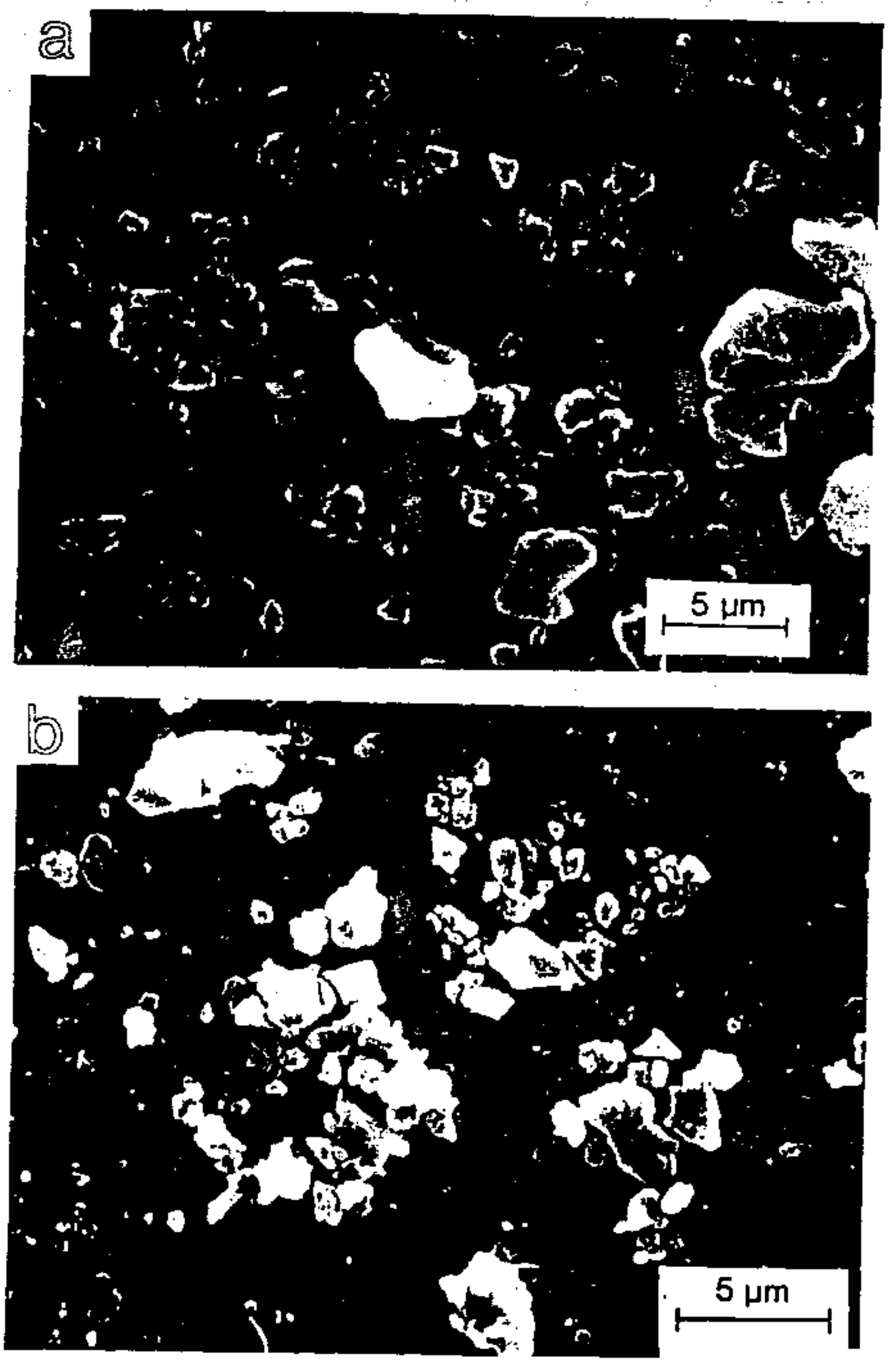
Standard respirable dust samples have been prepared from coals representing the western (high volatile A bituminous), central (medium volatile bituminous) and eastern (anthracite) mining areas of Pennsylvania. Quartz and kaolin clay samples, representing important mineral constituents of coal dust have also been prepared. Extensive characterization studies have been performed on the samples to evaluate chemical and mineralogical composition and the distributions of particle size and specific gravity. Detailed information on the original coals is available from the Penn State Coal Data Base. The standard coal dust samples appear to simulate actual mine dust very well with respect to particle size and shape, but generally have somewhat lower ash content. A comparison of a synthetic dust with a sample of actual mine dust is shown in Figure 4. There appear to be no noticeable differences in particle size and shape between the two, indicating that the synthetic dusts may indeed be appropriate for research into coal mine dust and Coal Workers' Pneumoconiosis. Samples of these standard dusts have been made available to research groups concerned with respirable dust in mines.

APPLICATIONS OF RESEARCH RESULTS

Because of the central role of characterization in the research activities of the center, the results of these investigations are directly applicable to a broad range of engineering and biomedical research projects. For example, the use of the laser diffraction/scattering technique (Microtrac SPA, Malvern 2600C) for rapid determination of dust size distributions has been adopted by a number of the research groups. The standard dust samples are being used extensively for instrument calibration, experiment set-up and for direct investigation.

CONTINUING WORK

Further refinement of the procedures for respirable dust characterization is a continuing objective of this on-going research project. Recent emphasis has been placed on extending the analyses to



b

Figure 4. Scanning electron micrographs of a) standard respirable dust from Upper Freeport seam and b) actual coal mine dust from Brookville seam.

ultrafine particles (<0.2μ) Specifically, we are investigating the problems of collecting ultrafine particles from airborne dust and size characterization by centrifugal sedimentation and dynamic light scattering. Additional studies of the sampling of airborne dust are also being carried out. The aims include evaluation of personal (cyclone) samples relative to total (filter) samples. The signicance of the respirable/non-respirable fractions as reported by different sampling systems is of particular interest. The problems of identifying and quantifying the extent of agglomeration in airborne dust are being investigated in a cooperative effort with Project No 4223. There is some evidence that loose, fragile agglomerates which may exist in an aerosol may be broken up (and therefore, not detected) by cascade impactors. Attempts are in progress to corroborate this evidence and to develop procedures for in-situ evaluation of such agglomerates.

Simple schemes for characterizing the shape of respirable dust particles are being investigated. In a cooperative effort with Project No. 4208, sets of perimeter points, generated from SEM images of particles, are being evaluated. Two factors which are believed to contribute to particle pathogenicity are sharp angles (e.g. quartz) and high length/width ratios (e.g. asbestos). We are attempting to devise simple descriptive parameters to define angularity and elongation indices for particles. To be useful in practice, it is necessary that these parameters be easy to determine and to interpret. Consequently, the selection of suitable criteria is being constrained so as to minimize the need for extensive data collection and processing.

TECHNOLOGY TRANSFER

The following is a list of publications which are based in whole or in part on research conducted under this project and which are of direct relevance to the problems of respirable dust characterization.

1. T. F. Dumm and R. Hogg, "Estimation of Particle Size Distributions using Pipet-Withdrawal Centrifuges", Particle Characterization, 3, 122-128, (1986).

2. R. Hogg and S. Chander, "Surface Characterization for Coal Processing", Chapter 17 in Fine Coal Processing, S. K. Mishra and R. R. Klimpel, Eds., Noyes Publications, 1987.

3. T. F. Dumm and R. Hogg, "Distribution of Sulfur and Ash in Ultrafine Coal", in Processing and Utilization of High Sulfur Coals II, Ed., Y. P. Chugh and R. D. Caudle, Elsevier, New York, pp. 23-32 (1987).

4. T. F. Dumm and R. Hogg, "Particle Size Distribution of Airborne Dust in Coal Mines", Chapter 21 in Proc. of the 3rd Mine Vent. Symp., Ed., J. M. Mutmansky, Littleton, CO, Soc. of Mining Engs., pp. 510-516 (1987).

5. T. F. Dumm and R. Hogg, "A Procedure for Extensive Characterization of Coal Mine Dust Using a Modified Personal Sampler", Respirable Dust in the Mineral Ind: Health Effects. Characterization and Control, Ed., R. L. Frantz and R. V. Ramani, Penn State U., University Park, PA, pp. 290-297 (1988).

6. T. F. Dumm and R. Hogg, "Standard Respirable Dusts", Respirable Dust in the Mineral Ind: Health Effects. Characterization and Control, Ed., R. L. Frantz and R. V. Ramani, Penn State U. Press, University Park, PA pp. 193-222 (1988).

7. R. Hogg, "Characterization Problems in Comminution - An Overview", Int'l. J. Mineral Processing, 22, 25-40, (1988).

8. T. F. Dumm and R. Hogg, "Washability of Ultrafine Coal", Min. and Metall. Processing, 5(1):25-32 (1988).

PSS/USBM 4207

Wetting Characteristics of Dust Particles in Relation to Dust Abatement

Chander, S.; Aplan, F. F.; Mohal, B. R. and Alaboyun, A.

INTRODUCTION

Suppression of mine dusts is an important mine health and safety measure for minimizing silicosis in ore miners and black lung in coal miners. The dusts generated in the mining of ores often contain a high silica content, and it was discovered earlier in this century that a switch from dry to wet drilling greatly reduced the incidence of silicosis. This is because silica is naturally wet by water (i.e. it is hydrophilic). Supression of coal dusts is a more difficult problem because many coals are not naturally wet by water (i.e. are hydrophobic) and also because there is a great range of hydrophobicity in coals ranging from strong hydrophobicity in high rank coals to very weak hydrophobicity in the lowest rank coals. In addition, aging or oxidation of the coal is known to reduce its hydrophobicity. A further complication is that coal mine dusts contain highly variable amounts of fine silica, clays and carbonaceous shale particles. As a consequence of the resulting variation in the hydrophobicity of coal mine dusts, it is small wonder that the literature is ambivalent as to the effectiveness of surfactant - containg water sprays in suppressing coal dusts with some reports claiming outstanding success while others show little effect.

We believe these differences can be explained by research aimed at developing a reliable wetting test, by a detailed study of the effect of coal properties and the interaction of coal mine dusts with a variety of surfactants, and a thorough evaluation of the processes by which a dust particle is captured by a water droplet. The use of surfactant-containing sprays to allay dusts differs from the commonly used process of ventilation (a dilution method) and water-only sprays (which rely heavily on the natural wettability of the particles in question). The successful development of a surfactant-containing suppression system thus offers the user an additional degree of freedom in controlling dusts; most especially those dust particles not rapidly wetted by water.

RATIONALE

The principal benefit claimed for the usefulness of surfactant-containing water spray droplets, used to supress coal mine dust, is their ability to make the dust particles easily wettable by the spray droplet. We may visualize this capture process as being comprised of the following sequence of sub-processes:

1. Collision between water droplets and dust particles.

2. Adhesion of the dust particle to the droplets.

3. Spreading of the water on the particle surface so that the particle is engulfed by the water droplet.

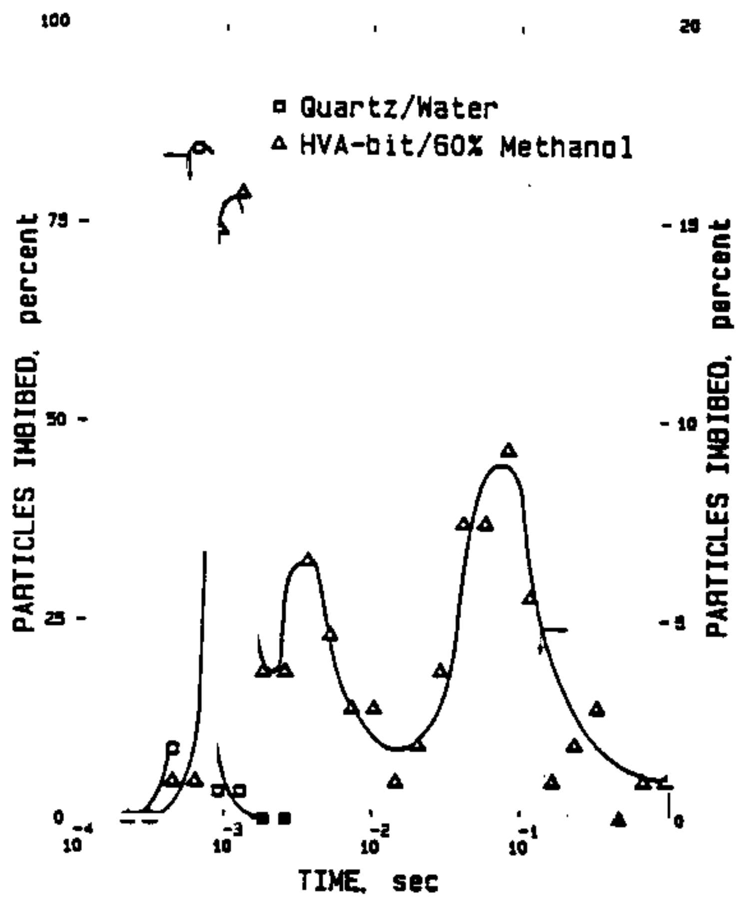


Figure 1. Imbibition times for a wet ground quartz in aqueous 2×10^{-3} M NaCl and a HVA bituminous (PSOC-1361P) coal in a 60 vol. % methanol-water mixture.

Although step 3 is not strictly necessary for dust removal, its occurrence should greatly improve the efficiency of the capture process since, unless engulfed, dust particles on the surface of water droplets will prevent other particles from attaching at or near that spot. The use of surfactants should make dust suppresion more favorable by increasing the effectiveness of all of the above sub-processes.

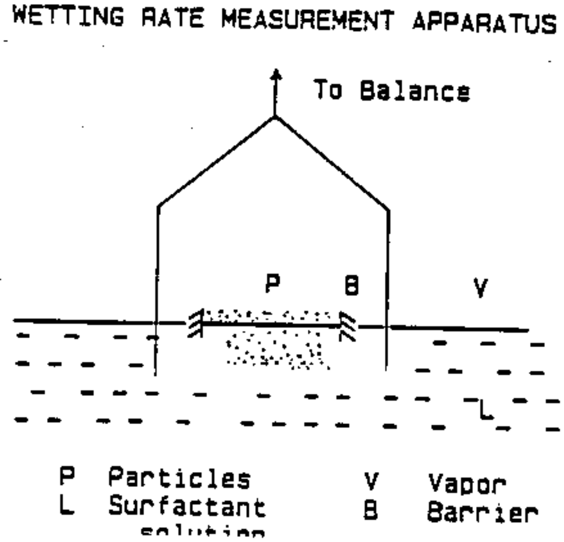


Figure 2. A schematic of the wetting rate measurement apparatus.

Step 1 is largely a circumstantial (i.e. the dust concentration) or a mechanical process (control of the size and concentration of droplets), but it can be augmented by increasing the force of attraction between particles and droplets and can thus be influenced by the nature of certain surfactants. Step 2 requires that the particle be naturally wet by water or that it be induced to do so as by the use of a wetting agent for hydrophobic particles. In Step 3 the spreading rate of water on a particle surface can be greatly enhanced by use of the proper surfactant.

One of the major problems in determining the effectiveness of a wetting agent is the need for a simple, predictive test. A great many methods have been given in the literature (see e.g. Zeller USBM RI 8815) and most of these involve polished specimens, the wetting of a bed of dust particles, zeta potential, or the time for a particle to sink in a given solution. Each of these techniques responds to different combinations of one or more of the above sub-processes, often only one. As a consequence it is not surprising that various experimentalists often using different methods, report different results. Further, if we add the complication of the differing nature of coal mine dusts from source to source, it is small wonder that different results have been reported as to the effectiveness of surfactants in suppresion of coal mine dusts.

As will be outlined below, we have addressed these major concerns of test procedure and the effect of the nature of the coal (rank and aging), and we continue to evaluate the mechanisms of the interaction between particles and surfactant solution with a view of tailoring a specific surfactant system to a specific mine dust.

SCOPE

The main objective of this research is to enhance the effectiveness of water droplets in suppressing mine dusts. Water droplets are employed in two of the most widely used dust suppresion systems: water sprays and flooded bed scrubbers.

The specific objectives of this research is:

* To evaluate and develop laboratory techniques to determine wettability of coal dust.
* To determine the effectiveness of various surfactants in wetting coal.
* To understand the basic mechanisms by which particles are captured by droplets.
* To determine wettability of coals of different ranks.
* To enhance wettability by using a mixture of surfactants.
* To understand the basic mechanisms by which surfactants attach onto coal.
* To develop guidelines to select wetting agents to suppress coal and quartz in dust.
* To study the capture behavior of particles by sprays of selected surfactant solutions.

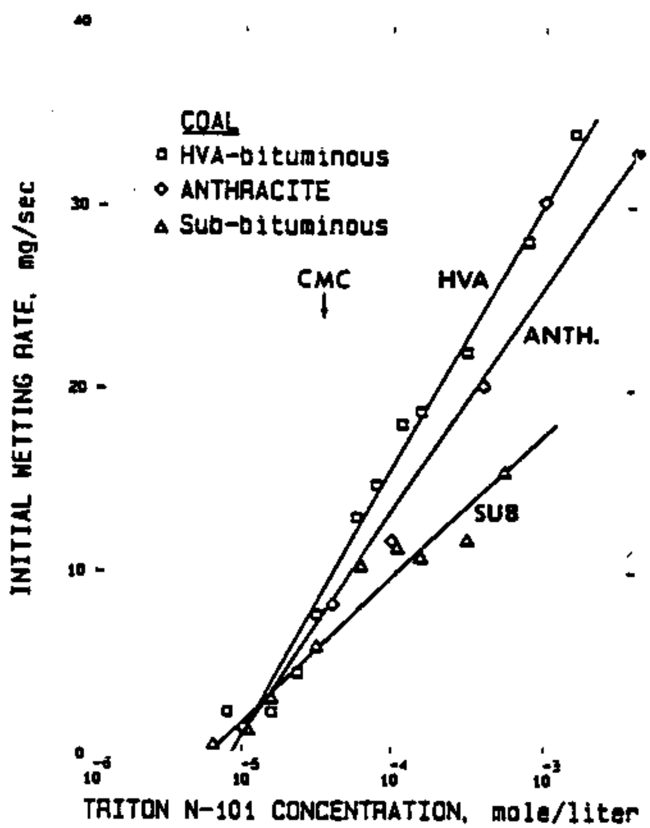


Figure 3. The initial wetting rates for various coals as a function of the Triton N-101 (nonlphenol with 9.5 moles ethylene oxide) concentration.

CONCLUSIONS

On the basis of the research conducted as part of this project, a general conclusion is that enhanced wetting of coal could lead to increase in capture efficiency of dust particles by water sprays. The enhancement of wetting can be achieved by using suitable surfactants. The choice of a surfactant and its concentration depend upon coal rank, degree of oxidation, etc. The results of our various investigations are described in the paragraphs that follow.

Characterization of Wetting Behavior of Coal Particles

A novel test procedure was developed to determine the degree of heterogeneity of a sample of coal particles with regard to its wetting behavior. This approach was considered necessary because, for a highly heterogeneous substance like coal, the use of an averaged parameter to represent wetting characteristics is not very satisfactory and could, in fact, be misleading as demonstrated by the research conducted as a part of this research program. In this technique, referred to as imbibition time measurements, the time between the instant a particle first impacts at a liquid/gas interface and the instant when the particle is completely engulfed by the liquid is measured. The number of particles imbibed can be plotted as a function of imbibition time to give a frequency distribution. From the shape of the frequency distribution curve, the wetting characteristics of a powder can be quantified. For example, a quartz powder with water as the wetting liquid gave a

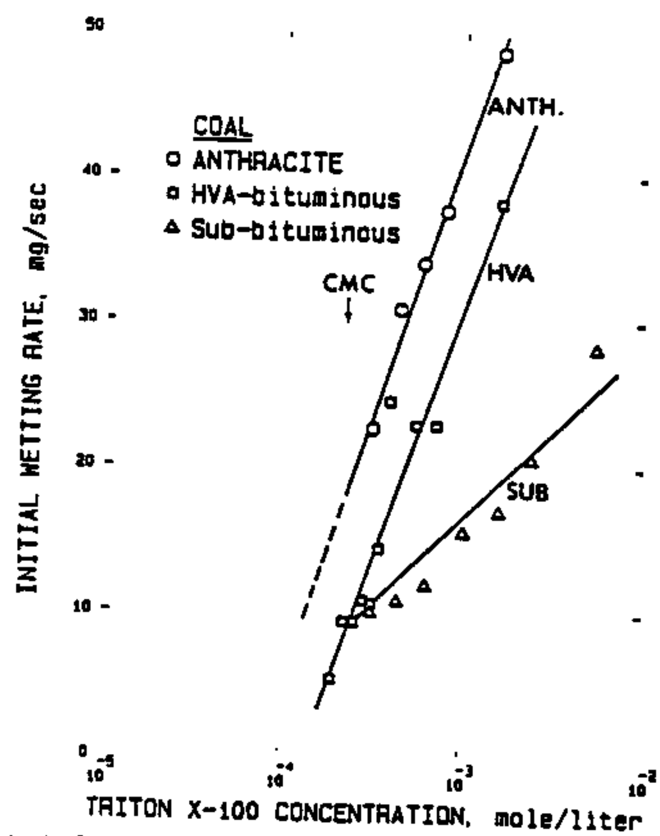


Figure 4. The initial wetting rates for various coals as a function of the Triton X-100 (octylphenol with 9.5 moles ethylene oxide) concentration.

relatively narrow frequency distribution with a mean imbibition time of 0.5 ms as shown in Figure 1. In comparison, a coal sample with a 60 vol. % methanol-water mixture as the wetting liquid gave a trimodal distribution which is also shown in Figure 1. The results imply that coal sample consists of three type of particles with average imbibition times of 0.9 ms, 2.1 ms and 60 ms, respectively. Although a great deal of information is obtained regarding the wetting characteristics of coals by this technique, the measurement of imbibition times requires special instrumentation and laborious experimentation. Therefore, alternate wetting methods were developed.

The initial rates of wetting were determined by a modified Walker technique in which the amount of coal imbibed is measured as a function of time. The pan of a Cahn electrobalance was placed beneath the liquid surface to measure the weight of coal wetted as shown schematically in Figure 2. Both these techniques were used to determine the effect of various parameters on wetting characteristics of coal. In addition, other methods such as contact angles, adsorption density measurements were also used to delineate the nature of interactions between surfactants and coal. Some selected results are given in the paragraph that follow.

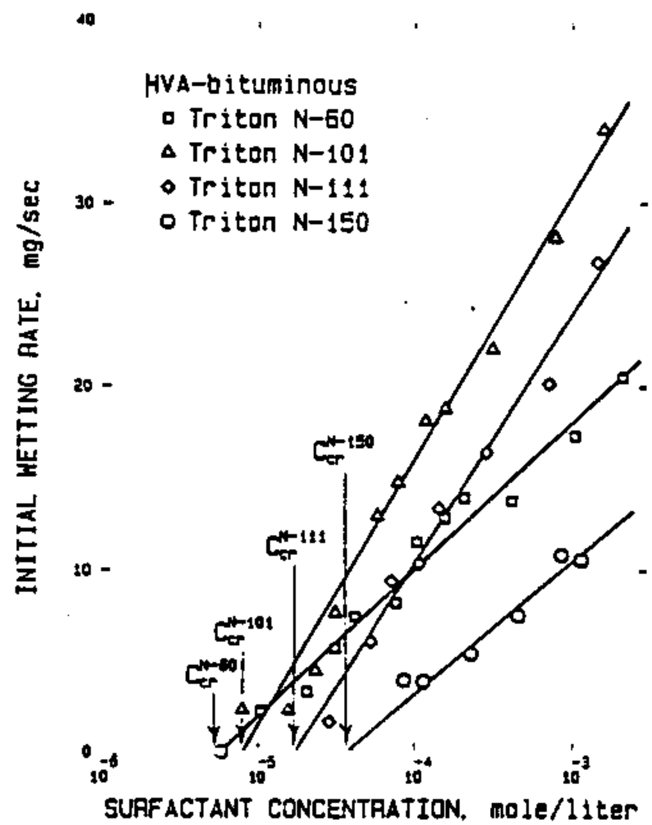


Figure 5. The initial wetting rates for a HVA bituminous coal for various ethoxylated nonylphenols (N-60 E=6; N-101 E=4; N-111 E=11; N-150 E=15).

Role of Coal Rank

Our results show that the effectiveness of a surfactant in enhancing the wetting behavior of a coal is a strong function of coal rank. For example, a HVA-bituminous coal is most readily wetted by an ethoxylated nonylphenol (Triton N-101) whereas an anthracite coal is most readily wetted by an ethoxylated octylphenol (Triton X-100). These results are given in Figures 3 and 4, respectively. The sub-bituminous coal is most difficult to wet by the non-ionic surfactants used in this part of the investigation. From Figures 3 and 4, it can also be seen that the rate of wetting generally increases with increase in concentration of the surfactant. Although lowering of surface tension is believed to be responsible for increased wetting, the value of surface tension does not correlate with the measured wetting rates. For example, the wetting rate increases with increase in concentration above the CMC (critical micelle concentration marked by arrow in Figures 3 and 4) even though the surface tension is constant. Similarly, the wetting behavior of a coal is different for different surfactants of the same surface tension. In order to explain these results, we are conducting studies of the adsorption behavior of surfactants on coal.

Role of Surfactant Type

As a part of this research program, we have investigated the effectiveness of non-ionic surfactants in enhancing wetting of coal. Complimentary studies are being carried out at the USBM Twin Cities Research Center, Minneapolis where effectiveness of anionic surfactants is being investigated. Several surfactant variables have been investigated in our study which include:

- number of ethoxy groups in the hydrophilic part of the ethoxylated phenol series of surfactants.
- number of carbon atoms in the hydrophobic part of the ethoxylated phenol series of surfactants.
- non-phenol based surfactants.

The effect of the number of ethoxyl groups in the hydrophilic chain is shown in Figure 5 for a nonylphenol series of surfactants. It can be seen that the effect is quite complex. As the number of ethoxy groups is increased, the wetting rate first increases and then decreases. Similar results were obtained with the octylphenol series of surfactants.

The number of ethoxy groups determine the hydrophile-lipophile balance (HLB) of a surfactant. It can be seen from Figure 6 that an optimum value of HLB exists at which the rate of wetting is maximum. Our investigations show that the optium HLB is a function of coal rank. For example, for a HVA-bituminous coal optimum HLB is 13.4 whereas for a sub-bituminous coal it is 11.6.

The effect of hydrocarbon chain is shown in Figure 7 where the wetting rates are given for three different hydrophobic groups containing 8, 9 and 12 carbon atoms, respectively. As the number of hydrocarbon atoms increases the minimum concentration required to make the coal wettable decreases. At higher concentrations, the wetting rate is highest for the surfactant which has the smallest number of carbon atoms, however.

Effect of Coal Aging

The effect of aging of the coal on the amount of surfactant adsorbed is given in Figure 8 in which the adsorption density is plotted as a function of surfactant concentration. For aging tests the coal sample were aged for a period of one week. The aged sample adsorbed considerably more quantities of the surfactant than the freshly ground sample. This order was reversed at higher surfactant concentrations, however. Higher wetting rates were also observed for the aged coal at lower surfactant concentrations. These results are in agreement with the adsorption results.

APPLICATIONS OF RESEARCH RESULTS

The technical knowledge obtained as a part of this research program might be used in several different ways. The following is a list of the potential applications:

1. Test procedures have been developed to screen various surfactants as wetting aids to suppress dusts.

2. A scientific rational has been developed and basic data obtained to tailor surfactants for coals of a given rank/degree of oxidation, etc.

3. The test work that is being presently carried out in an experimental dust chamber should prove useful in the design of spray systems for dust control.

CONTINUING WORK

The continued studies for this research program are focused on determination of the effectiveness of surfactant-bearing water droplets in capturing dust. In the past year, we have fabricated a dust chamber equipped with water sprays. The chamber is equipped with a device to measure, in-situ, the concentration and size distribution of water droplets and dust particles. The various components of the system are being individually tested and calibrated; the entire system is being tested with selected surfactants within the current grant-year. Once the apparatus is operational, the effect of several parameters will have to be measured to determine the parameters which govern the effectiveness of surfactant containing water droplets. Some of the important parameters are: Spray Parameters (droplet size, number density of droplets, charge on droplets, surfactant type and concentration, nozzle operating parameters (type, location, angle, etc.)) and Dust Parameters (coal rank, diesel exhaust particles, quartz content, particle size, surface charge).

TECHNOLOGY TRANSFER

Several publications and presentations at national and international meetings have resulted from this work. These include two publications in referred journals, two in proceedings of symposia and several presentations. One student has finished his Ph.D. thesis research while the research for another M.S. thesis is in progress. We have also coordinated our work with researchers at the USBM Research

Center at Minneapolis. Since we are working on a totally different class of surfactants then those being studied at the USBM Twin Cities Station, the two studies, taken together, should allow for a much better evaluation of the role of surfactants in mine dust suppression. In addition, we have held technical discussions with investigators at Hershey Medical Center and at NIOSH.

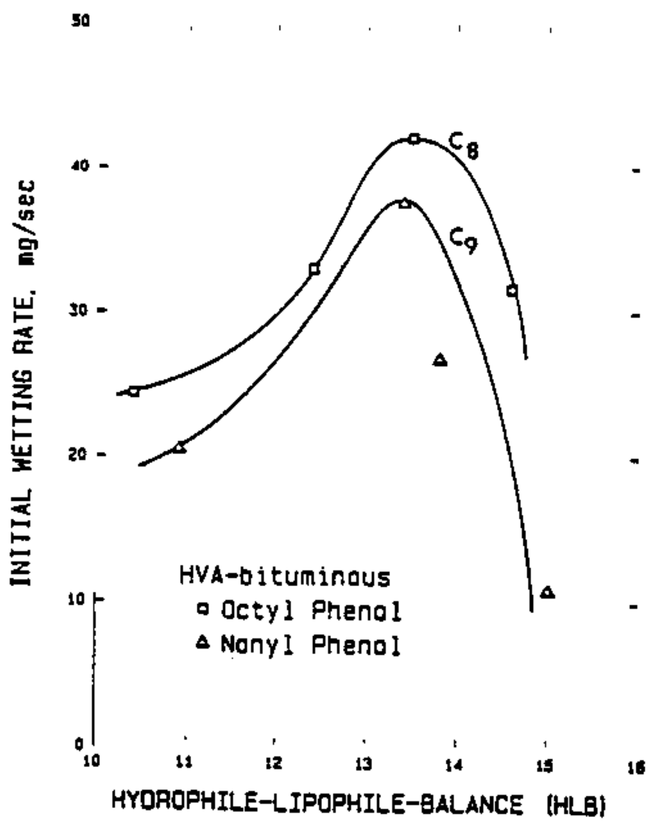


Figure 6. Initial wetting rates for HVA bituminous coal as a function of the HLB number ofr 0.1 wt % surfactant concentrations.

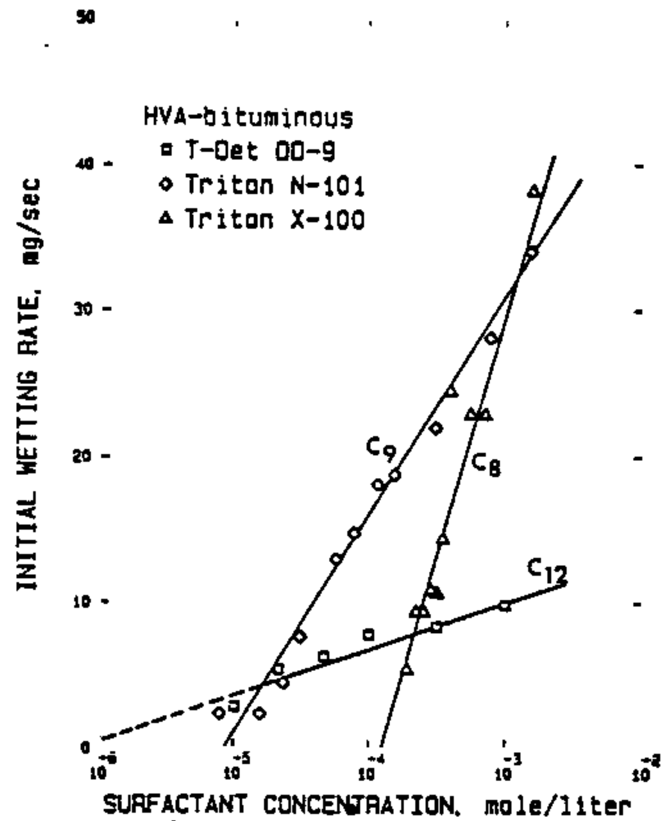


Figure 7. Initial wetting rates for T-Dt DD-9 (dodecylphenol with 9 moles ethylene oxide), Triton N-101 (nonylphenol with 9.5 moles ethylene oxide) and Triton X-100 (octylphenol with 9.5 moles ethylene oxide).

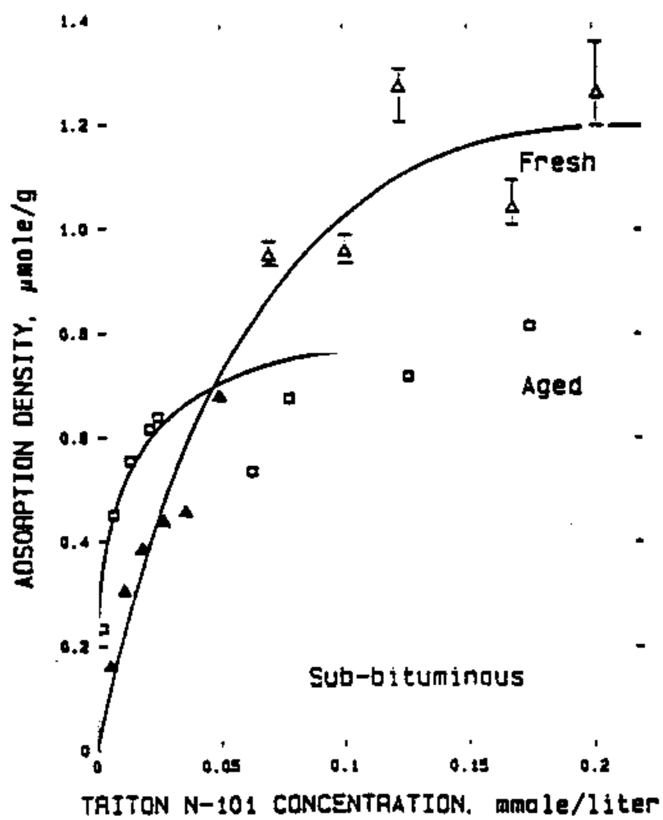


Figure 8. Absorption of Triton N-1-1 versus equilibrium concentration for a freshly ground and aged sub-bituminous coal. (For filled symbols error bars are less than symbol size.)

PS9/USBM 4208

Analysis of Coal Dust Particles on a One-By-One Basis Using an Automated Computer Controlled SEM with X-ray Fluorescense

Austin, L. G.; Hogg, R.; Dumm, T. F.; Gomez, C. and Rabinovich, A.

INTRODUCTION

The primary goal of this project is to develop an automated, particle-by-particle analysis technique using a computer controlled SEM and an energy dispersive X-ray spectrometer. This will provide a characterization tool which will be able to measure the size, shape and chemical composition of many hundreds of particles in a relatively short test time. This information could then be used to answer questions such as: How much silica is in the dust? Is it coarser or finer in size than the other coal particles? Does the silica have a more angular shape than the other particles? The development of several aspects of the total analysis technique have been considered in this research: (i) a complete system characterization in terms of how the electronic measurement devices collect raw data from a sample. This considers detector efficiency, peak overlap, etc. (ii) development of the most suitable sample preparation techniques for both large and small particles (iii) development and evaluation of shape indices and (iv) efforts to improve the chemical analysis of very small, irregularly shaped particles.

RATIONALE

Coal is a complex heterogeneous mixture of organic and inorganic substances. When coal is mined, very fine (respirable) coal dust is generated and can be inhaled into the workers lungs. This dust, which may pose a potential health risk, is also a heterogeneous mixture but may not have the same properties as coal of larger sizes. In order to understand more thoroughly the behavior of coal dust in human lungs, it is necessary to have as much accurate information on the physical and chemical properties of the dust as possible. Because coal dust is comprised of many distinct substances, bulk size and chemical analyses can often obscure important information needed to evaluate fully the toxicity of the dust. For example, if a bulk analysis determines there is 5% silica in a coal dust, we do not know if this material is present finely disseminated within organic particles or as separate and distinct quartz particles. Both types of particle extremes could have quite different effects within human lungs.

Also, it is often important not only to know just the size of dust particles but also the size and composition of the particles or size and shape or some other combination of properties. The scanning electron microscope (SEM) with energy dispersive spectrophotometer (EDS) has the potential to determine accurately three important characteristics of very fine coal dust: size, shape and composition, on a particle-by-particle basis. With this information obtained on many particles from a dust sample, many important clues about the toxicity of the dust could be revealed.

However, several significant problems must be resolved before the SEM's capability for characterizing respirable dusts can be fully utilized.

SCOPE OF WORK

The research in this project has been designed to develop procedures initially based on theoretical and empirical evaluation of known systems (glass spheres). Successful analyses and understanding of known systems will lead to adaption of procedures to pure systems (minerals) and finally to heterogeneous systems (coal). Coordinated efforts with project PS3/USBM 4203 will supply well characterized respirable coal of known size/specific gravity for use in comparative studies.

Theoretical Studies

Shape:

Having the ability to obtain the X and Y perimeter coordinates for a particle enables the researcher to apply a multitude of shape analyses. It is desired, however to have shape analysis which can be performed rapidly i.e. on-line, while original particle analysis is being done. Having studied photomicrographs of respirable samples of coal and quartz such as that of Figure 1 it was decided that the important shape features were the sharp, angular edges, or lack there of, of particles. A shape analysis procedure was implemented which fits a 20 sided polygon within the particle perimeter. (A 20 sided polygon has been shown to adequately reproduce the major features of a particle profile). The internal angles and the distance from the centroid to each of the 20 vertices can be determined. With this information, an "angularity" factor is determined. This factor is low (~0.35) for very rounded particles, and is higher (~1.0) for very elongated and sharp particles.

Composition:

When particles are dispersed on a substrate and excited by an electron beam, characteristic X-rays are emitted from the excited volume within the particle. As the X-rays travel through the particle, the probability exists for some X-rays to be absorbed by the components of the solid. If the path length through which the X-rays must travel is known, then corrections can be made to account for the absorbed X-rays. However, as can be seen in Figure 2, if the path lengths differ, as they would for dispersed irregular particles, then it would not be possible to adequately correct for this phenomenon known as the 'geometric effect'. Embedding particles in a resin and polishing to a mirror-flat surface is the only way to obtain uniform path lengths for X-rays.

However small particles less than ~ 10 µm are not suitable to this type of preparation as the particles are easily pulled from the resin matrix upon polishing.

Another consequence of analyzing very small particles less than about 10 µm with an electron beam is that as the particles become smaller than the size of the excited volume of the electron beam (a pear-drop shape of about 5-8 µm), correspondingly fewer characteristic X-rays are emitted.

If absorption path lengths were uniform, (i.e. no geometric effect existed) it would be a relatively simple matter to determine with

Figure 1. SEM photomicro graph of respirable quartz dispersed on a Nuclepore filter.

calibration samples of different sizes, the characteristic X-ray response of elements for a given particle size. An empirical function could then be used as the calibration standard for each element of interest, realizing that some predictable inherent error would exist in the form of X-ray counting statistics.

Experimental Studies

A specimen of closely-sized 20 µm glass spheres was prepared for analysis in the SEM by freeze-drying the particles onto a clean beryllium substrate. Figure 3 shows, with some electronic distortion (due to the instrument being relocated: this problem was recently been eliminated by repairing the electronics) that this technique appears to produce a well dispersed field of particles for analysis. The automated tracing routine was applied to the particles and X,Y perimeter coordinate points were collected and stored. In order to validate that representative images were being collected, the perimeter points were plotted and compared with the original image. As can be seen from Figure 4, the particle profiles appear to be sufficiently reproduced. From these and similar data of other shapes, 20 sided polygons were fitted, as shown in Figure 5 and 6, and angularities were determined.

Investigations were carried out to determine the geometric effect on spherical particles of various sizes. This was performed by traversing glass spheres of 40, 20 and 8 μm at uniform distances with the electron beam in the manual control mode (which includes Mg analysis) and collecting X-ray data at each point.

Data were also collected from 100 20 μm glass spheres which were dispersed on a beryllium substrate and 100 20 μm glass spheres which were embedded in an epoxy resin and polished to provide a flat surface. This was done to provide a chemical comparison between the ideal sample preparation versus the less ideal dispersion technique.

In order to determine the combined geometric effect and small-size effect, data were collected on -5 μm glass spheres which were prepared by freeze-drying onto a beryllium substrate.

Finally, dispersed samples of 2, 8, and 20 μm glass spheres were analyzed for size and chemical composition using a state-of-the-art Lemont Scientific image analysis system.

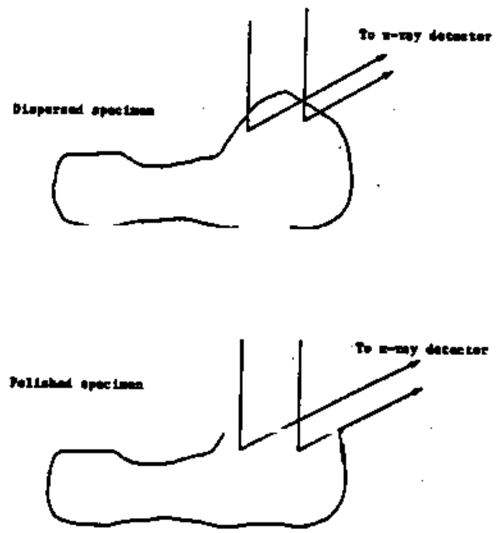


Figure 2. Effect of specimen type on the detected size and on the length of the X-ray absorption path.

Experimental Results

Perimeter coordinate points were obtained for spheres and quartz particles. The average angularity of the spheres (actually ellipsoids because of electronic distortion) was 0.41 ± 0.01 and the average angularity of quartz was 0.54 ± 0.11.

Figure 7 shows that for larger diameter spheres (20 and 40 μm), the position of the electron beam within the central area within the sphere is not critical for X-ray sampling. However for smaller spheres, for example 8 μm diameter, significant changes in composition will result from small position changes of the electron beam. It is felt however that the location of the centroid is sufficiently accurate for even very small particles (down to 1 μm) that the center of a sphere will usually always be located.

Results from chemical analysis of 100 20 μm glass spheres dispersed on beryllium substrate and 100 20 μm spheres embedded in epoxy resin and polished, reveal that there is no significant geometric effect. That is the chemical results of both samples are essentially the same as shown in Table 1. It was discovered that some glass spheres contained hollow voids which contributed to higher than expected standard deviations in elemental analysis of both types of samples. These hollowed spheres were removed prior to sample preparation and subsequent analysis revealed that standard deviations were significantly reduced. Figure 8 shows results of size and chemical analysis of -5 μm glass spheres (of which, glass spheres containing hollows were removed). It can be seen that as the size of the spheres decreases the X-ray intensity for silicon decreases. Also, as the size decreases, the standard deviation of the silicon intensity increases for a given size. It is this spread in values which would make it difficult to estimate the elemental composition of unknown substances. Even though there is an inherent standard deviation for each size which corresponds to the X-ray counting statistics, the experimental standard deviations are considerably larger.

Table 1

Element	Spectrochemical	Weight Percent Polished	Dispersed
Na	10.5	7.1	8.3
Mg	2.2	2.1	2.7
Al	0.5	0.1	-0.04
Si	33.5	32.7	33.5
S	0.06	0.98	1.07
K	0.12	2.17	1.82
Ca	5.9	7.6	7.1
Fe	0.2	0.9	0.7
O	46.0	46.4	47.8
'C'	1.0	0.05	-2.8

Table 1. Chemical compositions of 20 μm glass pheres as determined from 100 dispersed and polished specimens using manual microprobe of the SEM. Spectrochemical analysis of the spheres is given for comparison.

Chemical analyses of the homogeneous glass spheres by the Lemont Scientific Image Analysis System places each detected particle into a category based on the number and amounts of elements detected in that particle. This technique placed the spheres, which all contain about 35% Si, 10% Na and 6% Ca into as many as 14 different categories of elemental combinations, some of which could not possibly exist for this glass. This demonstrates that even a new highly sophisticated (and expensive) instrument will give wrong answers when the basic requirements for obtaining good analyses are not met.

CONCLUSIONS

A computer-controlled SEM appears to be a reliable tool for measuring the projected area size of well dispersed particles down to sizes of at least 1 μm. Perimeter tracing routines allow fairly accurate reproduction of particle silhouettes, which is a necessary requisite to any particle shape description. For particles with simple shapes such as spheres, energy dispersive spectroscopy provides a suitable means of measuring the amounts of inorganic elements in a particle. However, as particle shapes become more irregular and as particles below 10 μm are examined, it is seen that the standard deviations of of the mass fractions of elements of particles of known composition become very high.

The net effect of this is that, because the determination of mass fraction is on an absolute basis, carbon will often be attributed to particles with lower X-ray count intensities than expected. Thus it becomes difficult to distinguish a pure liberated mineral particle from a particle containing mineral plus coal. This is a fundamental problem common to all existing SEM-EDS systems.

APPLICATIONS OF RESEARCH RESULTS

(1) The automated SEM-EDS technique can perform rapid quantitative size, shape, and chemical analysis of particles in the size range of about 10 μm and larger. With development it may also be able to examine particles in the 1 to 10 μm size range.

(2) Although special consideration has been given to develop the technique for analysis of coal particles, the technique can be used

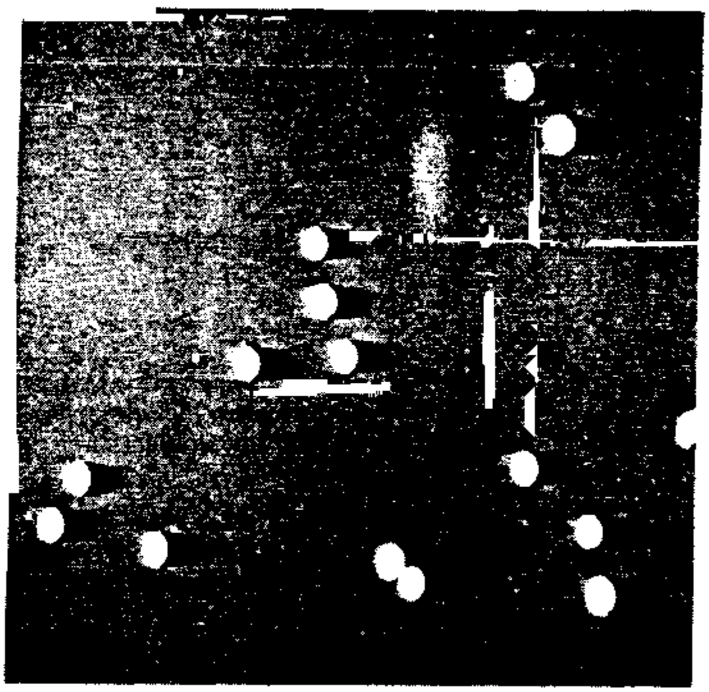


Figure 3. SEM photomicrograph of 20 µm glass spheres dispered on a beryllium substrate using freeze-dry technique.

on any substance particularly glasses which most favorably fulfill the major assumptions of the ZAF corrections.

(3) With particle-by-particle analysis of three important properties of dusts, it will be possible to look at the results of a particular dust in several dimensions such as size vs composition, composition vs shape, etc.

(4) This technique is particularly suited to the analysis of very small quantities of dusts which are not amenable to bulk analyses. Small samples from filters or cascade impactors would provide sufficient numbers of particles for analysis.

(5) In the area of coal combustion, this technique has been used to characterize the slagging and fouling potential of coals based on their chemical composition.

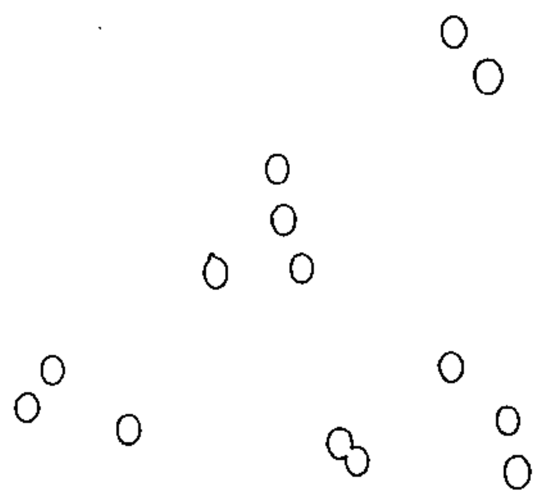


Figure 4. Computer reproduction of 20 μm glass sphere using X, Y perimeter coordinate points from tracing routine.

CONTINUING WORK

Work is continuing in the area of shape description. A suite of particle shapes is being obtained which will range in shape from rounded to sharp and angular. Angularities will be assigned to the various shapes and it will be determined if a one parameter shape description is sufficient to characterize a broad spectrum of particle shapes. It will probably be necessary to include a second parameter in order to distinguish between certain shapes.

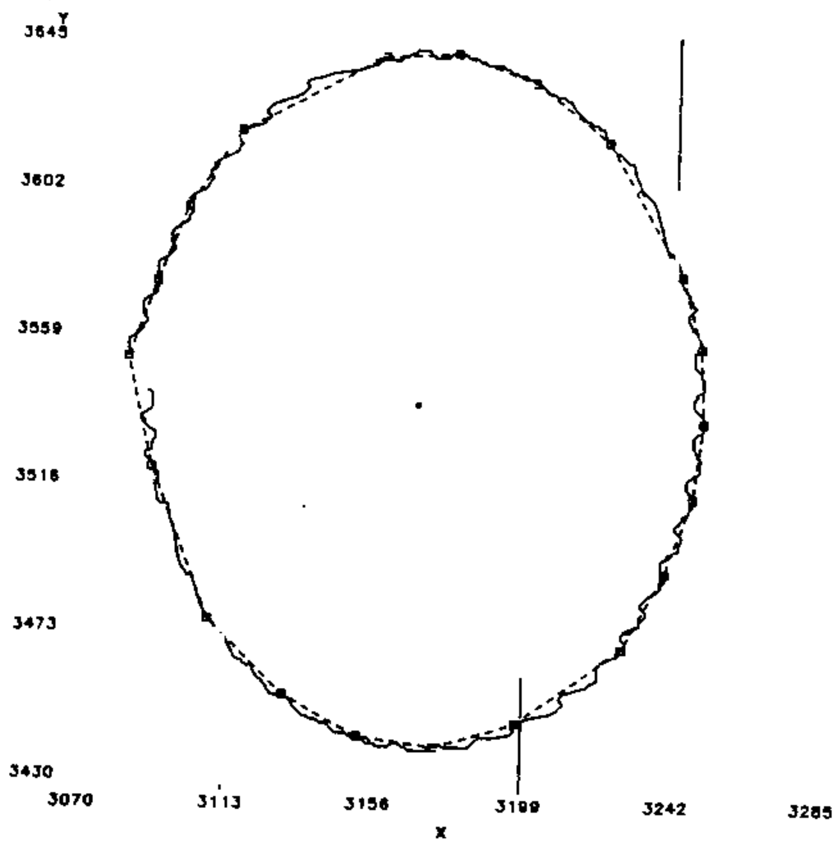
It appears that particle shape influences the standard deviation of X-ray intensities for a given particle size, rounded particles such as spheres give much lower standard deviations than more irregular particles like ground quartz. Efforts are continuing to determine if a relationship between shape and composition exists and is this can be used to improve chemical analysis of dispersed particles.

A statistical technique is being developed for estimating the range of possible compositions from a particular analysis. A knowledge of this uncertainty in the analysis will be helpful in avoiding incorrect conclusions concerning the variety of different particles present in a test dust.

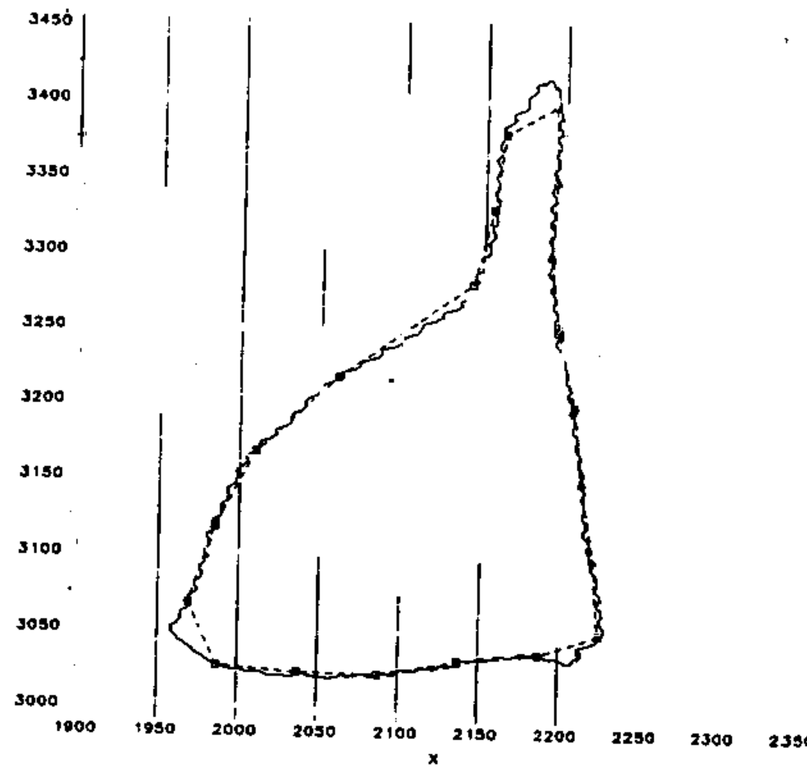
Figure 5. Computer reproduction of a 20 μm glass sphere using X, Y perimeter coordinate points from tracing routine. Inscribed within perimeter is the 20 sided polygon (dashed line).

Figure 6. Perimeter tracing and fitting of a 20 sided polygon to the shape of a quartz particle.

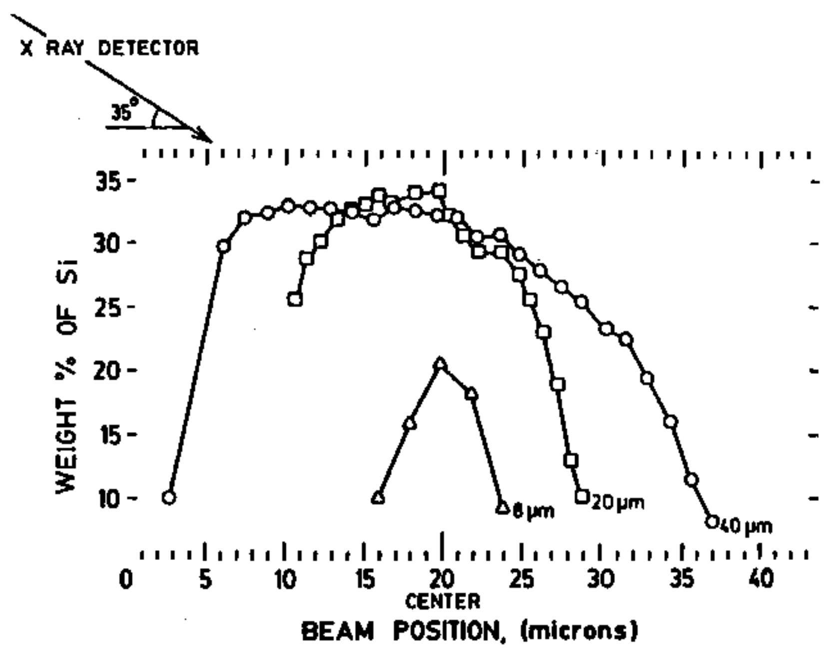
5



6



7



8

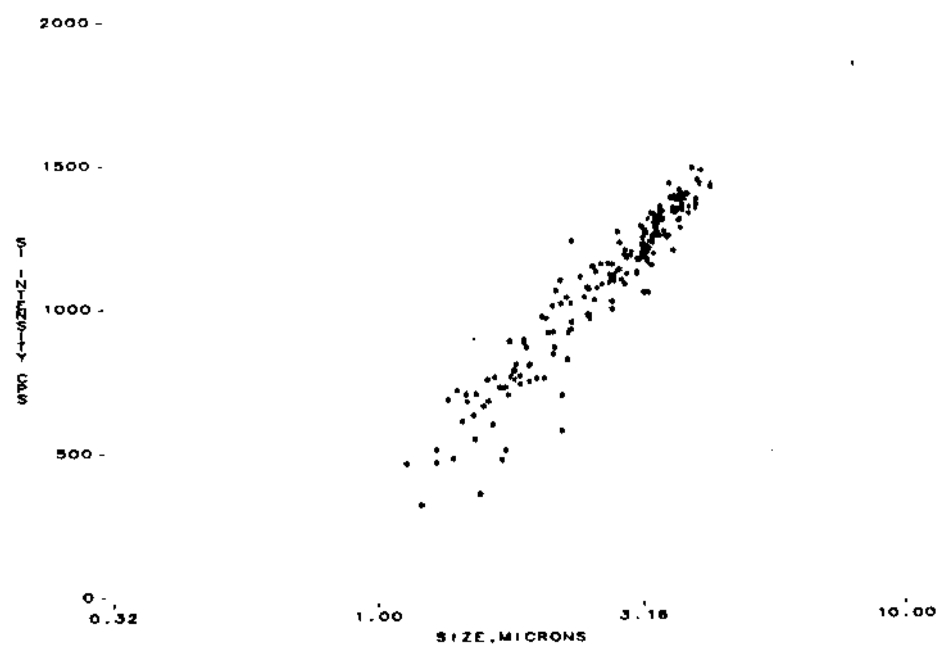


Figure 7. Calculated silicon percentage for dispersed glass spheres as a function of location of the sphere with respect to detector locations on line through center.

Figure 8. Silicon X-ray intensity versus particle size for minus ten micron glass spheres dispersed on a beryllium substrate.

PS15/USBM 4223

Adhesion, Aglomeration and Deposition of Respirable Dust

Chander, S.; **Hogg**, R.; Kohen, M.; Palat, M., Mohal, B.

INTRODUCTION

It is generally accepted that only a small fraction of the fine particles produced in mining operations actually become airborne. The majority of such particles are known to adhere to larger fragments but the mechanisms of the attachment phenomenon remain to be understood. The deviations between measured in-mine dust concentrations and those expected on the basis of theoretical models have been attributed to agglomeration and re-entrainment of particles. Although both of these phenomena depend on adhesion and agglomeration of particles, the basic knowledge needed to incorporate these effects into theoretical models is not yet available. Some of the critical aspects that remain to be explored are:

- Adhesion behavior of freshly generated dust particles.
- Agglomeration behavior of freshly generated dust particles.
- Effect of aging of particles on the adhesion and agglomeration behavior

In general, it is reasonable to assume that the amount of respirable dust which actually becomes airborne is determined by the amount generated, less the fraction adhering to larger particles, further modified by control actions such as water sprays, etc. Re-entrainment of dust previously deposited on the surfaces of airways etc., probably represents an important secondary source of airborne dust in the mine atmosphere. It is clear that adhesion and agglomeration phenomena play a determining role in each of these dust generation processes, and a better understanding of the nature of these phenomena and their dependence on such factors as mine environment, especially humidity, coal/rock type, etc., should be of considerable benefit in the development of dust control measures. Dust control by water sprays, etc., is beyond the scope of this project and is currently being investigated by researchers at the U.S. Department of Interior, Bureau of Mines and in another project of the Generic Technology Center for respirable dust. This project is concerned with the delineation of factors which control adhesion, agglomeration and deposition of respirable dust.

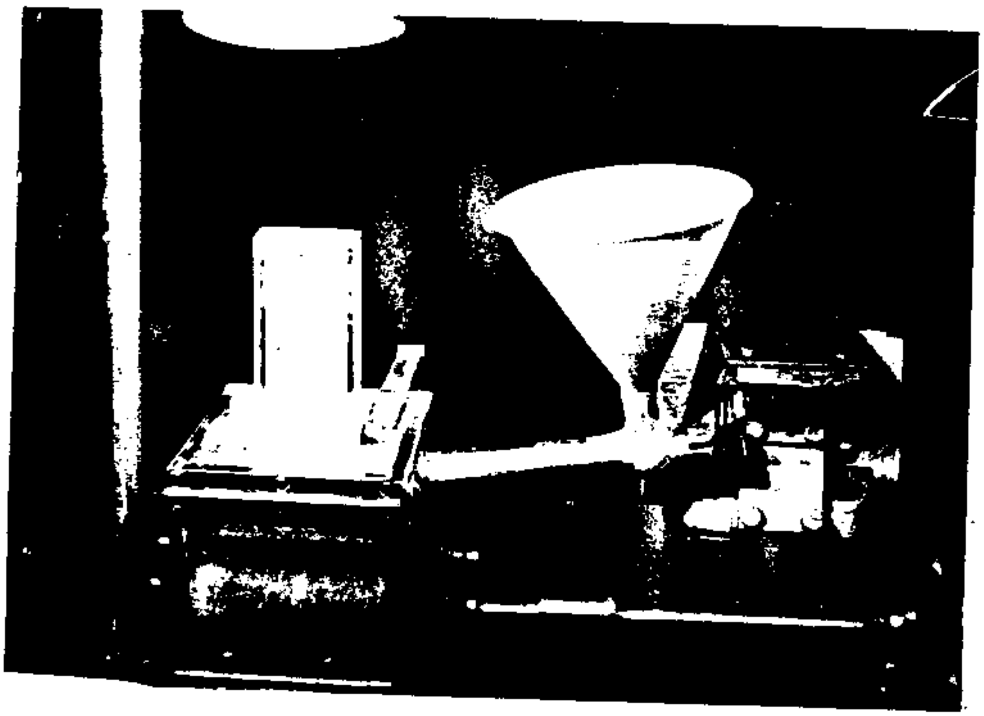
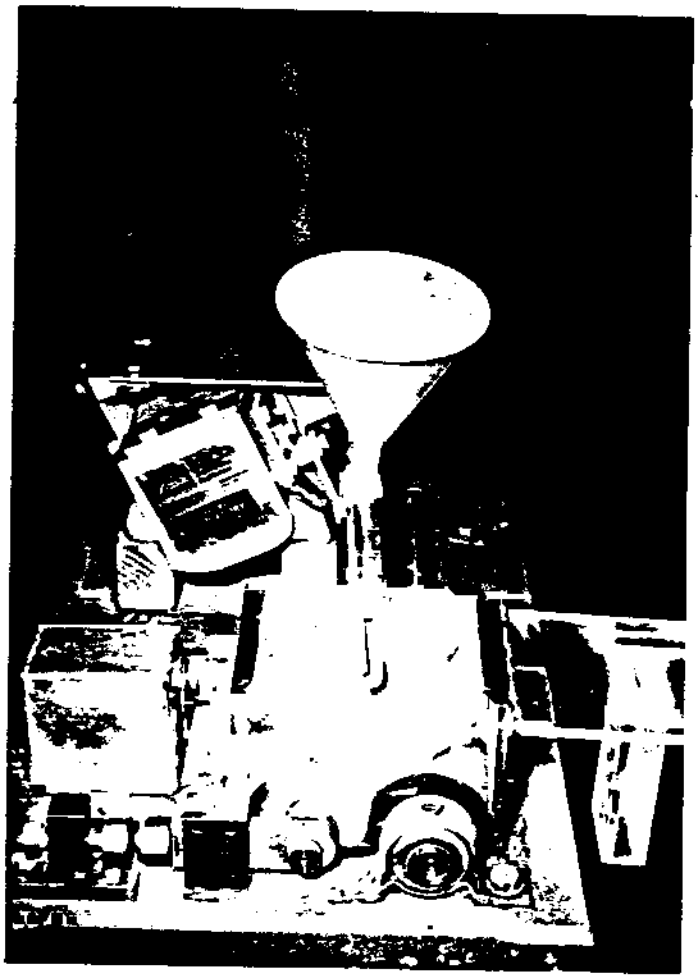


Figure 1. The 'fresh dust generator'. a) Internal view showing the crushing rolls and feeder arrangement.

RATIONALE

One approach to reduce the amount of dust in mine atmospheres is to promote the agglomeration and adhesion of particles. These two basic processes occur naturally and serve to prevent the majority of the dust from becoming airborne. However, changes in conditions in the mine could affect the adhesion and aggregation of particles and could substantially alter the quantity of dust which becomes airborne. The main objective of this project is to determine the factors which control the extent of adhesion and agglomeration so that conditions might be created to promote these phenomena.

Adhesion and agglomeration can occur in different ways: particles may remain in contact following the original fragmentation event or they may come into contact and adhere at some later time. In the first case, adhesion and agglomeration are essentially static processes which may, however, be modified by subsequent deaggregation processes. On the other hand, the formation of agglomerates from previously dispersed particles is a dynamic process which can be regarded as proceeding in two stages--initial approach of particles and adhesion on contact. Consequently, it is convenient to consider these processes in terms of collision frequency and adhesion efficiency.



b) The generator in operations.

The rates at which collisions occur between respirable dust particles and other particles or substrates depend on dust concentration, particle size distribution and relative particle motion. Extensive theoretical treatments are available which describe collision frequencies due to Brownian motion under quiescent conditions, laminar shear or turbulent diffusion in flowing air, and sedimentation due to gravity. At the concentration levels typically encountered in mine atmospheres (a few mg/m^3), collision rates are generally low and agglomeration may be essentially negligible. Immediately following fracture, however, local particle concentrations can be very high (up to a gram/cm^3) and agglomeration rates could be very high indeed.

Adhesion and agglomeration processes might also play a significant role in the re-entrainment of dust into an air stream. The tendency for particles to be re-entrained will generally depend on the strength of the bond between the particle and the substrate, and on the integrity of agglomerates which may have settled on the floor of airways, etc. A better understanding of the nature of the adhesion and agglomeration phenomena could lead to improved methods for the control of these secondary sources of airborne dust.

SCOPE

The main objective of this research project is to determine the conditions which favor adhesion, agglomeration and deposition of dust particles. The dust levels in mine atmospheres could be decreased by promoting the effectiveness of these processes.

Specific areas of investigation include:

- Development of procedures for fresh dust generation and characterization.
- Evaluation of the state of aggregation in airborne fresh dust. Investigation of the effects of environment (especially humidity) and short-term aging.
- Evaluation of aggregation in re-generated dusts.
- Theoretical evaluation of the dynamics of dust agglomeration. Exploration of the potential for control.
- Studies of the adhesion of fresh and aged dust to appropriate substrates.

Additional studies, including the break-up of aggregates under turbulent airflow conditions, and the detachment and re-entrainment of particles adhering to substrates or particle beds, will be conducted based on the results obtained and on the identification of practical problems.

CONCLUSIONS

Since the inception of this project less than a year ago, considerable progress has been made towards achieving some of the objectives. The progress to-date is described in the paragraphs that follow.

Fresh Dust Generation

The major sources of in-mine airborne dusts are:

1) rock cutting operations during mining, 2) intentional fracture and fragmentation of material during blasting, 3) re-entrainment of material by moving machinery, and 4) uncontrolled fracture and fragmentation of material in a roof collapse, etc., To understand the behavior of particles in such operations it is necessary to study the properties of both freshly generated and aged particles. As a part of this research program a fresh dust generator was designed and fabricated. A photograph of the device is given in Figure 1. The particles are generated by fracturing material between two rolls rotating in opposite directions. The material is compressed and fractured in a single pass through the crusher. Thus, the time at which fracture occurs, and hence particles are generated, is precisely known. The rate of generation of particles can be varied to a certain extent by changing the feed rate of the material to be fractured. Furthermore, the particles are available almost immediately after generation for characterization and other studies.

Characteristics of Dust Produced in Fresh Dust Generator

The size distribution of the dust generated by the fresh dust generator is given in Figure 2. If the feed rate to the dust generator is increased, the rate of generation of the dust increases but the size distribution of the dust particles does not change appreciably. This observation is important because it allows one to alter the amount of dust or dust concentration while maintaining a constant size distribution.

Our design of the dust generator allows us to carryout <u>in-situ</u> studies of the size distribution of airborne dust particles.

Preliminary studies show that the dust particles might be agglomerated in air. Additional studies are in progress to confirm these findings and to determine the size distribution and other properties of agglomerates. Confirmation of the agglomeration of freshly generated particles will enable us to conduct several studies on the factors which might control the agglomeration phenomena and on the properties of the agglomerates produced.

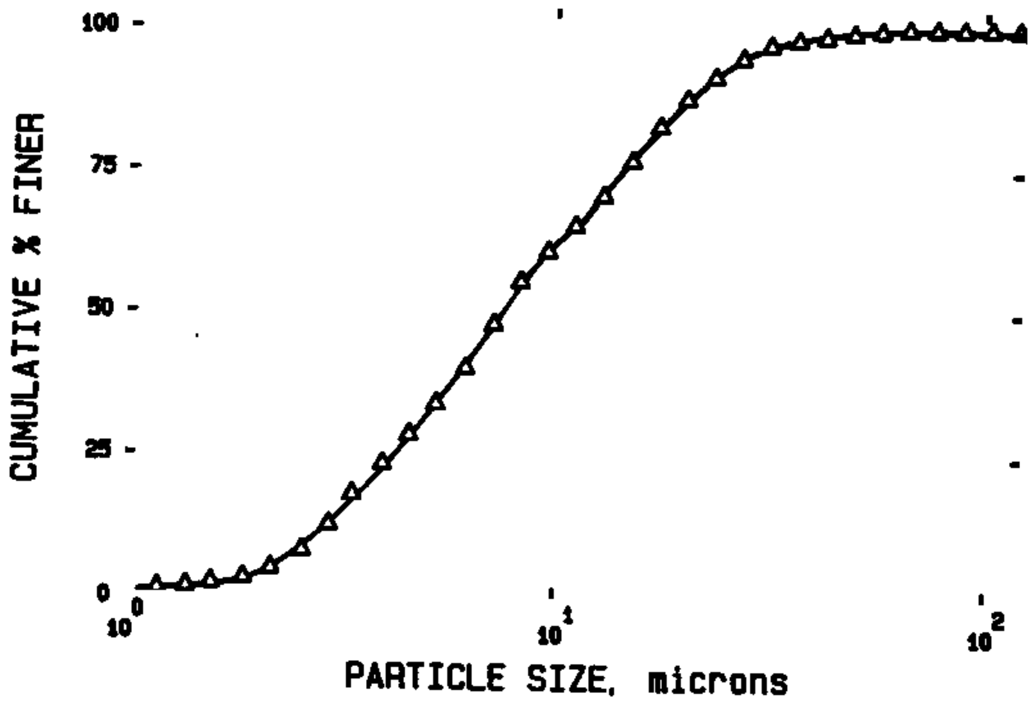


Figure 2. The size distribution of dust generated in the 'fresh dust generator.' The particles were dispersed in aqueous Aerosol-OT prior to Microtrac SPA measurements.

APPLICATIONS OF RESEARCH RESULTS

Information on the nature of the adhesion and agglomeration phenomena and a better understanding of their dependence on dust composition and environment are needed for the development of improved models for dust generation, dust transportation and deposition, and dust control. The results of these investigations will be available for direct application by research groups working in these related areas.

CONTINUING WORK

The continuing theoretical and laboratory studies for this research project are being directed towards determination of the effect of several variables on the adhesion, agglomeration and deposition behavior of particles. Since these processes occur simultaneously in many situations, carefully designed experiments will be conducted to separate the contributions from these effects. Studies will be carried out to determine the effect of humidity on the size distribution of airborne particles from the fresh dust generator.

Simultaneous measurement of the surface charge on particles will allow development of correlations between surface charge and these processes. It was stated in a previous section that preliminary studies show that particles produced from the fresh dust generator might be agglomerated. We propose to use a Spin Physics Motion Analysis System, Model SP2000 to directly observe the airborne particles. Alternatively, we might use optical or scanning electron microscopy to confirm agglomeration, if any. If agglomerates are observed, it might be possible for us to determine the density of agglomerates from which information with regard to the agglomerate structure could be obtained. We have extensive expertise in measurements of the density of agglomerates in liquids. We also plan to study the size distribution of airborne particles produced from mixtures of particles of known size distributions. These studies coupled with measurement of size distributions when particles are dispersed in liquid will enable us separate the contributions from various phenomena. These studies will be carried out for quartz as well as for coals of different rank.

TECHNOLOGY TRANSFER

A description of the fresh dust generation system and the characteristics of the dust products is currently being prepared for publication. Additional reports and publications will be prepared as the project progresses.

WV10/USBM 5409

Magnetic Resonance Characteristics of Paramagnetic Ions and Free Radicals in Coal Dust, Black Lung Tissue, and Lung Tissue Under Controlled Dust Exposure

Dalal, N.; Vallyathan, V.; Kahol, P.; Jafari, B.; Shi, X.; Deloose, J. and Martin, J.

INTRODUCTION AND RATIONALE

The biochemical pathways leading to coal workers' pneumoconiosis (CWP) are still not well understood, despite several decades of research. Based on a preliminary report by Artemov and Reznik [1], our hypothesis has been that short-lived, surface-based free radical species are one of the causative agents in the cytotoxicity of coal and quartz particles to lung tissue, and hence in the biochemical mechanism(s) of CWP. This hypothesis is supported by the observation that while the prevalence and severity of CWP differ markedly in different regions and mines despite comparable exposures, these findings can only partially be understood in terms of differences in the mineral composition and coal rank [2-4]. Laboratory animal studies using dust from different sources also do not correlate with human experimence [3-5], suggesting that perhaps there are some short-lived species in the fresh mine dust which a miner inhales, and, that such species might be absent in the "stale" dust used in the laboratory animal studies. Since free radicals are the obvious short-lived reactive chemical species, and since electron spin resonance (ESR) is the most direct technique for studying free radicals, we have undertaken correlated ESR-biochemical studies of a Pennsylvania anthracite coal (PSOC 867, 92% carbon), as well as quartz. The results obtained to date strongly suggest that mechanical fracture of coal as well as quartz does indeed lead to the formation of free radical species on the particle surfaces. Biochemical tests further demonstrate that freshly ground coal and quartz dust particles are indeed more cytotoxic than "stale" dust particles from the same stock.

SCOPE

The overall scope of this project is to provide new leads for the biochemical pathways of CWP. The observation of excess free radicals on freshly crushed or ground coal and quartz particles, directly via ESR spectroscopy, would help resolve the paradoxial observation as to why laboratory animal studies do not correspond to human (coal mines') development of CWP. Particularly significant would also be the results on the effects of radical scavenging enzymes systems, such as the superoxide dismutase (SOD) and catalase, as well as other radical scavenging chemicals such as dimethyl sulfoxide (DMSO), ethanol, mannitol etc., on the dust's free radical and cytotoxicity potential. The data obtained could suggest a chemical methodology for combating at least some of the primary events in the dust-cell interactions leading to the eventual development of CWP.

RESULTS AND DISCUSSIONS

One of the major outcomes of this project is that freshly crushed coal as well as quartz particles exhibit a high concentration of free radicals and that these radicals decay as a function of storage in air or buffer. Figure 1 shows a plot of the time dependence of parallel measurements of the free radical concentration and hemolysis for a Pennsylvania anthracite coal (PSOC 867, 92% carbon content). Detailed analysis of the time dependence of the radical concentration exhibited two main decay channels, a fast one with a half-life of a few minutes, depending on the oxygen pressure, and a slow one with half life of about a decay. The hemolysis measurements indicate a decrease in the cytotoxicity of the same dust in rough proportion with the radical concentration, thus implying a causal relationship between the free radical content and cytotoxicity. This is the first ever evidence for such correlation.

Figure 2 shows the time dependence of the concentration of the crushing-induced Si-oxygen based free radicals on the surface of freshly crushed quartz. The radical concentration decays with a half-life of about 36 hours. This result again shows that freshly made quartz dust would contain a much higher concentration of free radicals than stale dust from the same stock.

We also found that the freshly made quartz dust released hydroxyl (•OH) radicals in buffered solution. Figure 3 shows the change in the •OH-radical producing potential of the quartz dust as a function of the time of storage in air. It is again clear that the fresh dust releases more •OH radical in the buffer than the stale dust of the same stock [6,7]. Since •OH radicals are known to culminate a lipid peroxidation of tissue, it was thought worthwhile to measure the dependence of the lipid peroxidation rate as a function of time after grinding. Figure 4 shows the time dependence of the lipid peroxidation of a freshly ground quartz dust from the same stock. It can be clearly seen that the lipid peroxidation causes by quartz dust is maximum when fresh and it decreases as the dust "ages". These results suggest that lipid peroxidation might be one of the significant pathways in the fibrogenicity caused by quartz particles, at least in the case of acute silicosis [7].

Another significant result was that the •OH radical production could be completely suppressed by adding catalase, and, to a lesser extent, superoxide dismutase (SOD) to the incubating medium. These data thus show that the quartz cytotoxicity and fibrogenicity could be reduced via the use of catalase and SOD, thus providing a lead for controlling the biochemical activity of quartz dusts, especially in the case of acute silicosis [7,8].

CONTINUED WORK

The experimental results obtained thus far provide, for the first time, a clear indication that the radical moieties on the surfaces of coal and quartz particles play a role in the cytotoxicity of their dusts. In the case of quartz, it is also seen that the surface radical sites take part in reactions leading to the formation of the hydroxyl (•OH) radicals which are known to be the initiators of lipid peroxidation. In the continuation work we propose to carry out further spectroscopic and biological investigations with a view of understanding the following:

(a) The mechanism by which the surface-based radicals on both coal and quartz particles participate in the erythrocyte membrane damage, such as estimated via the erythrocyte hemolysis testing. The specific question to be answered will be: How significant is the role of the surface-based radicals in the mechanism of hemolysis by coal and quartz? To this end measurements will be made of the concentration of the surface radicals as a function of the thermal treatment up to 800°C, of autoclaving the dust particles in steam, coating the particle surface with radical scavengers in conjunction with thermal treatments, and comparing the observed changes with the corresponding variation in the hemolysis by the same samples.

(b) The mechanism by which quartz pasrticles release the •OH radicals in solution on reactions with the phosphate buffered saline (PBS) and related biological buffers. We shall be particularly interested in the role of the mineral content of the coal of quartz in the •OH radical formation, since the •OH radicals can be generated catalytically by many metal ions, such as Fe2+, via the so-called Fenton reaction. The change in the •OH radical concentration will be monitored via the ESR-spin-trapping methodology, as discussed elsewhere [6,7]. Comparison of these results with those obtained from freshly made dusts from the same samples and from dusts made from particles wash in nitric acid should yield significant information on the role of the surface-based metal ions in comparison with that of silicon-oxygen radicals and other sites. These results could then lead to new way of controlling the production of the •OH radicals and hence lipid peroxidation via silica.

(c) Start experimentation on the effects of trachial injection of fresh and stale quartz dusts of the same stock. The results might provide additional clue to the role of the surface-active sites (Free radicals or surface-metal complexes) in the cytotoxicity of coal and quartz dusts.

APPLICATIONS AND TECHNOLOGY TRANSFER

While the current focus on this project is the fundamental studies of the biochemical pathways of dust-cell interactions, with the hypothesis that free radicals play a significant role in the cytotoxicity and fibrogenicity potential of the coal and quartz dusts, we anticipate that the results obtained could provide new leads towards a biochemical methodology for combating silicosis and

REFERENCES

1. Artemov, A. V., Reznik, L. A. Questions on the methodology of biological investigations of the Fibrogenicity of coal dust. Gib. Tr. Zabol. 2:51-55 (1980).

2. Christian, R. T., Nelson, J. B., Cady T. E., et al.: Coal worker's pneumoconiosis: in vitro study of the chemical composition and particles size as causes of toxic effects on coal. *Environ. Res.* 20:358-365 (1979).

3. Christian, R. T., Nelson, J. B. Coal: response of cultured mannalian cells corresponds to the incidence of coal workers' pneumoconiosis. *Environ. Res.* 15:232-241 (1978).

4. Hatch, G. E., Gardener, D. E., Menzel D. B. Stimulation of oxidant production in alveolar macrophage by pollutant and latex particles. *Environ. Res.* 23:121-136 (1980).

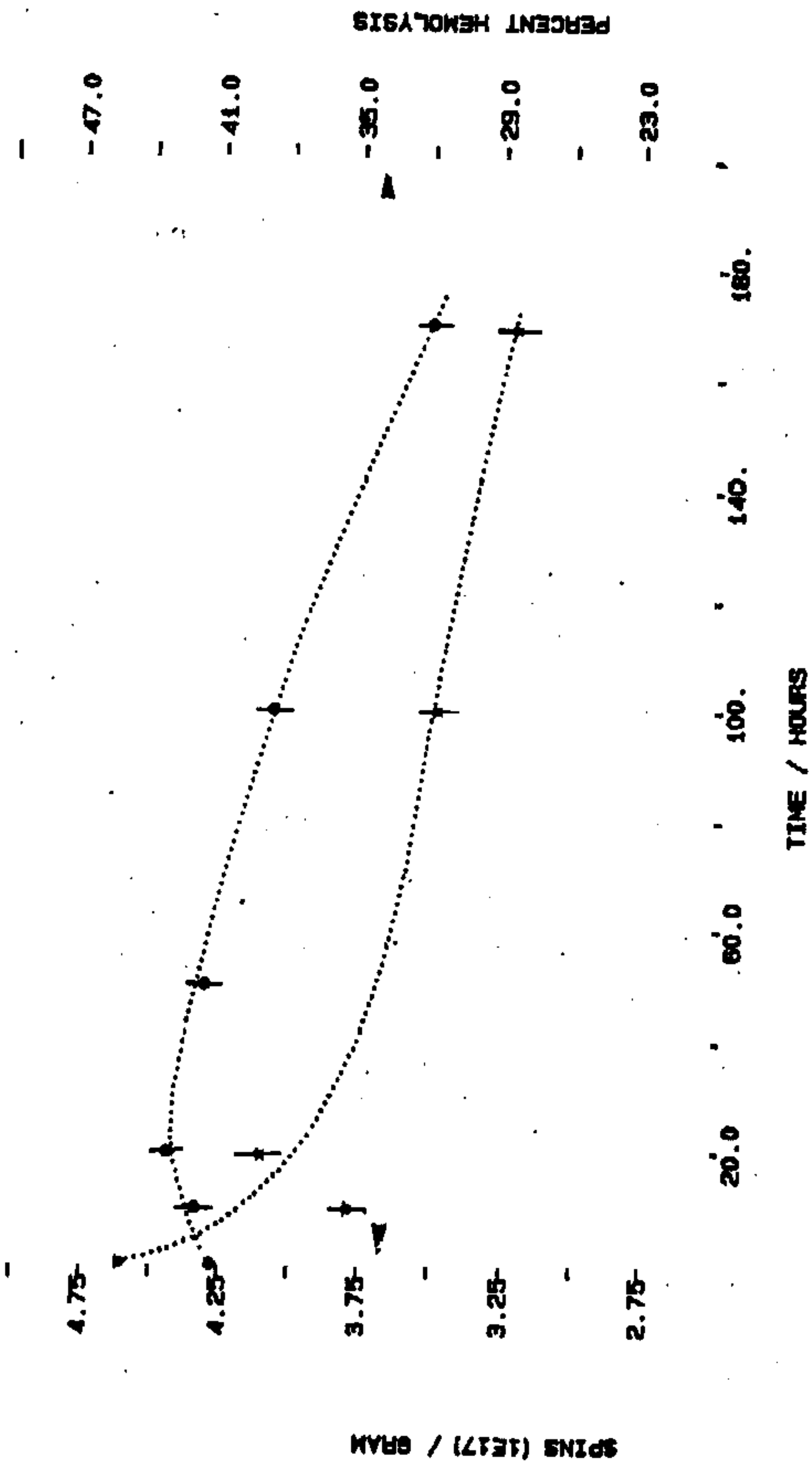
5. Heppleston, A. G. Changes in the lungs of rabbits and ponies inhaling coal dust underground. *J. Path. Bact.* 67:349-359 (1968).

6. Shi, X., Dalal, N. S., Vayylathan, V. ESR evidence for the hydroxyl radical formation in aqueous suspension of quartz particles and its possible significance to lipid peroxidation in silicosis. *J. Toxicol. Environ. Health* 25:000-000 (1988) (in press).

7. Vallyathan, V., Shi, X., Dalal, N. W. et al. Generation of free radicals from freshly fractured silica dust: potential role in acute silica-induced lung injury. *Am. Rev. Respir. Dis.* 138:000-000 (1988) (in press).

8. Dalal, N. S., Shi, X., Vallyathan, V. In: On the mechanism of hydroxyl radical formation in aqueous suspensions of fresh quartz. In: effects of Mineral Dusts on Cells (Mossman, B. T., ed.), Springer-Verlag, New York (in press).

Fig. 1 Time dependence of the free radical concentration and hemolytic potential of the dust from freshly crushed Pennsylvania anthracite coal, POSC 867.



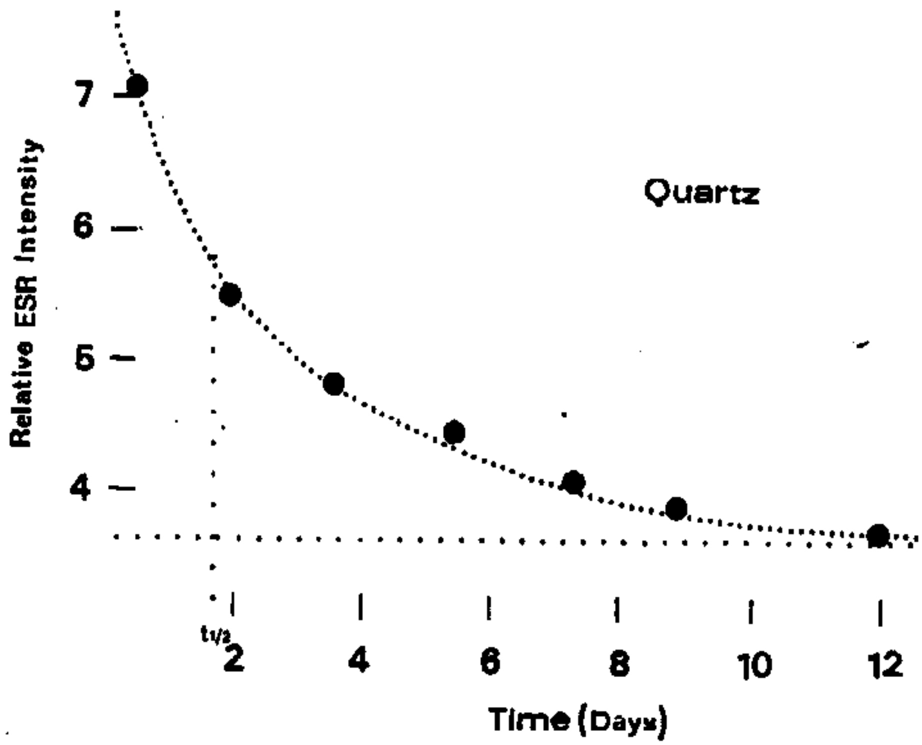


Fig. 2 Time dependence of the concentration of the silicon-oxygen radicals on the surface of freshly crushed quartz particles.

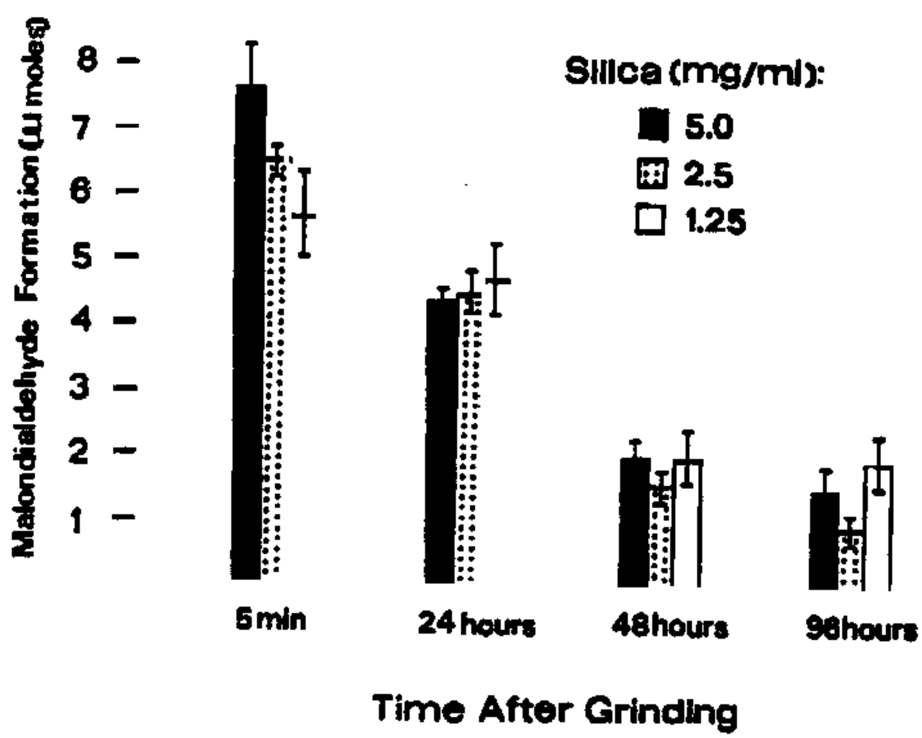
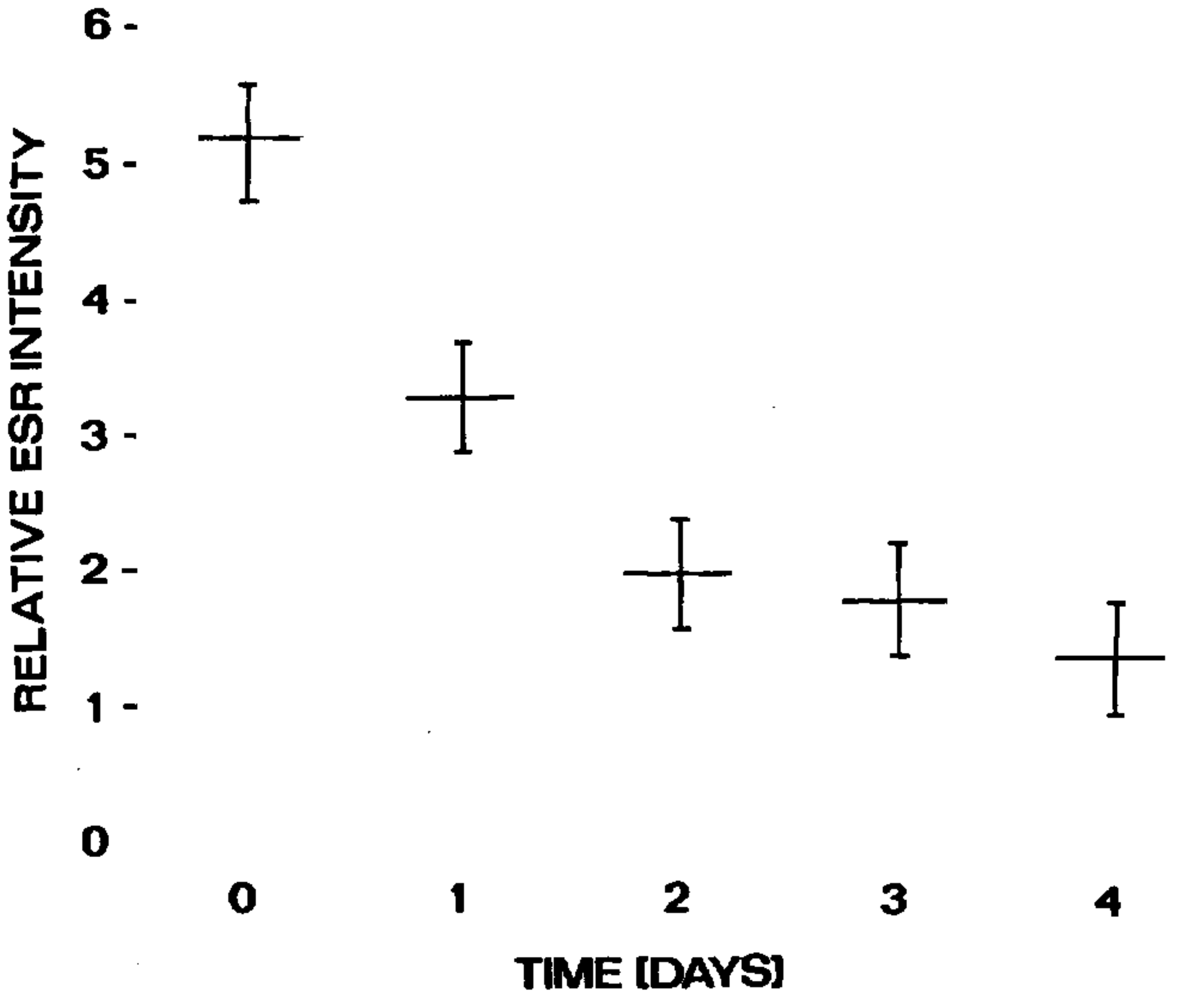


Fig. 4 Time dependence of the lipid peroxidation caused by quartz

Fig. 3 Time dependence of the concentration of hydroxyl ($\cdot OH$) radicals produced by the reaction of the quartz particles at various intervals after grinding and storage in air.



WV12/USBM 5411

Shape and Surface Characteristics of Respirable Mine Dust Particles

Meloy, T.; **Castranova**, V.; **Wallace**, W.; Hurter, P.; Flemmer, R.; Van Egmond, J.; Saus, F.; Keane, M.; Hill, C.; and Mike, P.

INTRODUCTION

Coal mine dust-induced disease is listed as an underlying or contributing cause of death for some 2000 Americans each year. The current prevalence of the disease may be attributed to the chronic manifestation of the disease in workers suffering exposures over a long working career, in part prior to current regulations on respirable dust and "free-silica" dust exposures of 2 mg/cubic meter and 100 micrograms/ cubic meter respectively. But the adequacy and appropriateness of these blanket standards is not yet known.

Epidemiological studies of Pennsylvania coal miners have indicated substantial differences in progression of pneumoconiosis resulting from equal respirable dust exposures in differing geologic regions of the State. And German research indicates regional differences in correlations of respirable silica dust exposures with disease. Specific dust properties which control the pneumoconiosis disease inducing potential of respirable dusts are unknown, other than a general but imperfect association of quartz content with disease and the explicit data that pure quartz dust is a highly fibrogenic material.

At the cellular and biochemical level the properties of quartz dust which cause its singular pathogenic potential are unknown. As an example, while quartz dust is highly pathogenic for pulmonary disease and is also very cytotoxic to pulmonary and other cells in vitro, kaolin clay dusts are equally cytotoxic while being pathogenic only under much more severe exposure conditions. Thus there is no correlation of dust cell-damaging ability and disease inducing potential.

That is, the current broad regulations are not based on knowledge of the mechanism of the disease process, and are based on limited epidemiological identification of two general dust exposure properties which do not fully correlate exposure and disease.

RATIONALE

Our objective is to determine the physico-chemical properties of respirable dusts which can be monitored to predict their pulmonary disease-inducing potentials. In the case of respirable silicate and alumino-silicate mineral dusts we assume that the critical properties are mineral surface composition or structure. The anomalous behavior of kaolin and quartz is the focus of much of our work.

Since quartz and kaolin clay are comparably cytotoxic when directly applied to cells _in vitro_ but are significantly different in inducing disease _in vivo_, this suggests that direct cell lytic ability is a necessary but not sufficient condition for pathogenic potential for pneumoconiosis, and does not provide a basis for distinguishing the disease-inducing potential of dusts. We therefore are investigating the initial events which occur upon deposition of a dust particle in the deep alveolar regions of the lung to attempt to find

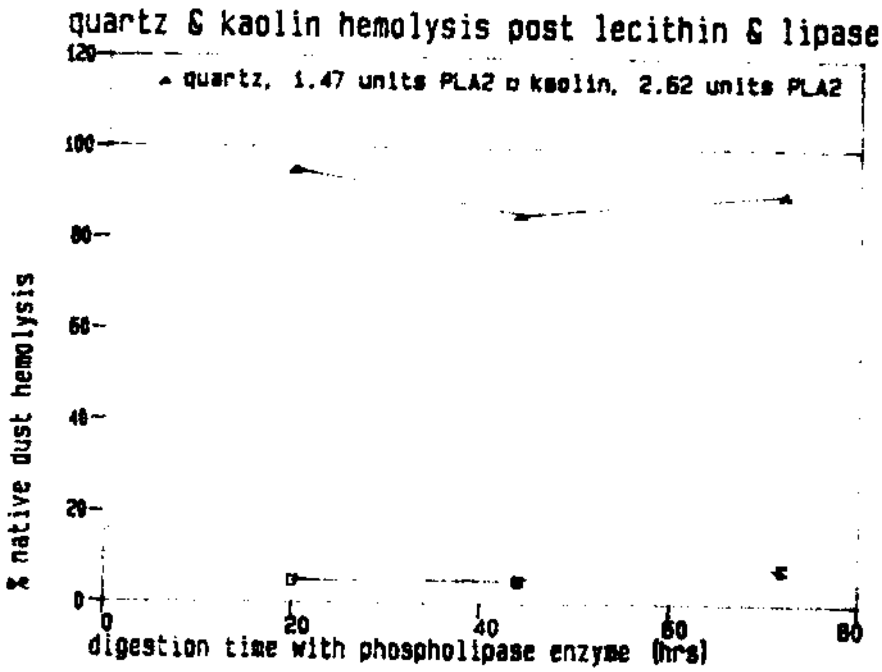


Figure 1. Different levels of re-toxification of equal masses of lecithin surfactant coated respirable quartz and kaolin dusts after phosopholipase enzymatic digestion.

the event and controlling dust properties which lead to divergent fates for quartz and other mineral particles in the lung.

Upon deposition a particle will initially contact a wet hypophase coating on the surface of the lung. We have examined the interaction of quartz and kaolin dusts with the major biochemical component of this fluid and found that it is adsorbed by both dusts. We test the cell damaging ability of the dusts by their lytic effects on pulmonary macrophage cells lavaged from the lung and by erythrocyte hemolysis assays.

We find adsorption of the surfactant neutralizes both dusts.

The next probable step in the lung is the uptake of the coated particle by a scavenger cell, a pulmonary macrophage, and the attempted digestion of the particle by digestive enzymes within the cell. We model this by incubating surfactant coated dusts with one or more enzymes found in the lysosomal vesicles in the cell which are responsible for the digestion of foreign materials phagocytized by the cell.

We find quartz loses its coating and is re-toxified faster than kaolin under the action of phospholipase enzymes in biochemical tests.

To determine the rates within the cell itself we have conceived and are testing a method to monitor the rate of digestion of radioactively labelled surfactant adsorbed on mineral dusts within the cell. If this difference in rates of removal is mineral surface dependent within the cell, and if rates for retoxification of quartz are significantly greater than the rates for other less pathogenic minerals, then this step may be a critical point distinguishing the disease-inducing potential of different minerals dusts. If that is the case then it provides a basis for chemical and bioassay evaluation of dusts.

The project is interactive with other Center projects, and with other USBOM and NIOSH research efforts to well-characterize the surface composition and properties of respirable mine dusts. Particular attention is being given to the possible role of mineral surface silanol group interaction with adsorbed surfactant on quartz and the roles of silanol and surface alumina group interactions with adsorbed surfactant on kaolin clay as a mechanistic basis for different rates of enzymatic digestion and re-toxification of different dusts. This would also provide a basis for surface characterization of mixed silicate dusts to better predict their diminished or exacerbated potential to induce pneumoconioses.

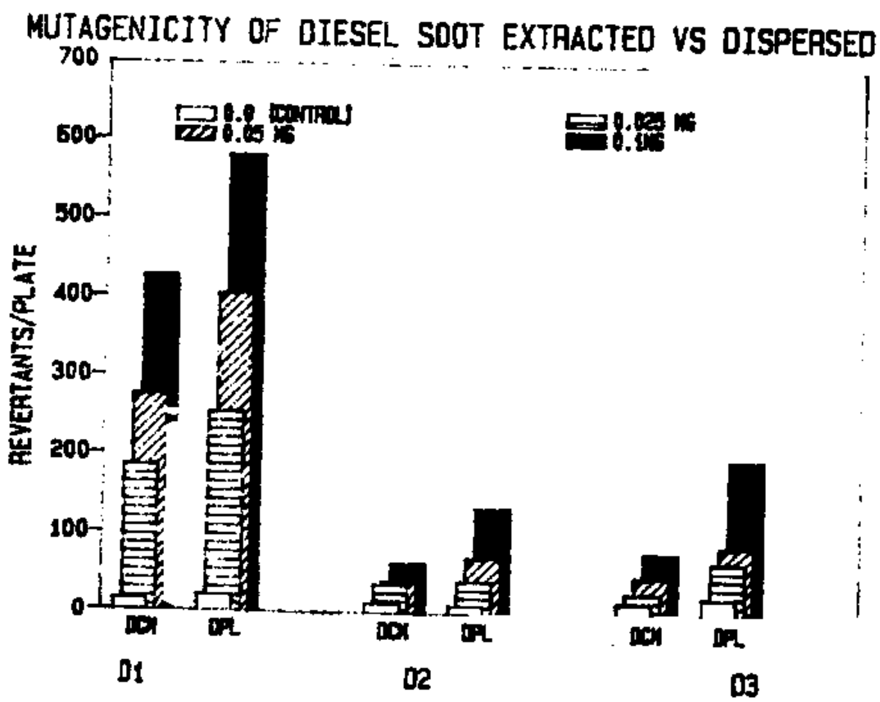


Figure 2. Mutagenic potential of diesel exhaust soots from three sources, tested as dichloromethane extracts (DCM) and as Lecithin surfactant dispersions (DPL).

As a spinoff of these investigations we have also looked at the interaction of organic particles with the primary component of pulmonary surfactant. The biologic endpoint here is mutagenicity as an indicator of the potential for induction of lung cancer. We have examined the Ames salmonella system mutagenic response for surfactant dispersed diesel soots and other organic particles. In the past such hydrophobic organic particles were assayed by extraction in organic solvent, in which they readily dissolve, and the filtrate mutagenic potential assayed in that dissolved condition. Attempts to similarly extract mutagenically active materials from the particles with pulmonary surfactants gave negative results in research performed by others. This left open the question of how soot or such hydrophobic particles could biologically transport to and into cells in the lung and initiate events leading to tumorogenesis.

We find organic soot particle solubilization by adsorption of pulmonary surfactant results in comparable or greater mutagenic response in the Ames assay system compared to the conventional organic solvent dissolution method.

This provides a method to investigate the genotoxic potential of particulate organics in the form they would manifest in the lung, retaining potential synergistic or antagonistic effects resultant from the particulate nature of the exposure.

SCOPE OF WORK

Quartz and Clay Dusts

Crystalline silica is known to be a potent pulmonary fibronigen. Quartz is the most abundant of the polymorphs of crystalline silica in mine dusts. Many mine dusts also contain large amounts of layered aluminosilicate dusts such as kaolin clay. Kaolin is shown by the epidemiologic record of clay mining and milling to be able to induce pneumoconioses, but requiring exposures well beyond those at which silica can initiate disease. We use a stock of respirable quartz and of respirable kaolin of measured specific surface area as representatives of comparably cytotoxic dusts with differing pathogenic potentials.

Suppression of Dust Cytototoxicity by A Pulmonary Surfactant

Diacyl glycerophosphorylcholine, called lecithin, is the primary component of pulmonary surfactant. We model the pulmonary hypophase coating by ultrasonically dispersing dipalmitoyl lecithin into physiological saline. Initial contact of respirable particles with the surface of the lung is modelled by incubating particles with this surfactant dispersion at 37C.

Cytotoxicity Assays

Biological assays of the cytotoxic potential of native and surfactant treated particles is performed by lactate dehydrogenase, beta-N-acetyl glucosaminidase, and beta glucuronidase release from challenged pulmonary macrophage cells which have been removed from animal lungs by pulmonary lavage. Frequently the erythrocyte hemolysis assay is used for speed and convenience and to minimize animal sacrifice.

Enzymatic Digestive Removal of Dusts' Surfactant Coating

Enzymatic digestion of the adsorbed surfactant on respirable particles is modelled in a cell-free system by incubating lecithin-coated dust particles in phospholipase enzymes at 37C. We perform these assays over a range of applied enzymatic activity levels and for time periods of up to three days incubation. The amount of lecithin remaining adsorbed to the particles, the amount of initial digestion product, lysolecithin, adsorbed to the particles, and the resultant erythrocyte hemolytic potential of the particles are measured as functions of applied activity and digestion time.

These tests have quantitated the rates for digestive removal of lecithin, and found the kaolin to retain a greater protective level of lecithin coating for longer times than quartz over a range of applied enzymatic activities (Fig.1).

One to two orders of magnitude greater applied enzyme activity is required to re-toxify kaolin compared to quartz over a three day period.

Intracellular Re-Toxification of Coated Dusts

When a surfactant coated particle is phagocytized by a pulmonary macrophage, intracellular vesicles, lysosomes, containing digestive enzymes combine with the phagosome to begin digestion of the ingested material. To measure the rates of digestion of the lecithin coating on particles within the macrophage, we have devised and are testing a radiolabelled surfactant method with lavaged pulmonary macrophage cells. Comparison will be made of the digestive re-toxification rates with macrophage residence times in the lung to see if mineral specific rates are physiologically significant. That is, if quartz re-toxification rates are rapid or comparable to clearance rates and if kaolin re-toxification rates are slow compared to clearance rates, then a mechanism which may distinguishe the disease potentials of the two dusts would be revealed.

Dust Surface Properties Controlling Enzymatic Re-Toxification

Lecithin is a phospholipid surfactant molecule with a zwitterionic head group. Electrostatic interactions are possible between the cationic amine of the lecithin and the quartz or kaolin surface acidic silanol groups. Electrostatic interactions are also possible between the lecithin anionic phosphate and kaolin surface basic alumina groups. The kaolin surface may thus adsorb lecithin with a configuration or strength which hinders enzymatic digestion to a degree greater than the hindrance for quartz-adsorbed lecithin. These specific mineral structural interactions are being investigated in collaboration with another Respirable Dust Center project and with NIOSH studies. If this surfactant de-toxification and enzymatic digestion re-toxification hypothesis is found to be an event of physiological significance in the lung, then cell-free chemical assays, spectroscopic surface characterizations and different tier bioassay suggest themselves as methods to better quantitate potentials for pneumoconioses associated with different mine dusts.

Organic Respirable Particle Genotoxic Potential

In addition to mineral dust exposures in mines there is the possibility for exposures to organic aerosols or complex mineral-organic mixed phase particles such as soot from diesel power units used in the mines, or complex particle structure of diesel exhaust organics adsorbed onto mineral or coal particle substrate. The principal health effects endpoint of concern here is cancer. Organic particles typically are tested for their genotoxic potential first by mutagenicity testing, typically in the Ames salmonella histidine reversion test system. We use the Ames TA98 salmonella mutagenicity assay. In the standard method, samples are prepared for testing by extraction with organic solvent, frequently by dissolution in dichloromethane and partitioning into dimethylsulfoxide, filtering, and testing the filtrate for its ability to mutate the salmonella. This destroys the particulate nature of the material, and any synergistic or antagonistic or biological transport effects associated with the particulate structure.

Attempts by other research groups to measure the mutagenic potential of diesel soot by extraction with pulmonary surfactants produced null results. However we found that mixing soots into pulmonary surfactant dispersion and testing the dispersion resulted in positive results. Typically we find mutagenic potentials for the surfactant dispersed soot particles to be comparable to or greater than the values obtained by solvent extraction (Fig.2).

CONCLUSIONS

We have found that

pulmonary surfactant neutralizes the prompt cytotoxicity of quartz and kaolin respirable dusts. We suggest that such interaction with the pulmonary surfactant coating is a first line of defense of the lung against prompt lytic effects of mineral dust inhalation. This and the comparable cytotoxic potentials of native quartz and kaolin dusts results in standard cytoxicity assays being unable to distinguish the pneumoconiosis-inducing potential of silica and alumino-silicate dusts.

Incubation of lecithin surfactant coated quartz and kaolin with phospholipase enzyme results in re-toxification of the dusts. We find the rate of digestive removal and re-toxification to be much more rapid for quartz-bound than for kaolin-bound lecithin. This suggests that re-toxification of neutralized dusts is possible by phagolysosomal digestion processes within lung cells.

Organic respirable aerosols such as diesel exhaust soot particles do not significantly dissolve or extract mutagenic materials in pulmonary surfactant fluids. However, the particles are solubilized, that is, coated and given a hydrophilic surface, by the surfactant. And the particles then express mutagenic potential in tha Ames assay in that dispersed phase. This suggests the method by which organic hydrophobic insoluble particles can interact with the acinar region of the lung to initiate genotoxic changes which can lead to cancer.

APPLICATIONS OF RESEARCH RESULTS

These results provide a research hypothesis as to a critical set of events which determine the potential for a respired dust to initiate pneumoconioses. If the current tests show significant mineral specific de-toxification and re-toxification rates under intracellular conditions then a basis is provided for improved dust characterization methods to better predict the pathogenic potential of mine dusts by:

using the cell culture method for digestive surfactant removal and re-toxification as a bioassay for field samples;

using the cell-free lipase digestion protocols as a biochemical assay

using identification of the mineral surface functional group- control of enzymatic surfactant digestion as a basis for spectroscopic dust analysis;

using the cell-free enzymatic digestion system followed by liquid phase separations to mass quantitate and obtain the dust fractions with higher pathogenic potential;

The results of the organic particle surfactant solubilization research is that:

dispersion of diesel soots or other small organic aerosols can now be tested direstly for their mutagenic potential in a form representative of the particles state in the lung.

CONTINUING WORK

Our current work is directed principally to determine if the re-toxification research hypothesis is incorrect or if it is correct in whole or in part, by completing the radionuclear in vitro measurements of digestion kinetics of dust-borne surfactant in the pulmonary macrophage test system, ane comparing those rate measurements with the applied enzyme digestion test results.

If the re-toxification hypothesis survives these tests then application will be made to silicate, aluminosilicate, and representative mixed composition mine dusts. Further, the above physical, chemical, spectroscopic, biochemical, and cellular assay systems based on the re-toxification hypothesis would be recommended for development and evaluation.

For the spinoff finding of the genotoxic potential of organic particles in pulmonary surfactant it is now appropriate to evaluate extension ofthe method to larger and complex structured respirable particles tested in higher tier eucaryotic cell test systems. This would determine the applicability of the test procedure to complex exposures in mines using diesel power.

TECHNOLOGY TRANSFER

Parts of our quartz and kaolin studies have been published in a peer reviewed journal and presented at three conferences. As discused above, if ongoing research finds the hypotehsis to be valid, then a number of mine dust assay procedures become possible which would better identify and quantitate respiratory dust exposure hazards, and thereby suggest control options..

The enzymatic re-toxification methodology also should provide a basis for evaluating potential chemical treatment procedures for the control of quartz-dust cytotoxicity. Lysosomal enzyme digestion could provide a means to evaluate the use of chemical prophylactic agents which have been proposed by CERCHAR and other mining research groups to control quartz dust pathogenicity.

The surfactant solubilization method for mutagenicity testing of diesel soot and similar organic aerosols can be used now for genotoxicity evaluations of respirable materials in a state representative of conditions in the lung. There have been numerous requests for our publication of those results. Requestors include the World Health Organization, p]etroleum and tobacco corporations, and several requests from the Soviet Union. Several Scandanavian visitors have expressed the intent to begin use of the method.

MIT1/USBM 2501

Respirable Dust Testing in Metal, Non-Metal Mines and Metallurgical Operations

Ring, T. A.

INTRODUCTION

The principal goals of this project were directed towards obtaining a better understanding of the physical and chemical character of respirable dusts that are to be found in certain types of quarrying, metallurgical and ceramic operations. Control of the dusts in such operations and protection of the work force from breathing the dusts requires identification of the nature of the dusts to be encountered in actual operations. The goals of the program were to:

(i) Collect respirable dusts in typical industrial operations.
(ii) Characterize the respirable portion of the industrial dusts as to their size distributions, mineralogy, morphology, and surface chemistry.

The research program involved development of equipment to collect respirable dust samples, characterization of particles for morphology, size and chemical composition, and to apply suitable statistical methods to the analysis of results on the size distribution of particles in collected samples. The program also included sampling and characterization of air samples from a sand and gravel quarry, a welding shop, a metal powder production facility, and evaluation of dusts that would be typical of certain ceramic processing activities.

RATIONALE

The types and amounts of respirable dusts produced in quarrying operations and in metallurgical and ceramic processing plants are expected to vary widely with the type of materials being processed and the processing methods being employed. For example, in quarrying, dust is generated by transportation and conveying operations as well as in crushing and handling the materials being processed. In metallurgical operations, the high temperatures of many processes generate metal fume and dusts of oxidized metals and slags. In ceramic processing, dusts arise from crushing and handling materials, and fumes and dusts arise from high temperature processing methods that often are employed.

The major components of the human respiratory tract differ markedly in structure, size and function, which affects their dust retention capabilities and sensitivity to deposited particles. For example, the nasal passages are efficient filters for particles greater than 10 micrometers in diameter. Thus the nasal passages would be affected most by particles greater than 10 micrometers, the respiratory tract by particles between 3.5 and 10 micrometers, and the lung at the end of the respiratory

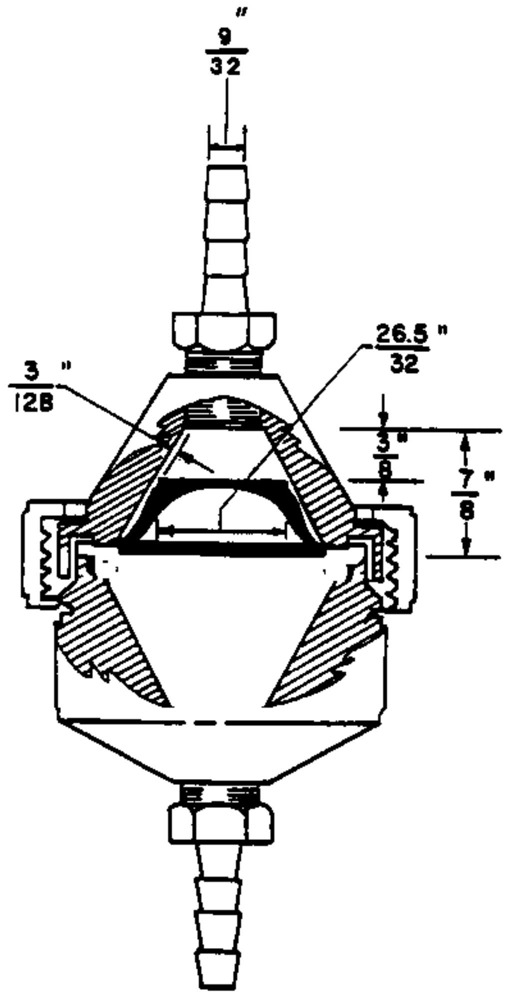


Figure 1. Structure of Filter Sampler.

tract would be affected most by particles less than 3.5 micrometers. Under exertion, the flow resistance of the nasal passage causes a shift to mouth breathing, and the sites of deposition of the larger particles will move deeper into the tracheal-bronchial region. The physiological effects of dust will depend on the region of deposition; the retention time at the deposition site and along the elimination pathways; and the physical, chemical and biological properties of the particles. Particles which are recently generated will have active surfaces and may adsorb gas from the air and water in the humid atmosphere of the conductive airways. Dissolved materials within the depositing particles can diffuse rapidly in the fluid lining of the airways. For this reason, particles which are highly soluble, or which have soluble components, may be the most irritating.

Compliance with regulatory standards in mining and milling operations is currently monitored by measuring the mass per cubic meter of air of particles in the respirable dust. For example, simple mass concentration of dust has not been shown to have a strong correlation with the development of pneumoconiosis; however, it is the principal basis that has been employed until very recently. A more detailed characterization of dusts is needed to determine the specific particle size distribution and the chemical composition of the dust particles, as well as the species adsorbed on the surface of the particles, since the surface species are expected to be the first to interact with the body.

SCOPE OF WORK

The research performed in the project of three years duration has developed (1) equipment to collect respirable dust samples, (2) experimental methods for particle-by-particle characterization of morphology, size and chemistry, (3) experimental methods for overall respirable dust sample characterization of size distribution, chemistry and crystallography, and (4) a new modified Student's t-test method to compare two or more aerosol size distributions in a rigorous statistical manner. Dusts from a sand and gravel quarry in Southern New Hampshire, a welding shop, a metal powder production facility, and ceramic processing activities have been sampled and characterized.

Equipment

A portable dust collection apparatus was built for use in the program. It consists of a box in which collection systems are housed, and which contains a power supply, control circuits, and ductwork for these systems. The box contains an Anderson cascade impactor and two Sierra personal cascade impactors, one with a mylar substrate coated with a silicone grease and the other with ungreased stainless steel substrates. At the normally employed air flow rate of 2 liters per minute, the effective cut-off diameter (ECD) for each of the six stages of this type of impactor is 10.0, 6.0, 3.5, 2.0, 0.9, and 0.5 micrometers, respectively, i.e., the range of sizes is from 400 to 20 microinches. The air stream then passes through a polyvinyl chloride filter after the last stage. The sampling box also contained a total respirable dust filter which separated particles greater the 10 micrometers in diameter from the collection system, and collected particles in the range of 10 to 0.2 micrometers on a commercially available filter. A sketch of this type of filter is shown in Fig. 1.

Characterization

Particles were captured in each stage of the cascade samplers on preweighed substrates, and these substrates were weighed carefully again after the samples were collected. The data on particle capture were correlated on the basis of the weight of sample collected on each substrate, and a plot of the log-normal distribution of cumulative percentage of total weight of samples against particle size (ECD) was obtained. The results obtained for several of the studies are shown in such a plot in Fig. 2.

The size, shape, and chemical analysis of samples collected on the stainless steel substrates were examined by electron optical methods, and the elemental chemical analysis of most of the samples was performed by

X-ray fluorescence (XRD). The crystal structures of minerals contained in dust samples were determined by X-ray diffraction methods.

Equipment Calibration

A series of samples were obtained from a single source by the simultaneous use of the two types of sampling devices. The purpose of this study was to obtain a statistical comparison of the two sets of results. A new technique was developed for making such a comparison that is based on the familiar Student's t-test. The modified method allows the quantitative calibration of the results of the Sierra personal collector with those from the Anderson cascade impactor, and an estimation of the error an experimental technique.

Kaolin and Quartz Respirable Dust Samples

Two samples, one of quartz and one of kaolin, have been circulated to the participants in the Generic Center for Respirable Dusts. Both samples were characterized as to size. Chemical analyses of the quartz sample showed that it had major impurities containing iron and aluminum, and minor impurities of potassium, chromium, nickel, copper and zinc. The kaolin consisted of particles in the size range of 2 to 0.1 micrometers, and it had major impurities of titanium and iron, and minor impurities of calcium and copper.

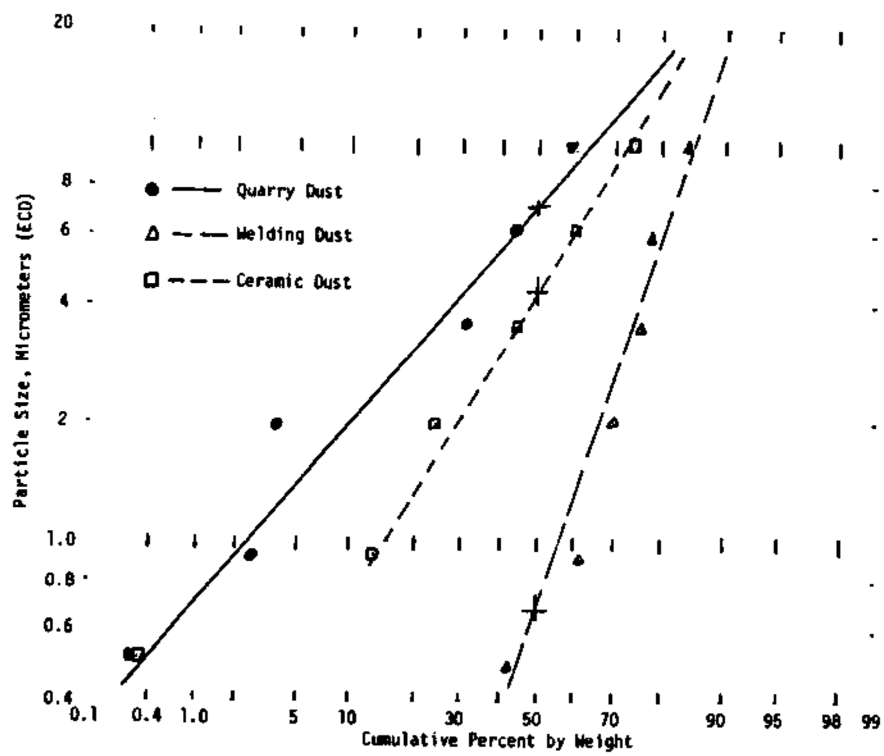


Figure 2. Examples of Size Distribution of Dusts. Indicates Mean Diameter.

Powder Metallurgy Facility

Air samples were obtained over a period of 8 hours during the operation of a facility for producing aluminum powder in the size range of 50 micrometers. In the process, a stream of liquid metal is atomized and solidified. Melting, atomization, and solidificiation are carried out in a sealed system, and the powder produced is collected in closed containers. The off-gas from the system is passed through cyclones and filters. Essentially no dust was found in the air around the apparatus, which shows that proper design and operation of such a system, and adequate measures in handling the product and off-gases, can avoid contamination of the atmosphere.

Sand and Gravel Quarry

The air in a Southern New Hampshire sand and gravel quarry was sampled with the samplers situated on a haul-road 30 yards from the classification operation. The respirable dust collected had a mass loading of 0.345 mg/m^3 and had a wide range of particle sizes (see Fig. 2). The particles observed on each stage of the cascade impactor had a broad range of chemical composition and crystal structure. The particles greater than 10 micrometers in size were predominantly quartz with significant numbers of feldspar, mica, and halloysite particles. Particles between 6 and 3.5 micrometers in size were predominantly feldspar, mica, and halloysite with fewer quartz particles and an increase in the number of clay aggregates. In the sample below 3 micrometers in size, feldspar, mica and clay particles were common, but almost no quartz particles were present.

The results obtained for the respirable dust were compared to a grab sample of the material being processed in the operation. This sample was rich in quartz, albite, microcline and muscovite. The biggest difference between the sand and gravel products and the dust was the percentage of quartz. While quartz was the dominant component in the sand and gravel, the respirable dust showed quartz only in the larger sizes. Halloysite, which was not detected in the sand and gravel, was present in every size of the sample of the respirable dust. The high ratio of clay particles in the small sizes was also a surprise since the sand and gravel sample did not show clays.

These results show that the respirable dust generated is not necessarily of the same chemical and mineral composition as the material being processed. Therefore, it may be erroneous to calculate the percentage of quartz in nuisance dust by using the percentage of quartz in the material being processed.

Welding

Respirable dust samples were obtained from a welding shop in Cambridge, Massachusetts, in which two types of welding were taking place; oxyacetylene gas welding and arc welding. A size distribution for one sample is shown in Fig. 2. In the gas welding, copper-coated mild steel rods were used. In the arc welding, flux-coated metallic electrodes were employed. The respirable welding dust was made up of three types of particles: metal drops, irregular platelets and their aggregates, and fluffy pieces. Attempts to identify the chemical compositions of individual particles of these three types were unsuccessful. However, by comparing the chemical compositions of the materials used in the welding operation with the collected dust and the composition changes between each stage of the cascade impactor, these three types of particles were identified.

The metal drops dominated the larger size range (greater than 3.5 micrometers), and the irregular platelets dominated the smaller size range (less than 1 micrometer). From the electron microscope pictures, the metal drops appeared to be much smaller than other types of particles on a particular cascade stage. This is because the cascade impactor collects particles based on their aerodynamic size in which the particle density and shape are important factors.

Since the gas welding rod contained only iron and copper and the arc welding electrode contained only iron, all other elements must have come from the electrode covering. The round particles were solidified metal drops spattered in the welding operation. With decreased particle size, the ratio of irregular platelets to round particles increased, the apparent levels of potassium and manganese increased, and iron decreased. This suggested that the irregular platelets are from the arc welding electrode covering. The fluffy particles less than 2.0 micrometers in diameter were the residues of incompletely oxidized organic materials in the coating, and they contained sulfur and chlorine.

Ceramic Powders

Samples of dust that would be generated with handling of fine powders of silicon carbide in ceramic processing were collected. The mean particle size was 4.06 micrometers (Fig. 2), and this showed that the dusts were in the respirable size range. The particles were predominantly silicon carbide, but zinc oxide was a major impurity, and potassium and titanium were minor impurities. These elements probably were contained in reagents added to facilitate processing and sintering operations. Analysis of the surfaces of the silicon carbide particles showed the presence of silicon-oxygen bonds. This suggests that consideration be given to the possibility that the human body may react to these particles as if they were quartz or silica-bearing materials.

CONCLUSIONS

Respirable dusts from several quarrying and metallurgical operations have been collected and characterized as to chemical composition and size distribution. The information developed in these studies has been reported. A general conclusion from the work is that the dusts generated in a process or operation may not, and probably will not, have the same chemical compositions of the materials being processed. It is also to be expected that the composition of the surface of a particle may differ in important ways from the average composition of the particle, or the composition of the interior of the particle.

A study of simple statistical methods for comparing quantitatively the size distribution of samples of a dust by two different methods was made. The result of the study is a new method of comparison of the two sample distributions which is based on the familiar Student's t-test.

APPLICATION OF RESEARCH RESULTS

The results of the study show generally that the chemical character of respirable dusts arising from several different types of operations may differ significantly from the materials being processed in a given operation. The measurements reported indicate that the details of the operation and the properties of materials involved in the process can be of importance. For example, a minor constituent present in the rock being quarried that is much more friable than the rock itself may be broken and ground readily to a fine powder. Thus, this constituent may become concentrated in the finer portions of the dust arising from the operation. Similarly, in a high-temperature metallurgical operation, the more volatile portions of the materials in process can be expected to appear in the dust that may arise from the operation.

CONTINUING WORK

The research activities reported here were terminated in 1986.

TECHNICAL TRANSFER

One publication and several discussions with groups in the minerals industry have resulted from this work.

MIT2/USBM 2521

Effect of Physical Properties of Respirable Dusts on Their Toxicity

Elliott, J. F.; McCarthy, J. F.; Bolsaitis, P.; Eppelsheimer, D.

INTRODUCTION

Dusts generated in the coal and metal mining and quarrying industries are physically and chemically heterogeneous in character. These dusts usually contain silica, and in base metals mining operations they can contain significant concentrations of compounds of the base metals, particularly the sulfides. Silica dusts, especially when freshly formed by fracture of rock, are known to cause serious health problems in human beings who are subjected to long term exposure to them. Although the concentrations of mineral species in an ore body are less than a few percent by weight, the concentrations of these species in the dusts generated in mining, transporting, and processing of the ores and overburden may be significant because many of the minerals are relatively brittle, and they usually exist as small particles in the ore. Thus the metal-bearing constitutents of an ore may be a relatively high fraction of the dust particles in the micron and submicron size ranges. It is important that the physical and chemical characteristics of particles in these smaller sizes, i.e., less than 5 micrometers, be determined, particularly as these properties relate to the physiological effects of dust particles on the human breathing apparatus.

According to one count, no less than 50 theories and hypotheses have been advanced to explain the mechanism by which silica particles contained in respirable dusts produce fibrosis (pneumoconiosis) of the lungs and other cytotoxic effects. These theories may be classified in three groups, according to the basic process assumed to induce silicosis: theories based on the dissolution of silica, theories based on physical and chemical interactions on the surface of solid silica particles, and theories based on the immune reactions resulting from the presence of silica.

Although we are still far from understanding the detailed mechanism that induces fibrosis of the lung, great strides have been made in recent years to narrow the numerous theories to a focus bounded by several reasonably well confined experimental facts. The most generally accepted scenario, at the present time, is based on the premise that silica particles interact with macrophage cell constituents to produce some agent ("fibrogenic factor") that stimulates collagen formation, i.e., fibrosis. The process is envisioned to consist of the following steps:

(1) A silica particle is coated in the alveoli by a pulmonary surfactant hydrogen-bonded to its surface.
(2) The coated particle is phagocytised by a macrophage.
(3) Within the macrophage a lysosome and its enzymes remove the surfactant layer.
(4) The bared particle hydrogen-bonds to certain components of the lysosome membrane leading to the rupture of this membrane and the release into the protoplasm of enzymes that lead to the destruction of the macrophage. It has been proposed that the particle surface (e.g., silica) acts as a catalyst in the synthesis of a new factor, possibly an enzyme, which, when released, stimulates the formation of fibrotic tissues. The bared particle is free to reinitiate the cycle at step 1.

On the basis of the above hypothesis, which serves as the working model for numerous present day investigations on silicosis, the importance of the silica particle surface is self evident; it is critically involved in the bonding of surfactants in step (1), in the rupture of cell walls in step (4), and, possibly, as the catalyst in the formation of enzymes critical to the formation of fibrotic tissue.

In the light of the importance of the solid particle surface in the pathogenic processes induced by respirable silica-base particles and the complexity of factors that affect these surface properties, the data available on the toxicity-surface structure relationship is relatively scarce. A number of studies have been conducted to evaluate the biological activities of silica particles of various crystal structures (vitreous silica, aerosil, silica gel, quartz, tridymite, cristobalite, coesite, and stishovite). The general finding of these studies is that tridymite is the most active material, with quartz and cristobalite following, while stishovite and amorphous forms of silica are less fibrogenic; however, the relative magnitudes of the effects caused by the different materials vary among the studies. Since quartz is the most common of the more active structures, it is generally identified as the causant of silicosis and is used as a reference material for control of respirable dusts and as the prototype material in biological studies on silicosis.

In most studies on the fibrogenicity of silica particles of respirable dust size range, the effects of type and degree of crystallinity have not been clearly separated from particle size effects. Although it is generally recognized that solid, crystalline silica particles in the 0.5-5.0 micron size range, in any form (except stishovite), are hazardous due to their potential fibrogenicity, still smaller crystalline particles (0.05-0.5 microns) may be even more dangerous, but this issue of size has not been specifically and critically tested. For example, much higher silicotic activity has been reported for coesite particles smaller than 0.5 microns than for quartz particles in the 1-3 micron size range.

Aside from crystal structure, crystallinity and particle size, there are other parameters that may influence the biological activity of silica based particles and which have not received major attention in previous investigations. Such are: morphology, the density and configuration of silanol groups (SiOH) on the particle surface, the effect of adsorbed metal ions, and, in dusts generated from rocks, occlusion on particle surfaces by other, finer particles.

It has long been recognized that the shape of silica particles, especially the sharp edges and corners observed on some crystalline particles, affects their fibrogenicity, although this effect has not been quantified. The presence and configuration of silenol groups on the silica surface is deemed essential for the hydrogen bonding associated with the adsorption of the surface to cell walls, and/or their catalytic activity in the production of harmful enzymes. It is known, for instance, that at a pH above 7, an increasing concentration of negative charge on the silica surface prevents hydrogen bond

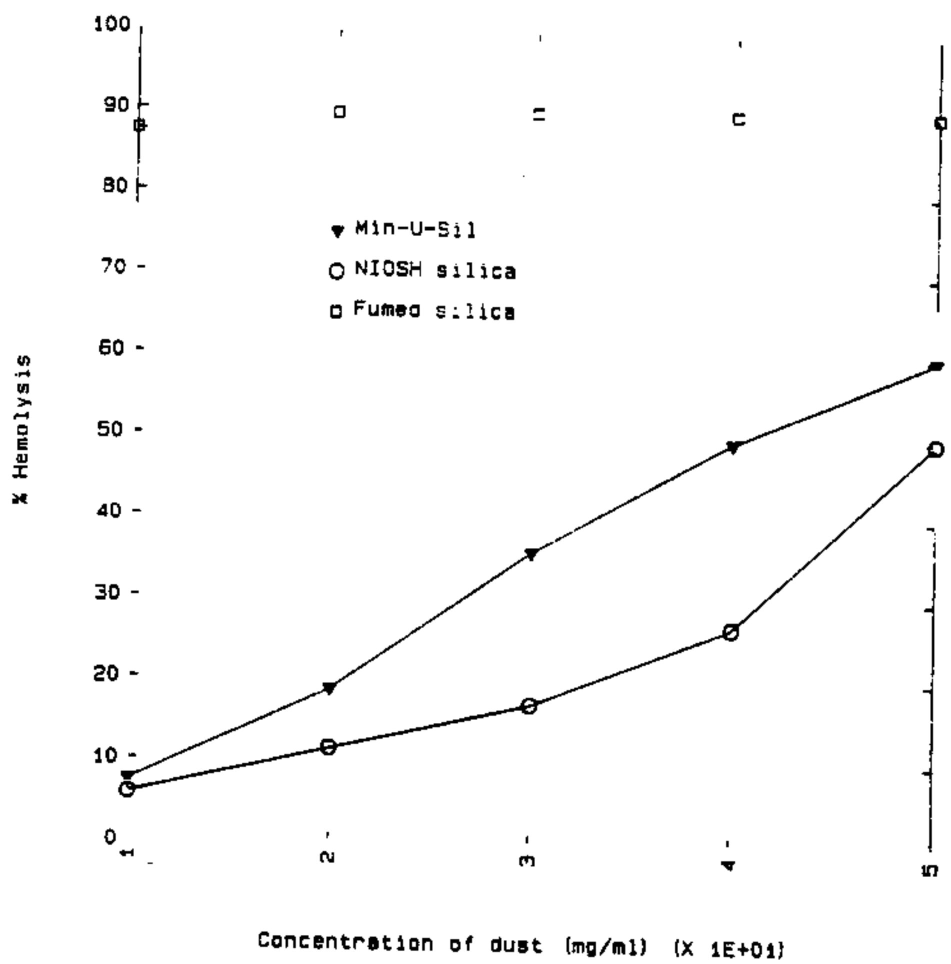


Figure 1. Differences in Memorolytic Activity by 3 Silicas.

formation near the charge sites. Similarly, soluble hydrolyzed ions (Zr(+4), Be(+2), Th(+4), Zn(+2), Fe(+3), Al(+3)) have been shown to adsorb strongly on silica surfaces reversing the surface charge from positive to negative. As the concentration of metal ions is increased, the silica surface becomes covered with metal polycations and the original zeta-potential increases from a negative to a positive value.

The dusts formed in mining operations are derived from the fracture of rocks. Such fracture is more likely to occur along facets where inclusions, impurities, or other defects facilitate crack initiation. Furthermore, freshly formed fracture surfaces should be preferred sites for adhesion and agglomeration of finer particles. All this leads to the supposition that the silica surfaces formed in mineral mining operations may have a broad range of effective biological activity.

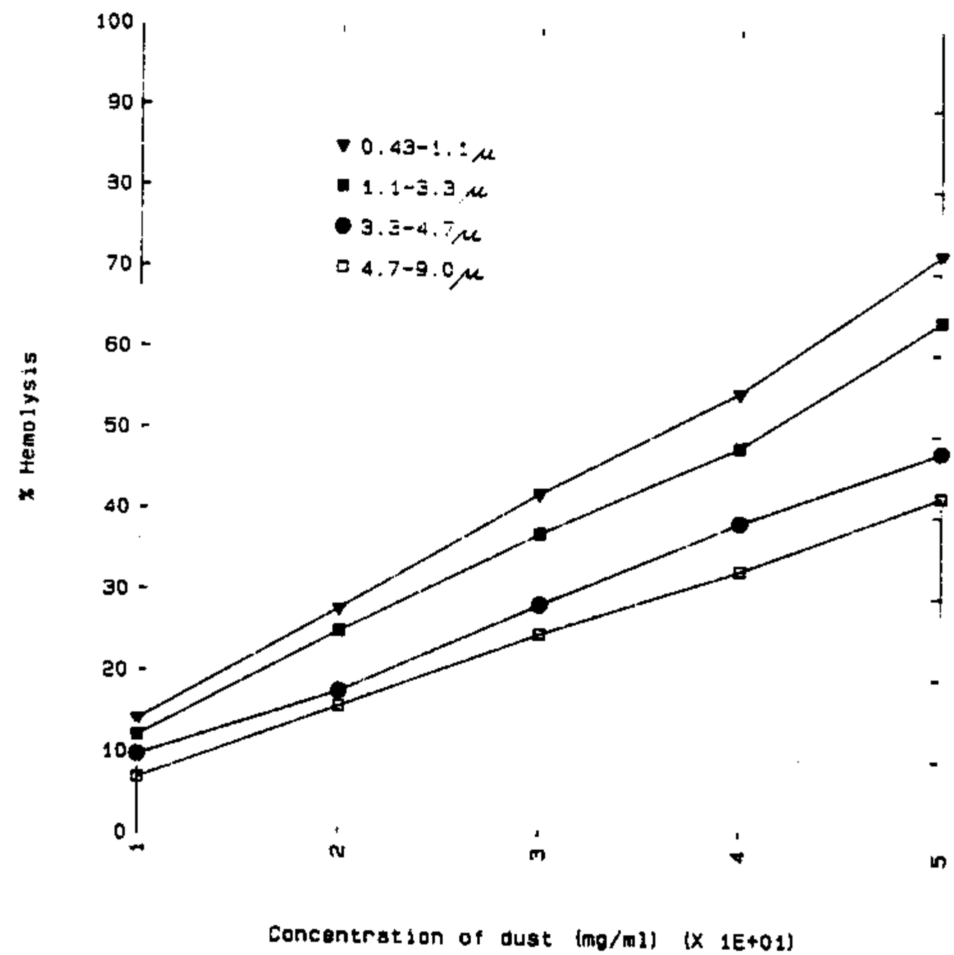


Figure 2. Min-U-Sil classified into 4 size fractions.

RATIONALE

The research conducted under this project is concerned with the identification of structural, morphological, and physico-chemical surface properties of silica based materials contained in respirable dusts that may affect the cytotoxicity of such materials. The purpose is to identify those variables that should be of primary concern in protecting workmen from hazardous exposure, and concurrently to advance the methodology for monitoring and controlling such factors.

The proposed methodology is first to conduct simple biological activity tests (erythrocyte hemolysis) on a range of silica and silica containing dust samples classified in narrow size ranges and well characterized in terms of their crystal structure, crystallinity, particle size, morphology, and composition. These tests lead, for the materials of most notable activity, to further experiments on cytotoxicity and fibrogenesis in other laboratories better equipped for biological work (e.g., W. E. Wallace's laboratory at NIOSH), Morgantown). The materials under study in this first stage include the standard quartz samples from the Generic Mineral Technology Center for Respirable Dust, rock quartz, fused silica, and samples from roof bolter dust boxes to be collected in a systematic sampling program to be conducted by NIOSH (Morgantown).

The hydrogen-bond forming capability is, most likely, the single most important factor defining the biological activity of silica surfaces. It is important to determine how this potential is affected by crystal structure and crystallinity, surface defects and adsorption of impurities, particle size, and morphology. Since all these variables may contribute simultaneously to the specific activity of the surface, it is proposed to seek a single physical parameter which may relate to the "hydrogen-bond forming capability" of the surfaces of interest and to correlate this parameter with biological activity of the surfaces (i.e., particles).

For oxide minerals such as quartz, the hydrogen ion concentration is, generally, potential-determining and pH strongly affects surfactant adsorption. The adsorption of surfactants or other ions, also affects the potential and can be followed by zeta-potential measurements.

SCOPE OF WORK

During the present phase of the project, work is proceeding with the following materials: standard quartz samples from the Generic Mineral Technology Center for Respirable Dust, and several types of samples derived from rock quartz, fumed silica, and samples from roof bolter dust boxes collected by NIOSH and supplied by W. E. Wallace. The dust samples are classified using impactors, particularly, for the micron size range below one micron, and the multi-orifice impactor classifier developed by V. A. Marple of the University of Minnesota. Coarse starting materials are comminuted by impaction, grinding, and/or jet milling to generate particles of various morphologies (sharpness of angles and corners) and crystallinity (degree of surface deformation), and size classified subsequently.

Particles of each size fraction of each material are examined by scanning electron microscopy and EDAX, and/or scanning Auger elemental microanalysis, to determine their morphology and microcomposition. They are analyzed subsequently by X-ray diffraction (possibly RHEED) to determine their relative degree of crystallinity. The size distribution within each fraction, and the specific surface area, is determined by mobility classifiers and BET adsorptometry, respectively.

The biological activity of the dust fractions that have been prepared and characterized are screened by in vitro erythrocyte hemolysis to determine particle characteristics of principal concern to be studied further by cytotoxicological or in vivo experiments at NIOSH or other facilities. Conversely the analytical facilities at MIT are used to assist with the characterization of materials of particular interest to other laboratories and to research groups within the Respirable Dust Center.

RESULTS

The results obtained to date indicate an ample variability of the cytotoxicity of respirable silica dusts. Figure 1 illustrates the difference between several forms of particles in terms of the measured hemolysis (rate of rupture of erythrocytes). Figure 2 shows how the size of particles affects their toxicity with evidence that there is a particular size, or maximum size, for any given type of material.

The effect of alteration of the surface characteristics by thermal and chemical treatments is illustrated in Figures 3 and 4. Finally, Figures 5 and 6 are examples of the changes in surface characteristics of materials as measured by a zeta-potential profile and photoacoustic infrared spectroscopy.

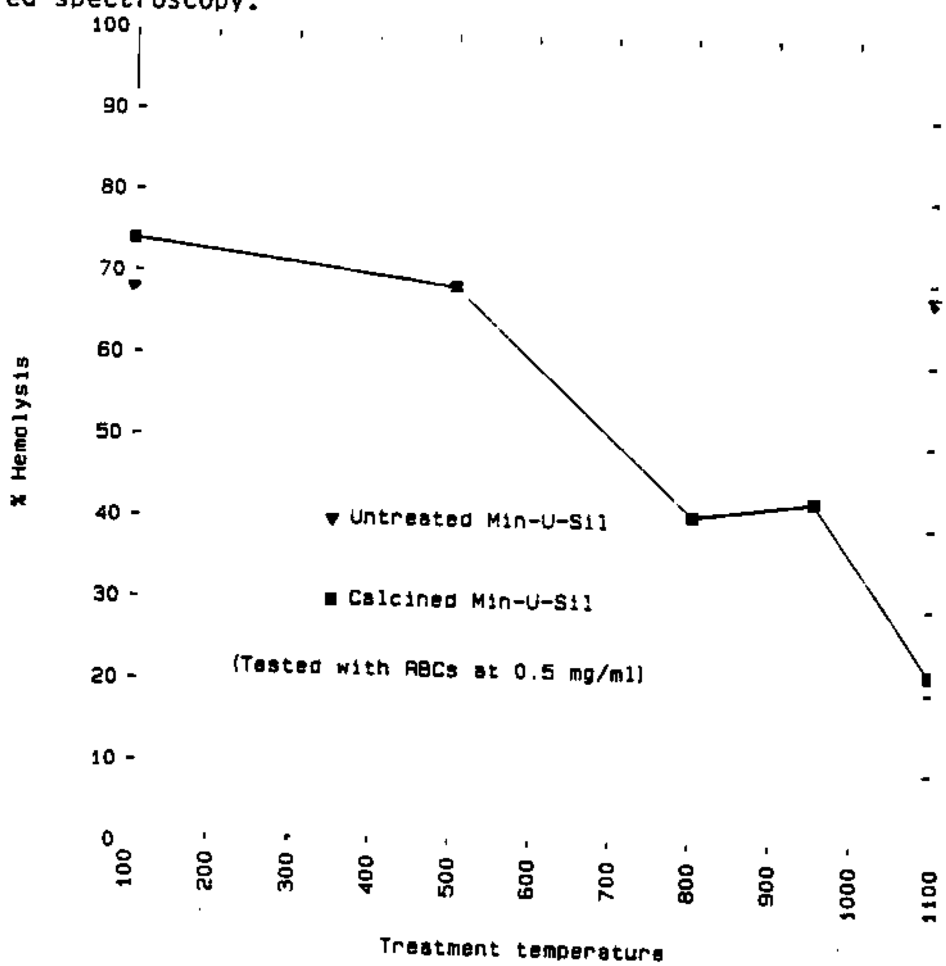


Figure 3. Min-U-Sil calcined at various temperatures.

The results of this research have been presented in four symposium papers, and three publications are currently in preparation. The toxicity tests will be extended to studies involving macrophage cells and, in collaboration with other research teams within the Generic Mineral Technology Center for Respirable Dust, to in-vivo inhalation experiments.

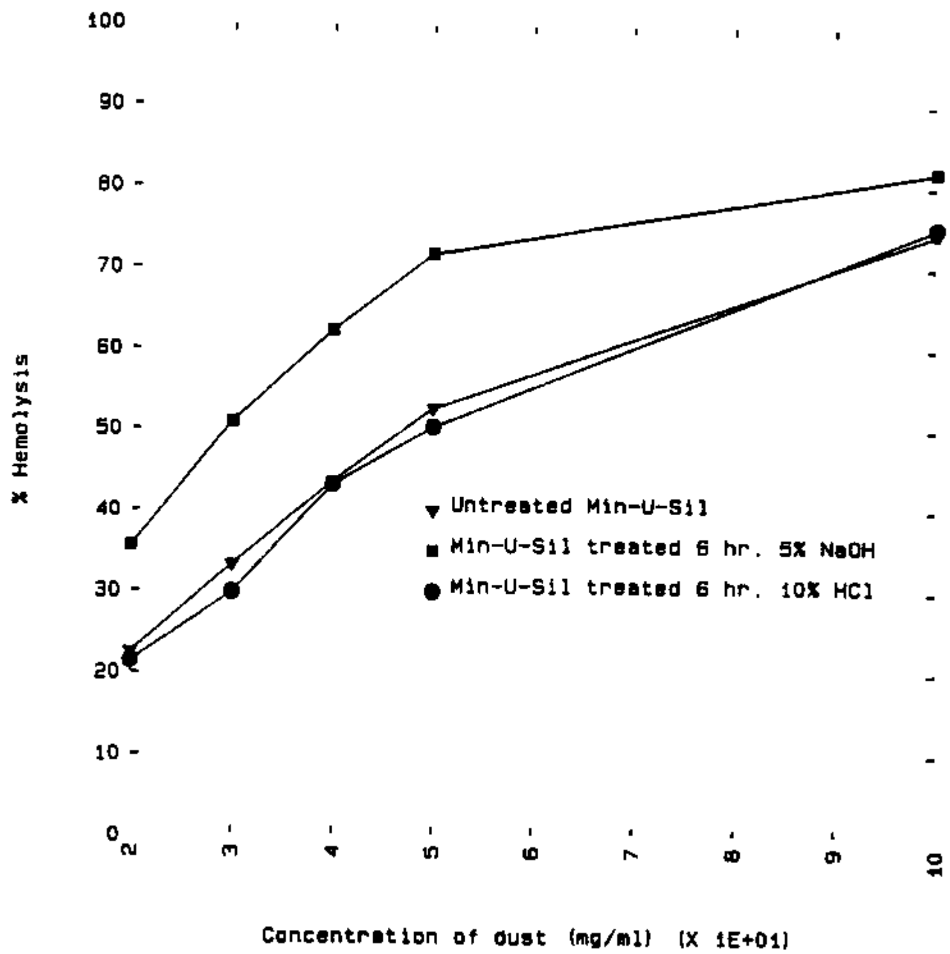


Figure 4. Min-U-Sil treated with 5% NaOH or 10% NCl.

CONCLUSIONS

The research conducted to date shows that size and surface characteristics of respirable particulate materials are directly related to their cytotoxicity as measured by erythrocyte hemolysis. With the help of state-of-the-art analytical techniques, it is now possible to identify the surface features associated with cytotoxicity in a quantitative manner. Thermal and chemical treatments may activate or passivate respirable dust materials.

These results indicate possibilities for developing better methods for setting safety standards for respirable dusts and, possibly, for passivating toxic dusts.

FUTURE WORK

The development of the techniques used for characterizing surface properties linked to toxicity (FTIR, PAIR, and zeta-potential fingerprinting) will be continued with the extension of these studies to a broader range of materials.

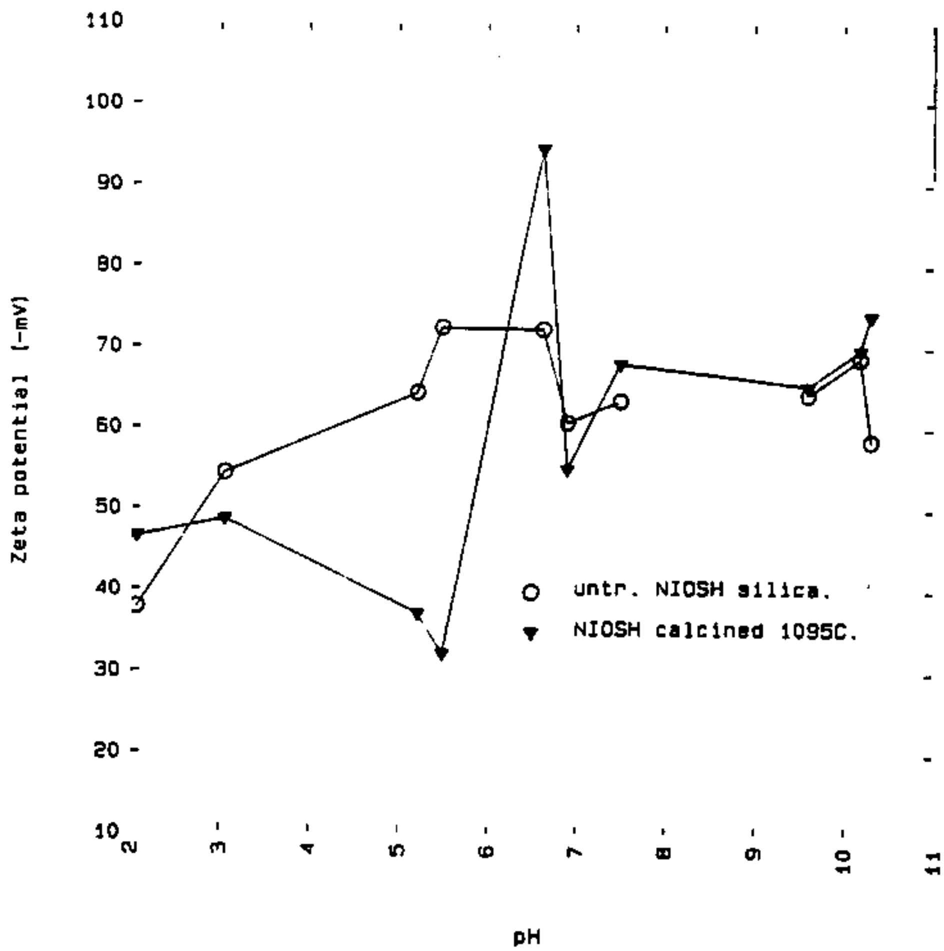


Figure 5. Zeta potential of NIOSH silica calcined at 1095C.

COLLABORATIVE ACTIVITIES

The research performed under this project has benefited by close collaboration with research teams at West Virginia University, NIOSH-Morgantown, and Penn State. Dr. Seehra of the Physics Department of WVU has participated in the PAIR analysis of samples, Dr. Hogg (Penn State) in the preparation of materials, and Dr. Wallace and co-workers of NIOSH in the establishment of testing protocols and in the planning of many joint experiments.

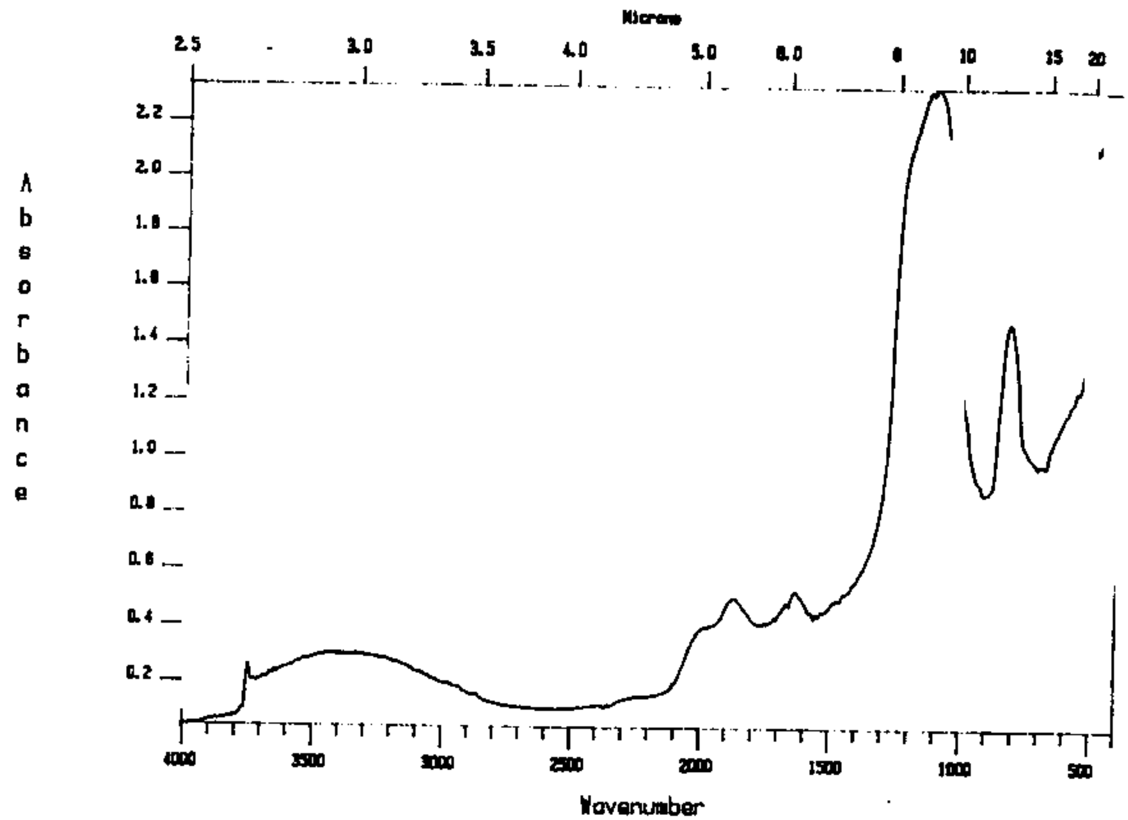


Figure 6a. Untreated Fumes Silica Cab-S-Sil/M5.

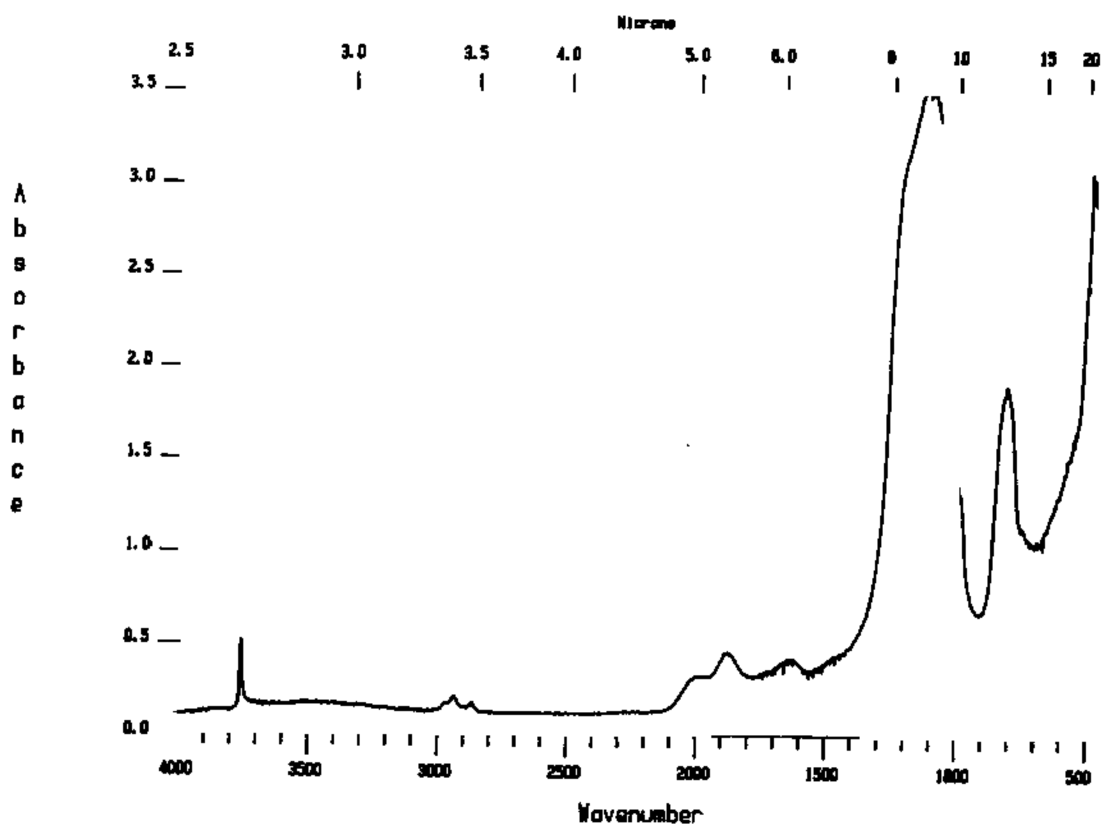


Figure 6b. Cab-O-Sil calcined for 41 hrs. at 800C.

MN1/USBM 2701

Coal Mine Dust Characterization

Marple, V. A.; **Rubow**, K. L.; **Pui**, D.; Fang, C. P.; Ananth, G.; Behm, S.; Cladow, R.

INTRODUCTION

Characterization of coal mine aerosol is an important first step in the study of the dangers of respirable coal dust. Some important factors are the size distribution, concentration and chemical composition of the dust aerosol, and the geometric shape of the dust particles. Although there are many instruments which can be used to determine properties of an aerosol, the number of instruments which can be used in gaseous mines is limited. It is the primary objective of this project to select state of the art instruments which can be safely used in a mine and to apply these instruments to characterize mine dust.

Another very important objective of this project is to make other investigators in the center aware of our findings for instrumentation. When several investigators are involved in a common goal project such as in this center, it is important that the sampling instruments and the characteristics of these instruments be used uniformly by all investigators. Therefore, a second objective of this project is to make the other investigators aware of the characteristics of the sampling instruments that they are using and to keep them abreast of any new developments in the field concerning instruments that may be of use in their research. In addition, if they are using an instrument which the sampling characteristics are unknown, another objective of this program is to characterize the instrument and determine its suitability for sampling of the aerosol.

The objectives mentioned above are those that cover the broad scope of this project. However, the finer detail of this project can be better understood by inspecting the more well-defined specific objectives listed below. These objectives cover instrument identification and evaluation, collaborative work with other investigators in measuring specific properties of the aerosol, development of samplers to fit specific needs of the center, development of techniques to analyze samples collected in the mine and information transfer to other investigators in the center.

* The primary objective in this activity is the identification and selection of instruments that can be used in the mine to characterize mine dust

* Apply Dust dispersion/Aerodynamic Particle Sizer instrument (DAPS) to measuring size distribution of mine dust.

* Adapt newly developed micro-orifice uniform deposit impactor (MOUDI) for in-mine use.

* Collaborative work with Bureau of Mines Twin Cities Research Center (TCRC) to determine particle size and electrical charge distributions generated during crushing of coal and rock samples.

* Develop sampler for collecting respirable particles directly in a liquid surfactant to simulate collection of particles in lung.

* Develop personal and area samplers which separate diesel exhaust particles from coal dust particles based on their aerodynamic diameter.

* Advise other investigators on availability and use of aerosol instrumentation. such as an impactor workshop in 1986.

* Develop technique to collect in-mine samples on filters and determine size distribution with DAPS.
  -analysis of mine dust samples collected by the U of MN
  -analysis of dust samples from other investigators

* Adapted respirable impactor technology to obtain size distribution analysis as well as respirable mass content.

RATIONALE

It is well known that Coal Workers' Pneumoconiosis (CWP) is a disease that coal mine workers contract from breathing of the coal or mine related dusts. The disease is therefore caused by some characteristic of the dust particles that the miner is exposed to while in the process of working in a coal mine. It is very important therefore in studying the causes of CWP to characterize the coal mine dust as thoroughly as possible.

There are many properties of the coal mine related aerosols which may be of importance. These include the particle size, the chemical composition of the particles as a function of their size, the geometric shape of the particles and of course, the concentration of the particles which are being inhaled by the worker. The problem is further complicated by the very real problem of sampling these particles in an atmosphere containing methane gas so that only the safe permissible samplers can be used.

Several samplers have historically been used in analyzing mine dust, such as impingers, respirable dust monitors employing beta attenuation sensors for monitoring mass and photometers. However, there are many instruments which are used to analyze dust aerosols which are not permissible and can not be used in the mine which include optical particle counters, electrical aerosol analyzers and condensation nucleus counters to name a few. In addition, the new instruments are continually becoming available for the analysis of particles such as the aerodynamic particle sizer and the micro-orifice uniform deposit impactor.

The purpose of this project is to consider all instruments which are available for characterizing particulate matter and devising methods by which they can be used to characterize coal mine dust. In some cases these instruments may not be taken into the mine and the mining dust will have to be brought to the instrument. In some cases the instrument may be intrinsically safe but techniques have to be developed where by it can be used in a mining atmosphere.

Furthermore, it is important that all investigators in the center be using the same or similar instruments when possible and be using the instruments correctly. This involves making sure that the sampling conditions are such that the sampling efficiency is satisfactory as well as transport efficiency to the instrument so that it does not allow for large amounts of particles to be lost. In addition, the samples which are collected by the instrument or the data which the instrument provides must be analyzed correctly and in a similar manner by all investigators in order for it to be possible to the compare the data from one investigator to another. This project provides a focal point for which information is deseminated to all investigators concerning new instruments that are available. Calibrations of instruments already being used in the fields and the proper use and data analysis of the instruments.

SCOPE OF WORK

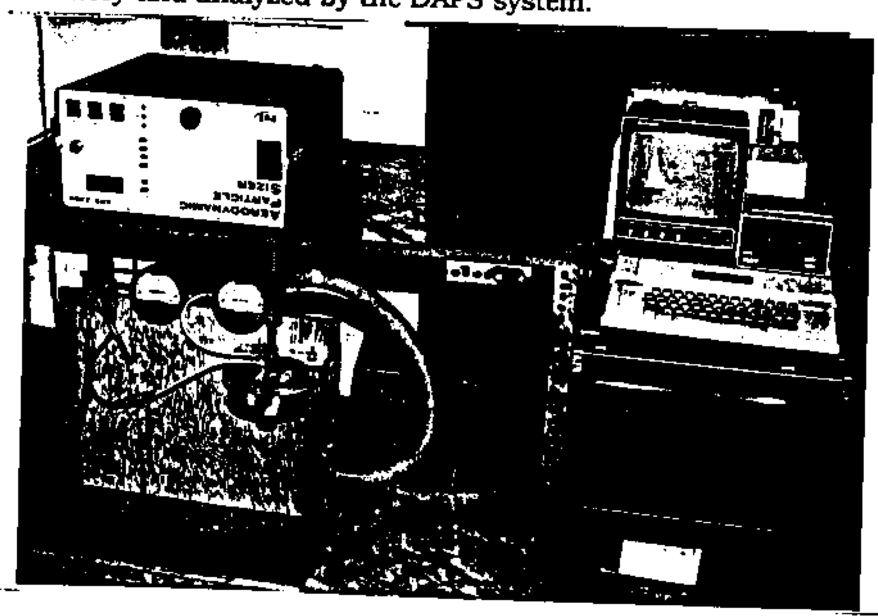
In the broad sense, the scope of work for this project is to investigate instruments and techniques for characterizing coal mine dust. This includes analyzing traditional instruments for analyzing coal dust as well as instruments for analyzing other types of particles that have not been specifically applied to coal dust or adapting new instruments which are being developed to characterize coal dust. To satisfy this broad scope of work, the project can be broken down into smaller projects, each of which have their scope of work. Such a list was given at the introduction of this report. Since this list covers a variety of subjects and instruments, the scope of work for each of those items are given below.

1. Identification and Selection of Instruments

In this task the work involves investigating all instruments that are used to analyze aerosol particles. These instruments can include those that are already used in a mine, those which are used to analyze characteristics of dust particles that are not used in the mine and those instruments which are used to analyze any type of aerosol particle. The investigation will center around the ability of the instrument to provide useful information on the coal mine dust, either its size distribution, concentration or a chemical or geometrical makeup. If an instrument is determined to be useful in characterizing the dust, then the application of this instrument will be considered. For example, the instrument may not be safe to use in a mine and dust have to be brought to the instrument or, the instrument may be newly available to the aerosol community but has not yet been adapted.

2. Dust Dispersion/Aerodynamic Particle Sizer (DAPS)

The aerodynamic particle sizer (APS) is an instrument recently developed by TSI Inc. to measure the aerodynamic particle sizer of aerosol particles. The major problem with the instrument being used in the mine is that it was quite large, heavy and not permissible. Therefore, it was necessary to develop a technique by which dust could be brought from the mine to the APS for analysis. To accomplish this, a device had to be developed to redisperse particles from a filter and introduce them into the APS so that particles could be collected out of mines face on a filter transported to the surface or laboratory and analyzed by the DAPS system.



3. Micro-orifice Uniform Deposit Impactor (MOUDI)

The MOUDI is a newly developed cascade impactor which can size particles from 0.1 to 15 microns in 8 stages. This instrument is basically a high technology cascade impactor which deposits the particles uniformly upon the substrates and extends the range of the impactor into the submicron range beyond where impactors have normally been operated. Since impactors are a major instrument in the analysis of dust aerosol particles, the adaptation of the MOUDI to study mine dust is very desirable and will lead to new knowledge in the size distribution and composition of mining particles as a function of particle size.

4. U of M/TCRC Coal and Rock Crushing Experiments

It is believed that when the coal or rock are crushed into dust particles that the particles may pick up a high electrical charge. A collaborative project with the Bureau of Mines - Twin Cities Research Center (TCRC) is to be performed using the rock crushing facilities at this TCRC and the instrumentation and sampling expertise at the University of Minnesota. The scope of work for this project is to crush samples under a load and as the rock or coal disintegrates, flush the particles immediately into a sampling duct where by they are analyzed by cascade impactors and an APS to obtain particle size distribution and through electrical mobility analyzers to determine the electrical charge distribution on the particles.

5. Respirable Particles into a Liquid Surfactant Sampler

It is believed that some characteristics of the dust may change from the time it is generated at the mine face to when it is analyzed on the surface. Since the dust may be more hazardous if is is breathed immediately upon the generation at the mine face a sampler has been developed to sample the particles into a lung surfactant at the mine face and preserve them in the surfactant for later analysis or use in medical studies.

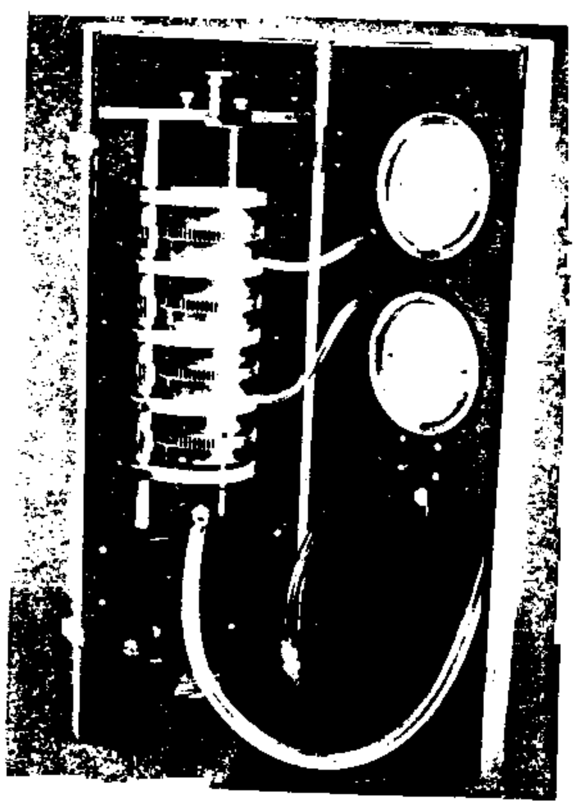


Figure 2. Micro-orifice uniform deposit impactor (MOUDI).

6. Coal Dust/Diesel Exhaust Samplers

It has been found that coal dust particles can be separated by diesel exhaust particles if the particles are separated at .08 μm with the diesel particles being less than 0.8 μm and the dust particles being larger. Therefore, it would be convenient in studying mines where diesel exhaust is present to have a sampler that would classify particles at 0.8 μm into two classifications, one being 0.8 μm and the other less than 0.8μm. Furthermore, it is desirable to have area samplers which can collect large quantities of particles and personal samplers which can be worn by the individuals in the mine.

7. Advice on Instrument Usage

It is desirable when several investigators are working on a common problem to have the investigators using common sampling techniques and instruments where possible. The scope of this task is to provide a means by which all investigators will be using similar instruments in a similar manner. This has lead to an initial meeting at the University of Minnesota where the basic instruments were discussed and also to an impactor workshop which was attended by all investigators. In the workshop the different impactors were described, usage techniques recommended and the data analysis described.

8. Use of DAPS to Analyze Dust on Filters

In task 2 it was described how a dust dispersion system was developed for use with the aerodynamic particle sizer to disperse mine dust particles into the APS. In this task a method was developed where by the particles could be collected at the mine face on the filter transported to the DAPS and particles redispered into the instrument. It is necessary for this to be accurate that the size distribution of the particles redispersed from the filter be the same as the size distribution laid down on the filter. Upon development of the technique the technique should be applied to dust samples collected by people at the University of Minnesota as well as from dust samples from other investigators.

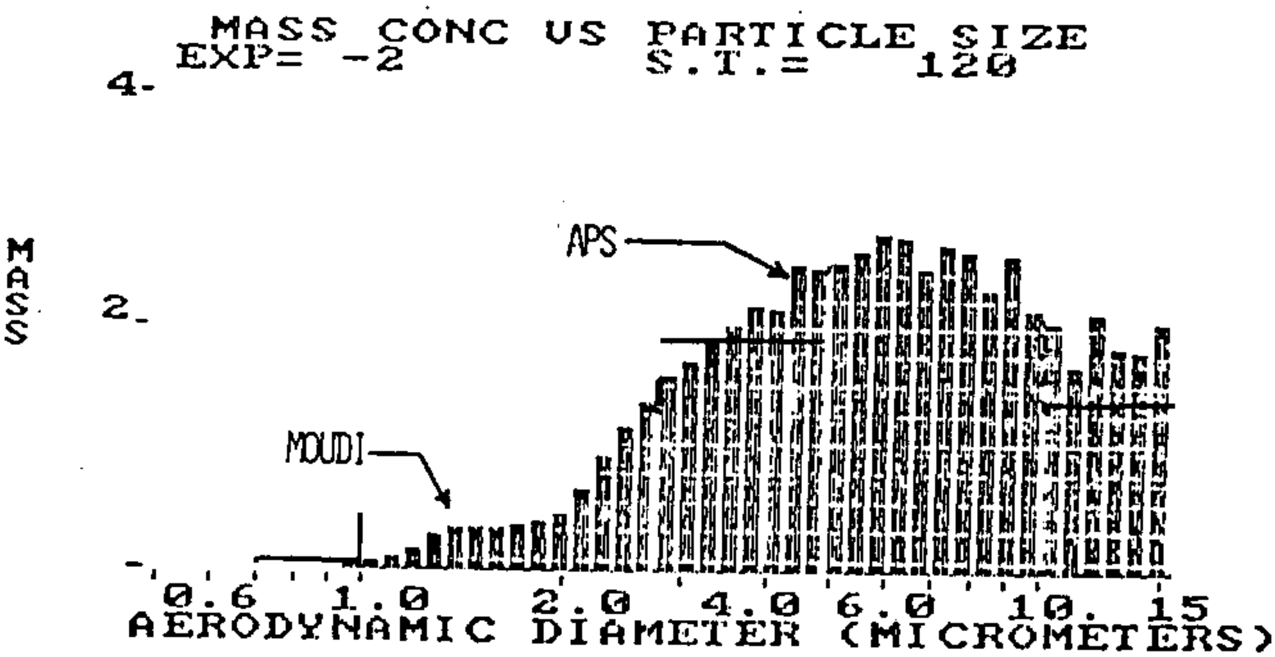


Figure 3. Mass size distribution of coal dust as measured with MOUDI in a electric powered coal mine and the APS after redispersion from the filter.

9. Respirable Mass/Size Distribution Impactor

Cascade impactors have long been used to get the size distribution of aerosol particles. Respirable impactors have been used to determine the quantity of respirable mass in a sample. It is the objective of this task to combine the two technologies into one sampler which will provide the mass concentration of the respirable fraction of the aerosol as well as some information of the size distribution of the particles is the respirable range. This is possible since in respirable impactor the respirable curve is approximated by cutting the aerosol into three size fractions and taking the fraction that penetrates these three stages as the respirable mass. It is also possible to take the quantity of particles that have collected at the three stages and obtain a cumulative mass size distribution.

CONCLUSIONS

There have been numerous results due to the efforts on this project. First, the aerodynamic particle sizer is now used quite extensively in analyzing coal dust. This is primarily due to the dust dispersion system developed under this contract can now

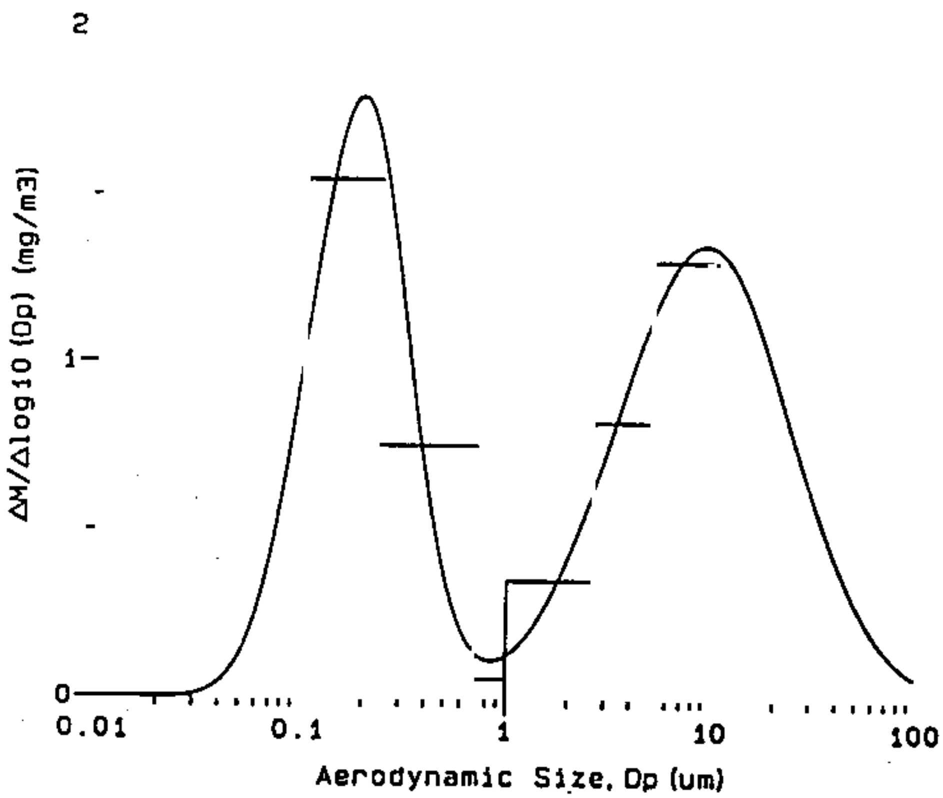


Figure 4. Typical aerosol size distribution along haulage way in dieseel powered coal mine.

aerosolize particle from a bulk sample or can aerosolize particles collected on a filter within the mine. Figure 1 shows the prototype of the dust dispersion system coupled to the TSI Areodynamic Particle Sizer (APS). Second, the micro-orifice uniform deposit impactor, showed in Figure 2, has been adapted and used in analyzing mine dust aerosol. Figure 3 shows a comparison of the coal dust size distribution as measured in an underground mine with the MOUDI and that simultaneously collected on a Telfon membrane filter and subsequently redispersed and measured with the APS. This particular mine utilized only electric powered equipment. Particle size distribution results from the MOUDI for a diesel powered mine are presented in Figure 4. The size distribution data indicate that in diesel mines there is a particle size distribution mode less than 0.8 μm diameter that is primarily diesel particulates while the particles larger than 0.8 μm are primarily coal dust. This finding has led to the development of a sampler to be used in diesel/coal mines with a separation point of 0.8 μm. Both area and personal samplers, shown in Figure 5, are being developed to collect particles in the greater than 0.8 μm (coal dust) and less than 0.8 μm (diesel exhaust particles). Third, the new samplers are being developed for special purposes such as the sampler that collects particles directly into a liquid surfactant to simulate the collection of particles. Analysis of particles collected in this fashion and those collected on a filter or in a bulk sample can be analyzed to see if there is a difference in the toxicity of the particles due to aging of particles outside the lung surfactant. Fourth, the respirable impactor technology has been modified to obtain size distribution and concentration information as well the concentration of respirable aerosol. This enables one instrument to do the work of two in that previously a cascade instrument will give the size distribution and a respirable classifier such as a cyclone or impactor would give the respirable mass. Sixth, the University of Minnesota and the TCRC personnel have been collaborating on experiments to determine the size distribution and electrical charge of the functional size on freshly crushed particles of coal and rock.

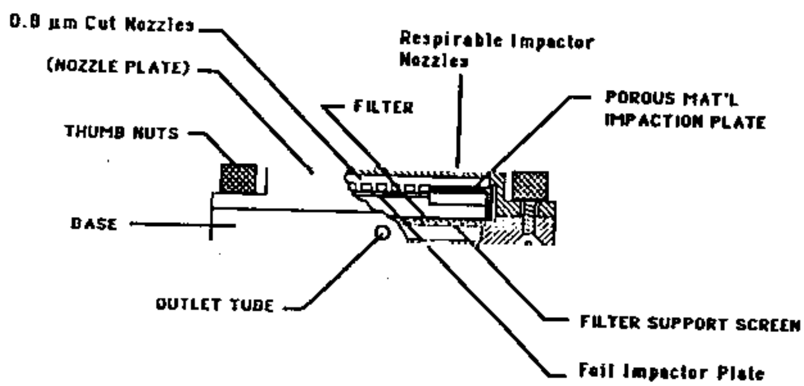


Figure 5. Schematic diagram of personal diesel particle sampler.

APPLICATION OF RESEARCH RESULTS

The results of this research has been applied widely in the work of the center. Since, instrumentation is used on many of the other projects. For example, many investigators are using impactors and analyzing the data following recommendations given in the Impactor Workshop. In addition, investigators are using the aerodynamic particle sizer to determine the size distribution of particles from filters and bulk samples. Some of the instruments being developed under this project have not been used by other investigators as of yet because of their being only recently developed or evaluated. These include the Micro-orifice Uniform Deposit Impactor, the instrument to collect particles in a liquid surfactant and the diesel exhaust/coal dust particles sampler.

CONTINUING WORK

As indicated in the introduction, the primary objective of this activity is the identification and selection of instruments that can be used in the mine characterized mine dust. Therefore, we are continuously keeping abreast of new instruments and evaluation techniques which are becoming available to people working with the aerosol particles. If the instrument or technique appears to be useful we will work to make it adaptable we will work to make it adaptable to characterizing mine dust.

Some of the new samplers which have been developed such as the micro-orifice impactor, the diesel/coal dust sampler, the dust in a liquid surfactant sampler and the dust dispersion system for APS will be continued to be developed and made more useful for analyzing coal particles.

TECH TRANSFER

The research conducted during this project has resulted in significant transfer of technology in the form of conference presentation, publication and interaction in an instrument manufacturer. There have been ten conference presentation, five publications and one doctorial thesis. Furthermore, this project has fostered much interaction with the other members of the Generic Center both in the area of information pertaining to instrumentation and collaborative testing.

REFERENCES

Marple, V. A., K. Rubow, G. Ananth and H. J. Fissan, "Micro-orifice Uniform Deposit Impactor", J. Aerosol Sci. 17:489-494 (1986).

Ananth, G. and J. C. Wilson, "Theoretical Analysis of the Performance of the TSI Aerodynamic Particle Sizer: The Effect of Density on Response", Accepted for publication, Aerosol Science and Technology, (1988).

Marple, V. A. and K. L. Rubow, "Instrumentation for the Measurement of Respirable Coal Mine Dust", Proc. Coal Mine Dust Conf., Morrgantown, WV, pp. 214-221 (1984).

Rubow, K. L. and V. A. Marple, "Application of a Particle Dispersion System for Obtaining the Size Distribution of Particles Collected on Filter Samples", Aerosols: Formation and Reactivity. 2nd Int. Aerosol Conf., Pergamon Journals Ltd., pp. 809-812 (1986).

Fang, C., "A Fundamental Study of Multi-Nozzle Mirco-Orifice Impactors", Ph.D. Thesis, Mechanical Engineering Dept., University of Minnesota (1988).

Rubow, K. L., B. K. Cantrell and V. A. Marple, "Meassurement of Coal Dust and Diesel Exhaust Aerosols in Underground Mines", Proc. of the VIIth Int. Pneumoconioses Conf., Pittsburgh, PA, Aug., (1988).

MN3/USBM 2703

Determination of Silica Particle Concentrations in Respirable Size Range

Marple, V. A.; Rubow, K. L.; Pignolet-Brandom, S.; Reed, K.; Fang, C. P.; Tongen, W.

INTRODUCTION

The primary objective of this project is to investigate instruments and experimental methods and procedures that can be used to determine the quantity of silica particles in coal dust samples. It would be most desirable if an instrument could be developed for the non-destructive interrogation of a sample providing a measurement of the silica particle concentration. Such a device, if not expensive, could be used at the mine to determine the quantity of silica on personal sampler filters before the mass of dust is measured gravemetrically to allow for selection of only high silica concentration samples to be analyzed.

It is realized, however, that an instrument that can measure the concentration of silica on a filter non-destructively and is yet rather inexpensive may not be possible with current technology. Therefore, current technology which can measure the concentration of silica particles in coal samples will be investigated and experimental methods devised for transferring samples from a collection device to the silica analyzing instruments in such a manner that the sample analyzed is representative of the sample collected.

Of particular interest, from a research viewpoint, is the analysis of silica particle concentration as a function of particle size. This allows for the analysis of a general sample and determination of the respirable fraction by the application of the respirable criteria, either ACGIH or BMRC. Two methods can be used to determine the silica particle concentration as a function of particle size. One can either collect a sample in a cascade inertial impactor, thereby segregating particles by their aerodynamic diameter or use a silica analyzing instrument which interrogates the sample particle by particle while simultaneously measuring the size of each particle, thus, determining the silica particle size distribution.

In summary, this project is one which considered the current silica analysis technology and devised methods for transferring particles from sampler to analyzer in a representable fashion. Investigations were made into new technology which may be used for the non-destructive analysis of samples to determine the silica concentration. Funds were not provided in this study for the development of such an instrument but only to investigate the possibilities of analysis techniques.

RATIONALE

The presence of silica particles in respirable coal dust is one of the factors thought to contribute to the health hazard of the dust. Thus, it would be desirable to have convenient instrumentation that would be capable of measuring the quantity of silica particles in coal dust samples. In particular, for research purposes, it would be advantageous to be able to determine the concentration of silica particles as a function of the particle size. This will require silica analysis instrumentation which can analyze the dust, particle by particle, or require the development of experimental methods and procedures for transferring particles from size classification instrumentation to a form suitable for silica analysis.

Current common practice for silica analysis is to analyze by ashing or x-ray diffraction techniques. Since the ashing techniques are rather time consuming, it would be advantageous to be able to apply other techniques such as the x-ray diffraction to this analysis. However, these analysis techniques require the transfer of the deposits from such devices as impactors to other media in a fashion that would insure a representative sample of the dust being analyzed.

One instrument that might be of aid in determining the silica content as a function of particle size is the Australian developed QEM*SEM (Quantitative Evaluation of Materials by Scanning Electron Microscopy) (International Scientific Instruments, Inc. Santa Clara, CA). This instrument is based on using a scanning electron microscope where the analyzer uses the signals obtained from an energy-dispersive x-ray detector and a back-scattered electron detector to map the minerals present at each of the series of points covering a sample.

The need for instrumentation to determine the quantity of silica in coal samples is obvious; the silica is thought to be a hazardous component of the coal dust. At present, much of the activity in the Generic Center is involved in the characterization of coal dust particles. A part of this characterization must be the determination of the quantity of silica particles in the coal dust. The rational for this project is to aid in determining methods that can be used to measure the quantity of the silica particles in coal dust. For research purposes, the technique investigated is for determining the quantity of silica as a function of particle size.

SCOPE OF WORK

The workplan for this project has been broken into a number of separate. These tasks include the items necessary to devise methods for the members of the Generic Center on Respirable Dust to be able to measure the quantity of silica in the coal dust samples as a function of particle size. One task involves an investigation of a newly developed instrument which may aid in the determination of the silica content as a function of particle size. Another task is to investigate other techniques that would allow one determine the silica concentration as a function of particle size.

One of the techniques which can be used for determining the quantity of silica in coal dust samples as a function of particle size is to collect the dust in a cascade impactor or other size classification device. This deposited dust can then be transferred to substrates which are compatible with instruments such as the SEM for measurement of silica in the dust sample.

The Mineral Resources Research Center at the University Of Minnesota has a QEM*SEM instrument from International Scientific Products, Inc. This is a newly developed automated method for the analysis of deposits using an energy dispersive x-ray detector and a back-scattering detector on a scanning electron microscope. Currently, the suitability of this instrument to determine the quantity of silica in a coal dust sample in the respirable size range is not know. The instrument, however, can determine the silica content in particles larger that 5 microns and provide the information as a function of particle size of the primary dust and the size of the silica deposit in the primary particle. Thus, it is the purpose of this task to investigate the possibility of extending the use of this instrument to analyze coal dust samples in the respirable size range. Again, this will involve developing techniques to transfer the deposit from a sampler to the instrument for subsequent analysis. Since the instrument is capable of sizing particles as well as determining the silica content, it may be possible to take a bulk sample of the dust rather than remove a deposit from a size selective sampler. This could greatly simplify the analysis of the dust for silica content. If this instrument does prove to be useful for this type of analysis, it can be made available to the Generic Center for sample analysis.

Another approach for determining the quantity of silica in a respirable sample of mine dust involves the use of the micro-orifice uniform deposit impactor (MOUDI). This instrument size fractionates the particles from 0.1 to 15 μm into 8 size intervals. The silica concentration in the particle deposit for each impactor stage can to determined using standard analytical techniques such as infrared spectroscopy of x-ray diffraction. The unique advantage of the MOUDI over other impactors is its ability to collect greater quantities of particles in each size fraction. This results from its sampling flow rate of 30 l/m which is higher than most impactors. Secondly, more particles can be deposited on each stage before the stage overloading problems occur because the impaction surface can be rotated relative to the impactor nozzle, thereby utilizing a greater fraction of the collection surface. In addition, any type of substrate can be used in the impactor so as to be compatible with a particular type of silica analysis method. Finally, the impactor has specially designed removable impaction plates so as to be convenient for use in a mining atmosphere where impaction substrates must be changed in a rather poor environment.

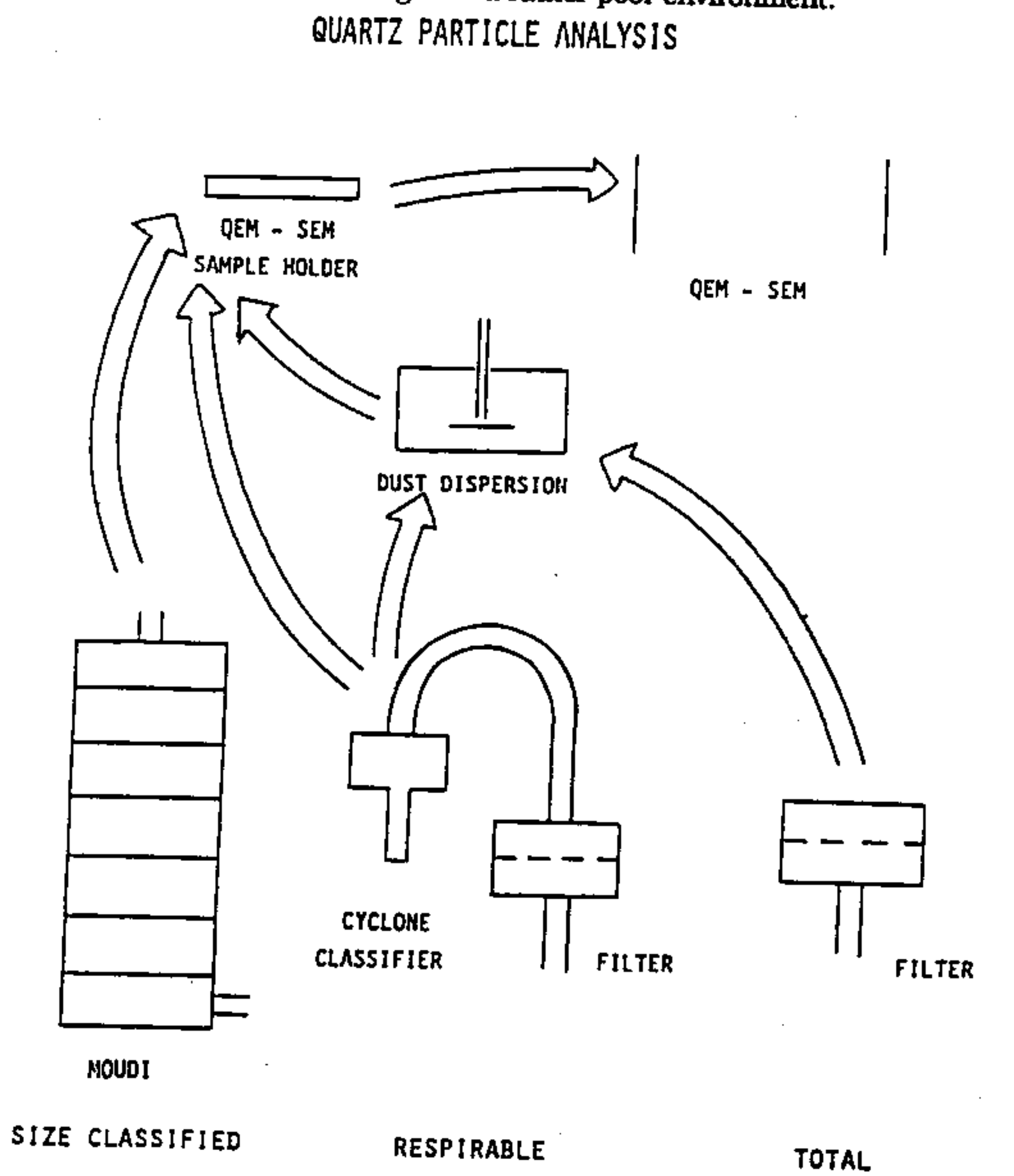


Figure 1. Techniques developed for preparing samples for SEM analysis.

CONCLUSIONS

A method was devised by where particles could be collected upon a filter, cyclone classifier, or MOUDI stage and transferred to a sample holder for the QEM/SEM (or any SEM) either directly as is the case with the MOUDI or through redispersing of the dust through a dust dispersion system as shown in Figure 1. However, the procedure has been difficult to completely utilized because of the lower detection limit of the QEM*SEM. The current detection limit is approximately 2 μm.

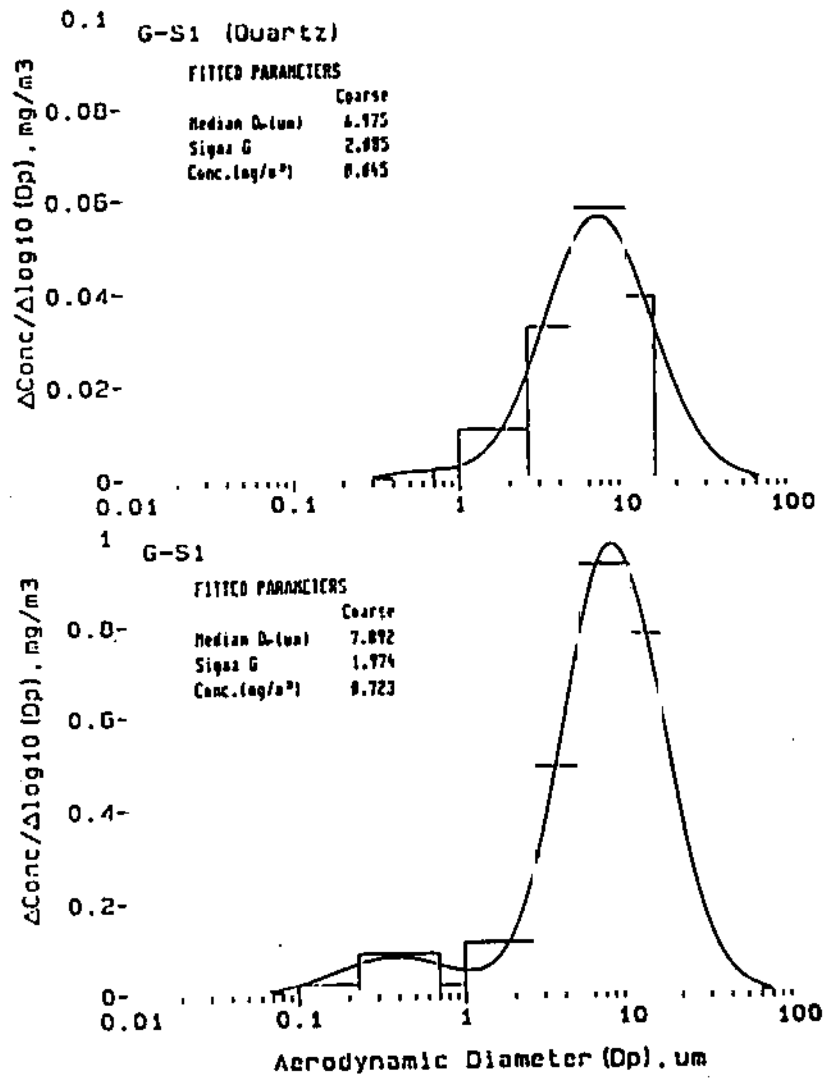


Figure 2. Mass size distribution of coal dust and its silica component as obtained using the MOUDI method.

The more successful technique has been the use of the MOUDI for in-mine particle sampling followed by MSHA determining the silica concentration on each MOUDI stage using a modification to their standard silica analysis. Since the MOUDI has a sampling flow rate of 30 l/m, sufficient particle mass is collected on each stage of the MOUDI to not only obtain the total mass concentration in each particle size range, but also to perform the silica analysis. MSHA is currently using Fourier transform infrared spectroscopy for the analysis. Figure 2 shows the particle mass size distribution for a dust sample collected in an underground coal mine located in the Pittsburgh No. 6 seam. Also shown is the corresponding size distribution of the silica particles. The silica particles, which are 6% of the total mass concentration, have nearly the identical size distribution as the total dust for particles in the 1 to 15 µm diameter size range. This indicates that the quartz is distributed uniformally throughout all particle size ranges rather then preferentially located in a particular size range.

APPLICATIONS

The application of MOUDI technique for use in silica analysis as a function of particle size is currently developed to a point where a researcher can employ this tool. The MOUDI can be used to obtain a particle sample from a mine. The silica determination can then be make using either infrared spectroscopy or x-ray diffraction.

Continuing Work

Work should continue in the areas of techniques that can be used to determine the quantity of silica particles contained within an individual particle or in a bulk sample. This work should look at new developments occurring in the field of elemental analysis as well as investigations into developing new techniques for this type of analysis. In a parallel effort, the best techniques that we currently have, the use of the MOUDI with infrared spectroscopic analysis should continue to be developed. The MOUDI, with a flow rate of 30 l/m is somewhat awkward to use in a gaseous mine since there is not a permissible pump which will pull this type of flow rate. Therefore, techniques for using the MOUDI in the mine should be investigated including development of new pumps or developing techniques for obtaining the proper flow rate at the location where the MOUDI should be located in the mine.

TECH TRANSFER

The successful employment of the MOUDI for silica analysis is a recent development in this project. This technique will be presented for the first time at a conference in the spring of 1989.

WV13/USBM 5412

Determination of Biologically Active Silica Using Photoacoustic Spectroscopy

Seehra, M. S.; Wallace, W. E. (NIOSH) and Cheng, L.

1. INTRODUCTION

The inhalation of mine dusts by coal miners is believed to be the major cause of lung diseases known as CWP (Coal Worker's Pneumoconiosis). Coal dusts contain many minerals such as silica quartz, kaolin, pyrite etc besides coal particles. At present mines are regulated for total dust concentration and for percentage of 'free' silica quartz (<100 μg/m³), since silica is known to cause injury to lungs. However recent epidemiological studies indicate that the progression of CWP does not correlate well with the amount of free silica alone. A recent hypothesis is that it is the surface available (SA) silica and not total or free silica that is biologically active in causing CWP. SA silica is silica that is not occluded or covered by clays and other minerals.

2. RATIONALE:

At present, free silica in mine dusts is being determined by IR (Infrared) spectroscopy using the MSHA P7 method. This technique however cannot distinguish between the free silica and SA silica. Since initiation of this project in October 1986 the main objectives of this research have been to develop Photoacoustic (PA) spectroscopy to determine SA silica along with free silica concentrations, apply the technique to various mine dusts, followed by cytotoxicity and biological testing. Since PA spectroscopy can be done on a modified FTIR spectrometer, a successful development of this technique shall provide a simpler modification of the existing P7 method than any other kind of surface spectroscopy for determining SA silica. Another advantage of PAS is that samples can be studied as received without major preparations or modifications as are necessary in the P7 method.

In summary, the objectives of this project are to:

(i) Develop PA spectroscopy for determining SA silica as well as free silica in mine dusts;

(ii) Apply PA spectroscopy to characterize mine dusts from 16 mines in the USBM/NIOSH study; and

(iii) Test the hypothesis of the role of SA silica in causing CWP by cytotoxicity and biological testing.

3. SCOPE OF WORK:

In line with the objectives stated above, a work plan involving both experimental and theoretical studies was organized. This consisted of (1) Acquisition and standardization of a PA/FTIR spectrometer, (2) theoretical analysis of the photoacoustic effect (Rosencwaig-Gersho theory) in solids and its application to powdered materials, (3) PA spectroscopy of silica and kaolin and development of criteria for distinguishing SA silica and free silica, (4) biological effects of silica in collaboration with W. E. Wallace of NIOSH and P. Bolsaitis of MIT, and (5) PA spectroscopy of mine dusts. So far, tasks 1 and 2 noted above have been completed and tasks 3 and 4 are under progress and task 5 will be undertaken in the coming year.

Photoacoustic Spectroscopy of Silica:

Along with the acquisition and standardization of the PA/FTIR spectrometer (Cygnus 100, Mattson Instruments), a critical examination of the Rosencwaig-Gersho (RG) theory of the photoacoustic effect in silica was undertaken. Results of this work are contained in the following publications:

(1) 'Theory of photoacoustic spectroscopy and spectra of quartz', M.S. Thesis of Leung H. Cheng, West Virginia University, 1987;

(2) 'Photoacoustic Spectroscopy of Quartz: Chopping Frequency Dependence, Saturation Phenomenon and Quantitative Analysis', M.S. Seehra, P.S. Raghoottama and L. Cheng, Applied Spectroscopy (in press).

(3) Photoacoustic Spectroscopy of Quartz and Kaolin, P.S. Raghoottama and M.S. Seehra, to be presented at the ACS meeting.

A significant result of these studies is that the RG theory, which was developed for a thin-film sample seems to work rather well for respirable size silica particles. The chopping frequency dependence is in agreement with the prediction of the RG theory. This is important since it is the chopping frequency dependence of the photoacoustic signal that is likely to be used for distinguishing between SA silica and free silica. Other results of this work include the derivation of equations for mass dependence of the PA signal and verifications of these equations by studies on silica. These results have clearly demonstrated that for respirable size dust samples obtained from coal mines, the PA spectroscopy can be used for quantitative analysis of silica and kaolin in mine dusts.

Toxicity of Amorphous and Crystalline Silica:

Recently we have carried out PA spectroscopy of crystalline and fumed silica samples supplied by Prof. Bolsaitis of MIT prepared under different conditions. Our work has shown that in fumed silica, several of the IR modes are missing, attesting to the amorphous nature of this silica. According to Prof. Bolsaitis, fumed silica has considerably higher toxicity than crystalline silica and our work has shown that certain surface IR modes may play a key role in this toxicity. Further work is underway to determine the nature of the mechanism of toxicity. This work is expected to contribute significantly to our understanding of the biological activity of silica. A paper on this work is under preparation, in collaboration with Prof. Bolsaitis.

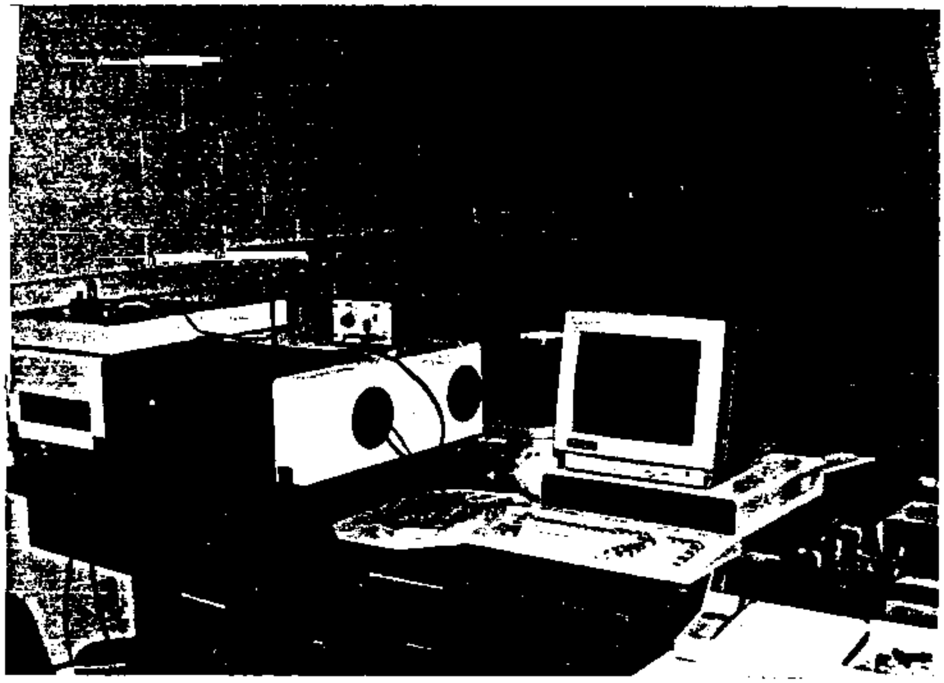


Figure 1. Photograph of the Cygnus 100 (Mattson Instruments) FTIR/Photoacoustic Spectrometer.

Interaction of Silica and Kaolin with Lecithin:

The PA and FTIR spectroscopy of silica and kaolin coated with DPL (Dipalmitoyl Lecithin), a major component of pulmonary surfactant has recently been carried out in collaboration with Wallace et al at the NIOSH laboratories in Morgantown. A paper entitled "Respirable Particulate Surface Interactions with the Lecithin Component of Pulmonary Surfactant" by M.J. Keane, W.E. Wallace, M.S. Seehra, C.A. Hill, P.S. Raghoottama, and P. Mike is planned to be presented at the VII International Pneumoconioses Conference to be held in Pittsburgh (August 1988). Our PA spectroscopy has provided some insight as to how silica and kaolin differ in their interaction with DPL.

4. CONCLUSIONS:

(1) With the sophisticated instrumentation available at present and the current theoretical understanding, the PA spectroscopy is proving to be a very versatile and valuable analytical technique for characterizing mine dusts.

(2) The PA spectroscopy of different forms of silica and kaolin has shown how these materials differ in their IR properties as well as in their biological activity.

5. CONTINUING WORK:

Work is under progress to develop PA spectroscopy to distinguish between SA silica and free silica and to characterize mine dusts from different mines. Also, studies on the relationship between the IR properties of silicas, kaolin and DPL coated silicas and kaolin and their biological activity are under progress. Successful completion of these projects shall provide us a new and versatile technique of PA spectroscopy to characterize mine dusts and a deep understanding of how mine dusts cause lung damage in miners. These achievements might lead us to devise new ways to reduce the severity of CWP.

6. APPLICATIONS AND TECHNOLOGY TRANSFER:

We are developing a systematic procedure for using PA spectroscopy for quantitative analysis of minerals in mine dusts. Compared to the standard FTIR spectroscopy used in the P7 method, the PA spectroscopy is considerably simpler in operation and provides more information than is possible with the FTIR spectroscopy. A report on this procedure shall be provided to the U.S. Bureau of Mines for use by the Mining Industries.

Our collaborative studies on the biological and toxicity effects of different forms of silica are expected to show how silicas cause lung damage. The role of surface available silica vis-a-vis total silica in causing lung damage should also become clear once these projects are completed.

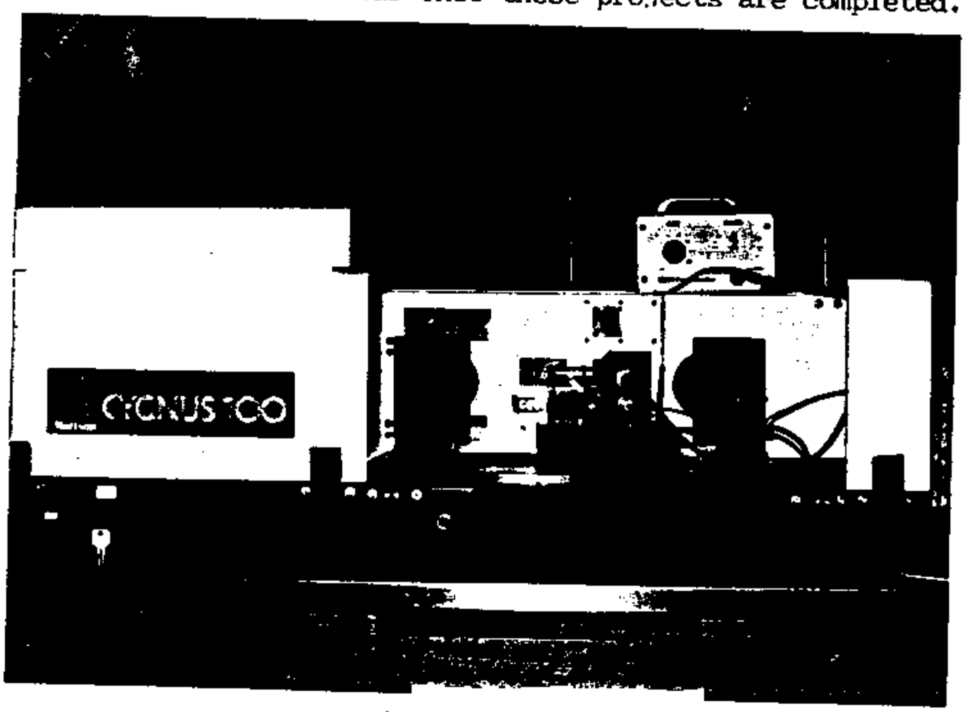


Figure 2. Photograph of the Photoacoustic Cell in the sample compartment of the spectrometer. The computer which controls the operation of the spectroment is not visible in the photographs.

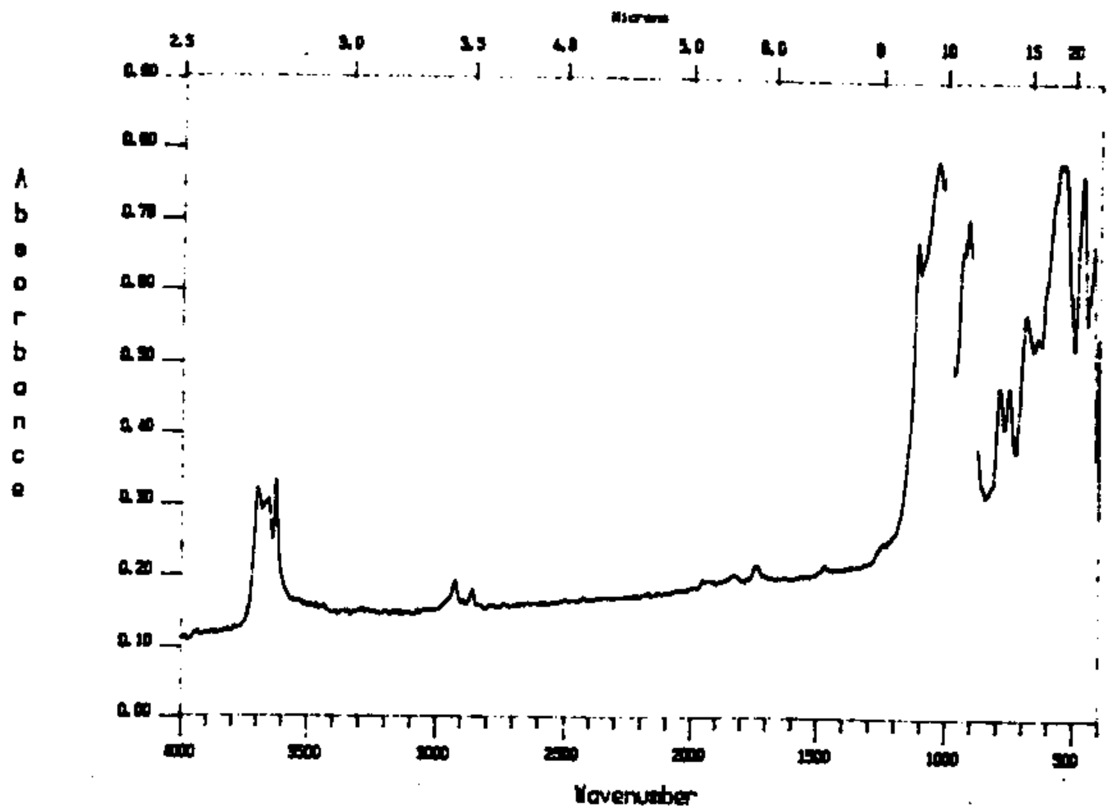


Figure 3. IR spectra of Kaolin coalted with DPL (Dipalmitoyl Licithin) using PA spectroscopy.

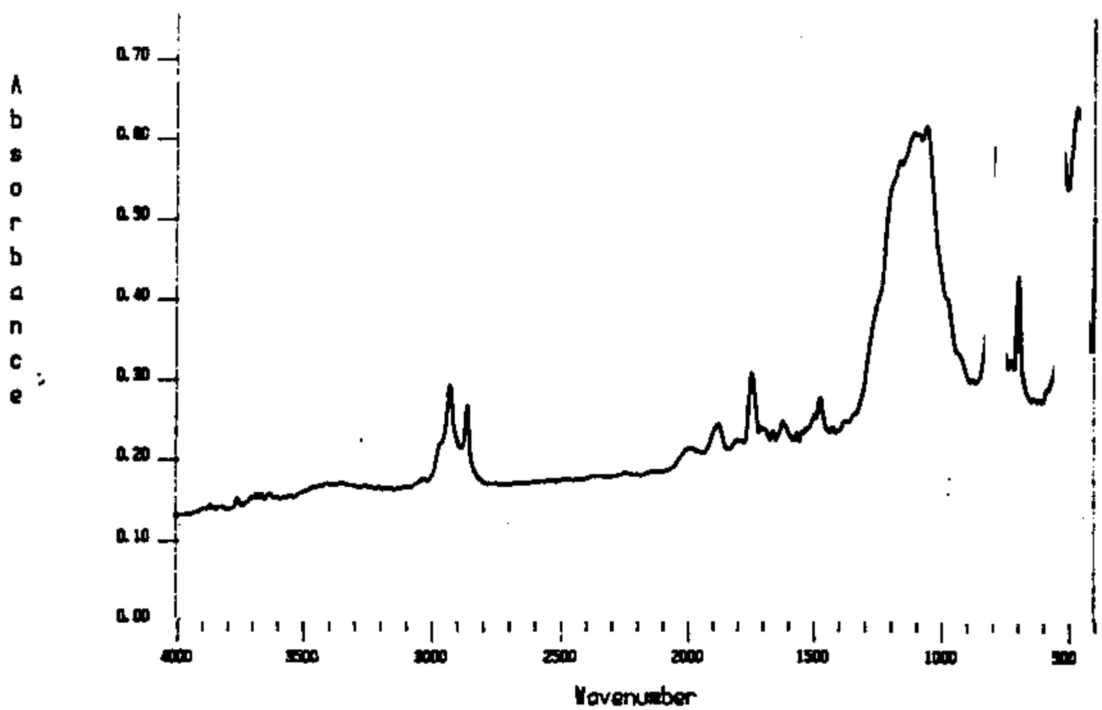


Figure 4. IR spectra of silica coated with DPL using PA spectroscopy. Bands near 2900 cm^{-1} and 1800 cm^{-1} are due to DPL.

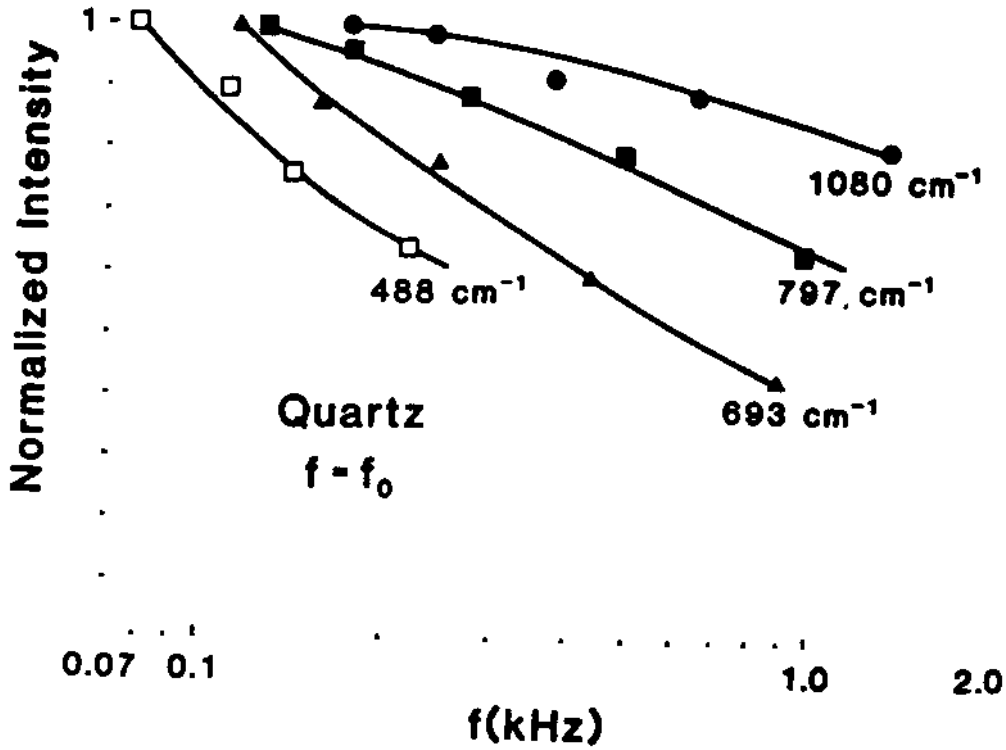


Figure 5. Chopping frequency dependence of the intensities of the four major bands of silica. Solid lines are form theory.

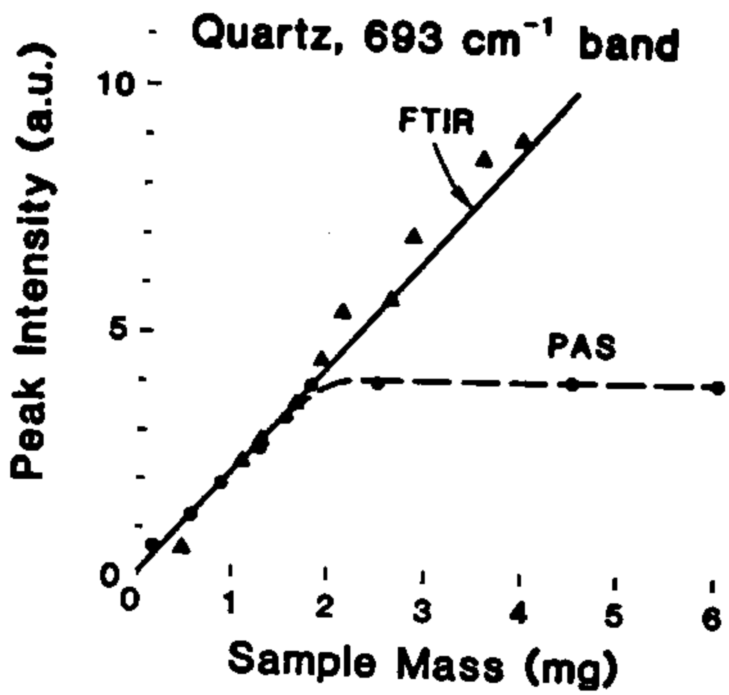


Figure 6. Comparison of the mass dependence of the signal using FTIR and PA spectroscopy. Below 2 mg, PAS can be used for quantitative work.

4.3

Relationship of Mine Environment, Geology and Seam Characterization to Dust Generation and Mobility

PS5/USBM 4205

Establishment of Standard Procedures for Characterization of Respirable Coal Mine Dust Potential

Mutmansky, J. M.; **Bise**, C. J.; **Frantz**, R. L.; Johnson, C.; Xu, L.; Padmanabhan, S.

INTRODUCTION

It is evident that the incidence of coal worker's pneumoconiosis (CWP) or black lung disease varies in different coal producing regions of the United States. Many people have hypothesized about the reasons for the differing occurrences, but because underground coal mining involves many mining methods under changing geological conditions, several factors may be involved in contracting CWP such as: the trace elements in the respirable dust, the amount of quartz in the respirable dust, the rank of the coal (bituminous, anthracite) that produced the respirable dust, the amount of respirable dust, etc.

Recognizing the uniqueness of underground coal mining and CWP, the main purpose of this project was to establish standard procedures for characterizing some factors that may be involved in contracting CWP. This has been accomplished by the in-mine sampling of airborne dust at various worker locations and by performing laboratory analyses of mined material (coal and rock) taken from the mines. After standard procedures have been established, certain factors contributing to CWP may be identified and prevented during pre-mine planning or remedied by engineering controls in an operating mine.

This project has developed a method of classifying coal seams according to their potential to generate respirable dust, has performed statistical analyses of the size and locational variations of the elemental compositions of respirable coal mine dust in operating underground mines from seams located in the eastern, midwestern and western United States (see Table 1), and is currently completing research which has investigated the relationship between the elemental compositions of respirable dust sampled near a continuous-mining machine and a laboratory-produced respirable dust.

The project has also been investigating the best means of determining the mineralogical content of small dust samples using a scanning electron microscope (SEM) and the P-7 methods. In addition, SEM methods for characterizing some of the physical parameters of the dust have been attempted.

The ultimate goal of the project is to provide methods for obtaining the chemical, mineralogical and physical characteristics of respirable coal mine dust samples. In addition, the methods will be applied to dust samples taken from twenty coal mines of varying rank throughout the country and statistically related to CWP occurrences obtained through the medical records of the National Institute of Occupational Safety and Health.

Seam	State	Type of Coal
Brookville	PA	Bituminous
Upper Freeport	PA	Bituminous
Pittsburgh	PA	Bituminous
Lower Kittanning	PA	Bituminous
Lykens Valley	PA	Anthracite
Orchard	PA	Anthracite
Pittsburgh	OH	Bituminous
Lower Freeport	OH	Bituminous
Lower Kittanning	WV	Bituminous
No. 2 Gas	WV	Bituminous
Lower Eagle	WV	Bituminous
Middle Eagle	WV	Bituminous
Illinois No. 5	IL	Bituminous
Illinois No. 6	IL	Bituminous
Kentucky No. 9	KY	Bituminous
F Seam	CO	Bituminous
Wadge	CO	Bituminous
Lower O'Conner	UT	Bituminous
Hiawatha	UT	Bituminous

Table 1. Coal seams and locations sampled.

RATIONALE OF THE PROJECT

Coal mine dust physical, mineralogical and elemental characteristics as well as the amount of respirable dust entrained in the mine atmosphere make a difference in the incidence and severity of CWP. Coal mine dust consists of many sizes, shapes, and densities of particles which are transported through the mine by the ventilating air. Not only does mine dust consist of coal particles, but also of rock particles that are unavoidably cut in the mining process. Thus, as coal and rock composition change, the potential to produce respirable dust and the elemental content of the dust entrained in the mine atmosphere change.

Much respirable dust is produced with the breakage of coal and rock. Fortunately, only a small portion of it becomes airborne because it adheres to larger pieces of coal and rock. The dust that does become airborne travels through the mine with larger, heavier particles dropping out of the airstream. This gives rise to a locational variation in the size distribution of the dust. Also, a variation in the elemental composition occurs as a function of size.

SCOPE OF THE WORK.

The research performed for this project was designed to investigate the differences in coal mine dust characteristics within a mine and from mines located in various seams throughout the major coal producing regions of the United States.

Because the ultimate objective of the research is to contribute to the identification of coal mine dust characteristics that may play a role in the development of CWP, a sampling strategy was designed to give a good representation of the dust variation in a working section. Further laboratory work was dedicated to choosing dust sampling equipment such as multi-stage cascade impactors and selecting the best impaction medium and proper sampling times for the instruments. Additionally, a modified Hardgrove grindability test was developed to produce a laboratory-generated respirable dust.

The sampling procedures were first tested in the laboratory using an Elpram Systems aerosol chamber to determine the optimal sampling times for the range of mass concentrations that are normally encountered in an underground coal mine. In addition, channel sampling procedures were developed that would enable the research team to relate the coal in place to the airborne coal dust. The procedures were then applied to samples taken at 20 mines across the country.

Because the project was oriented toward the chemical, mineralogical and physical characteristics of the dust, procedures had to be developed to determine these basic properties. To determine the elemental compositions of the dusts sampled the Proton-Induced X-Ray Emission (PIXE) Spectroscopy method was chosen. This procedure can be used to perform a simultaneous multi-element analysis of minute quantities of coal dust nondestructively. This allows dust samples to be analyzed further for other characteristics by other methods or archived for future studies.

The mineralogy of the samples was performed in part by the P-7 method. The particle-by-particle method of determining mineralogy on a scanning electron microscope (SEM) was also considered but was not used primarily due to the lack of accuracy of the mineral determination on particles of less than 2 µm in size. The SEM will be used, however, to determine the shape characteristics of the particles in various size ranges from 1 to 5 µm.

EXPERIMENTAL RESULTS AND CONCLUSIONS

To date, the project has reached the results and conclusions stage in a number of different areas. A great deal of analysis has been accomplished in the area of elemental composition and size analysis of airborne dusts. In this area of endeavor, a sampling plan similar to that in Figure 1 was followed. Based upon the results of analysis of the elemental and size data in seven Pennsylvania mines, the following conclusions were made:

(1) variation in the elemental composition of coal with rank is significant;
(2) size variation is obviously a function of location in the mining section, particularly downwind of the continuous miner;

(3) elemental composition of the airborne coal mine dusts vary significantly with location;
(4) intake air often contains abnormal percentages of such elements as Ca and Cl;
(5) significant amounts of dust appear to be reentrained along with shuttle car paths;
(6) dust particles in the respirable size range are likely to be transported through the working area;
(7) the coal seam appears to be the primary source of the major elements in the airborne coal mine dust; and
(8) no consistent source appears to exist for the trace elements in the airborne coal dust.

Additional work was completed to develop a technique to determine the quantity of respirable dust that a coal seam will produce when subjected to size reduction under standardized conditions. The technique that was developed is based on the test used to determine a coal's Hardgrove Grindability Index (HGI). An equation relating Hardgrove Grindability Index to respirable dust quantity was obtained after 25 coal samples from Pennsylvania seams were crushed in a ball-and-race mill and analyzed in a Microtrac Particle Size Analyzer. The results of this study, summarized in Figure 2, suggest that there is a definite statistical relationship between the HGI of a coal and the quantity of dust generated when the coal is mined and that higher dust concentrations will normally be generated in "softer" coals.

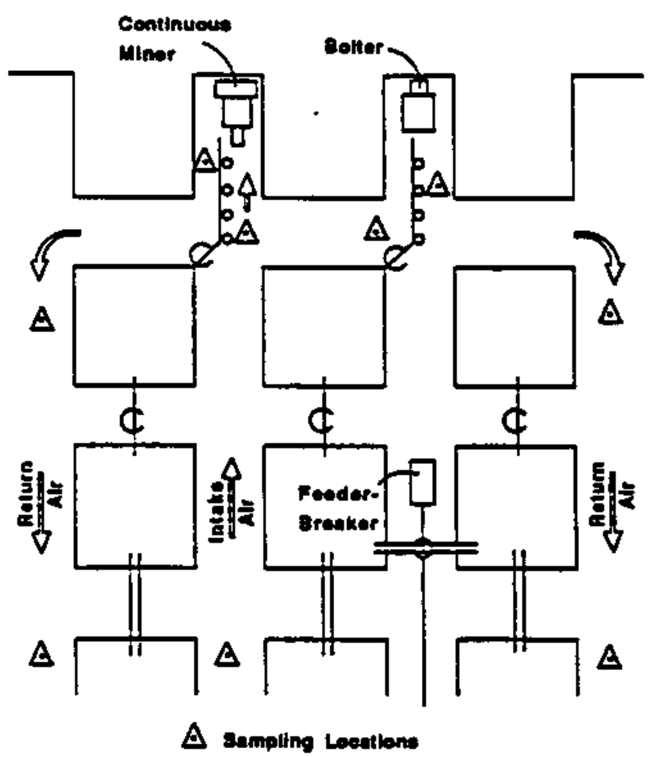


Figure 1. General layout of the samplers in a typical continuous miner section.

The comparison between the elemental composition of dust in the immediate ventilation return of a continuous miner and the laboratory dust generated from the same coal has been successful. Presented in Figure 3 are the results from the analysis performed on the element lead, one of 32 elements analyzed. This shows that it may be possible to predict the content of a mine's elemental composition in the

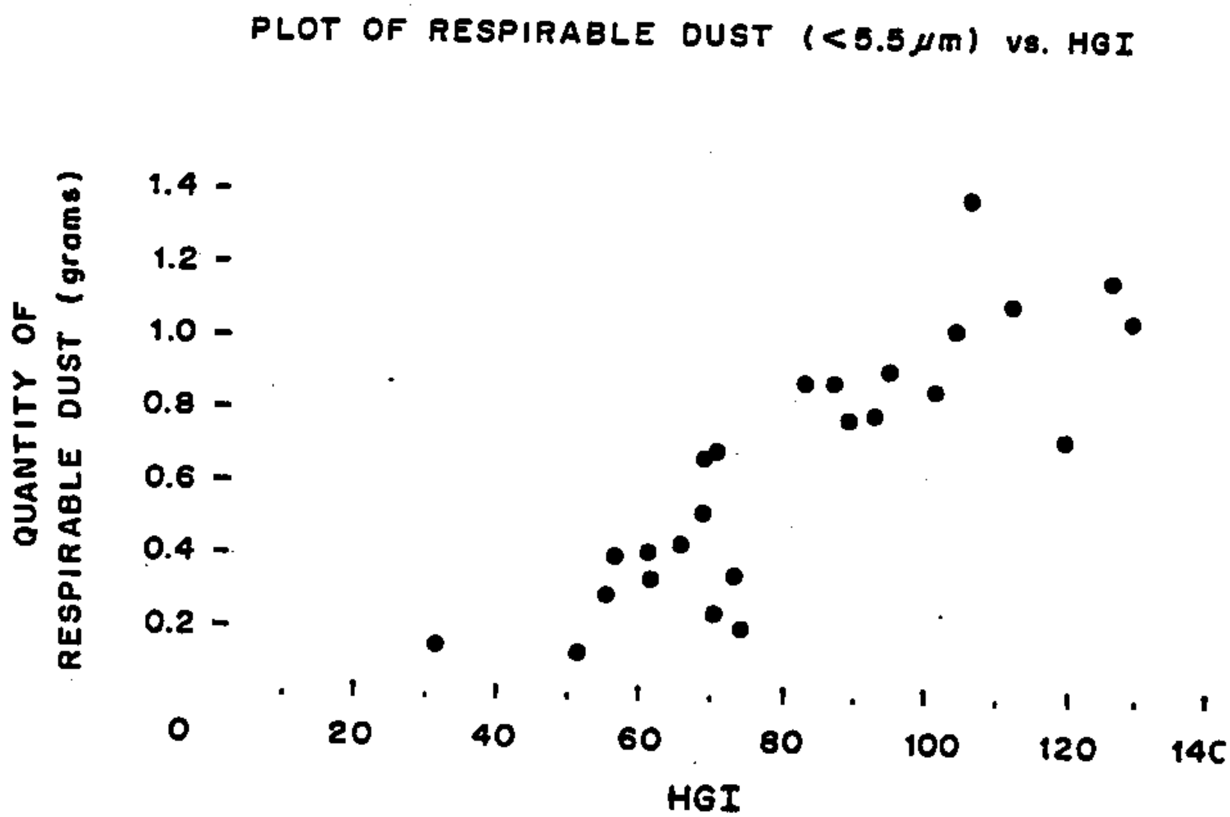


Figure 2. Plot of dust less than 5.5 microns generated versus the Hardgrove Grindability Index.

immediate ventilation return. As can be seen, the lead content varies from the impactor stages 3, 5 and 7 (10, 3.5, and 0.9 µm, respectively) and from mine to mine. Thus, if a new mine is being planned, hazardous elements contained in the coal and rock may be identified and subsequent pre-mine planning may prevent the exposure of underground personnel to these potentially dangerous elements. Also, remedial measures may be taken to improve conditions in currently producing mines.

APPLICATIONS TO REDUCE THE INCIDENCE AND SEVERITY OF CWP

By knowing the size and locational variations of the elemental composition of mine dust, efforts can be exerted to implement special dust control techniques to remedy the situation. For example, if the roof bolting operation and intake air dust are significant sources for elements in airborne coal mine dust, more effort can be placed on dust control measures for those operations.

As mentioned earlier, knowing that a particular coal seam has the potential to produce more respirable-sized particles can lead to using improved technology to more comprehensively control the airborne particles by methods such as spray fans, flooded-bed scrubbers, use of surfactants in water spray systems, more frequent changes of cutting bits or any other method to reduce the amount of respirable dust released into the mine environment.

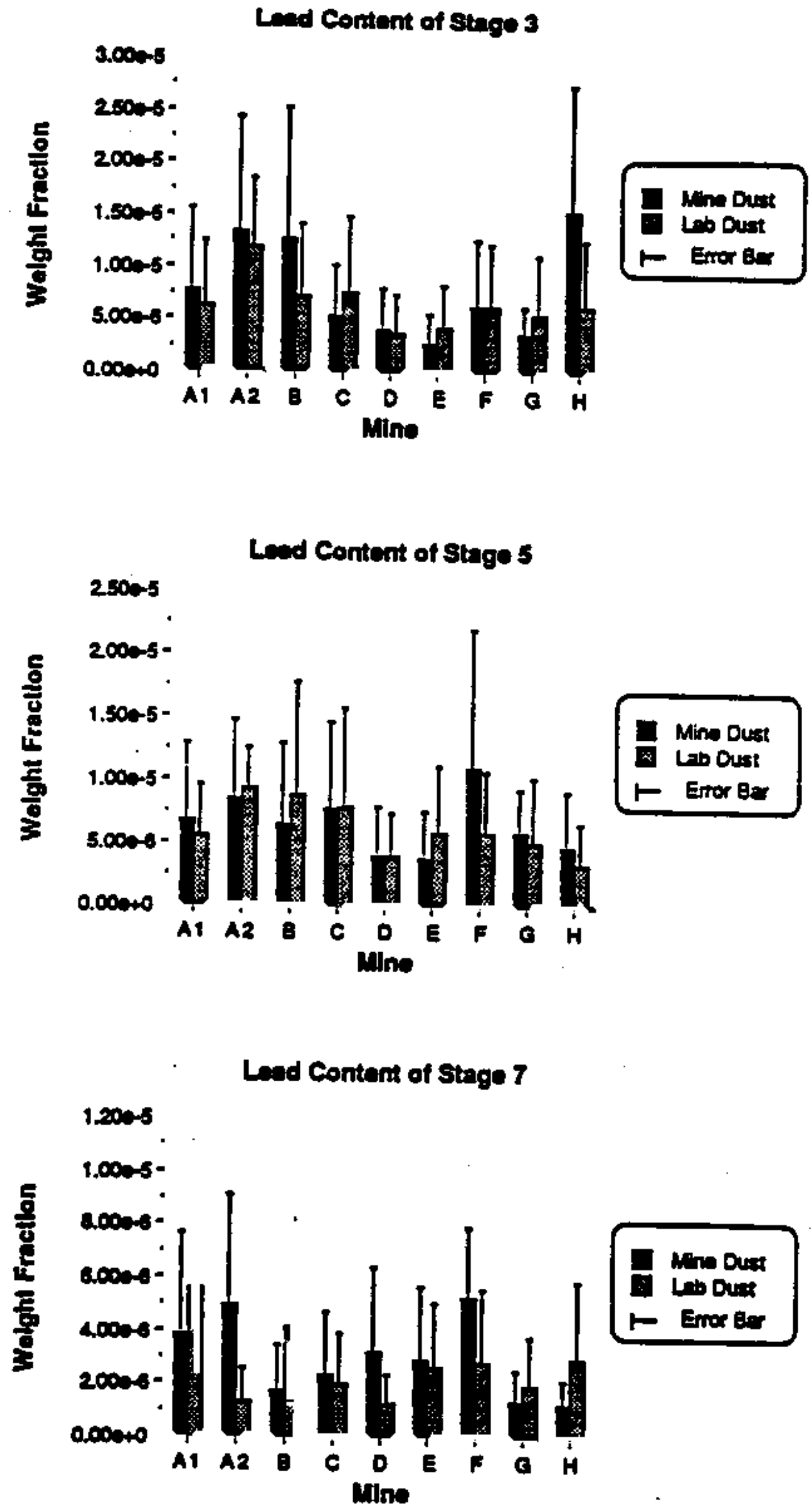


Figure 3. Comparison of lead content in coal mine dust and laboratory-generated dust.

Many people are concentrated in the area surrounding the continuous mining machine: the continuous mining machine operator, the continuous mining machine operator helper, shuttle car operators, mechanics, electricians and the section foremen. If dust rollback occurs, usually due to low air velocity, these people as well as any personnel who must pass through the immediate ventilation return produced at the working face may be exposed to dust. Thus, being able to predict the elemental composition of a potentially dusty, congested area of a mine is valuable. If exploratory core samples of the coal property are used to generate the laboratory-produced respirable dust, potentially hazardous elements in the coal seam can be identified, and proper pre-mine planning can assure that workers are not exposed to potentially hazardous elements. This would reduce the risk of developing CWP.

FUTURE STUDIES

Several major areas of research remain to be completed on this project. These include analysis of the mineralogical and physical characteristics of the airborne coal mine dusts. The quartz and kaolinite contents of the dust have already been determined by the P-7 method on three size ranges of the samples taken. Previous work on only four mines has indicated that the quartz is concentrated in airborne dust compared to that in the coal seam and that the finer sizes of dust have higher concentrations of dust. It will be our goal to verify these trends for a much wider sampling of coal mines.

The second major area of investigation that remains is the analysis of dust particle shape and the relationship between this variable and the occurrences of CWP. This work will be performed by SEM methods with computer-controlled physical measurements of the respirable dust particles. Work will then proceed toward analyzing the impact of particle shape on the incidence of disease.

Finally, a more comprehensive relationship between the chemical, mineralogical and physical properties of coal mines dusts and the seam-by-seam incidences of CWP will be investigated. Gathering of the dust data is continuing and will be complete soon. Epidemiological data is currently being gathered and the data, as comprehensive as possible, will be gathered from NIOSH files. The combined file will then be investigated to relate the coal variables with the disease occurrences.

TECHNOLOGY TRANSFER

To date, the project has provided technical communication primarily through theses and technical publications. A list of the completed materials available is as follows:

(1) two M.S. theses,
(2) one Ph.D. thesis,
(3) eight technical papers, and
(4) one NTIS report.

In addition, two more M.S. theses have been outlined for completion in the future. Several additional areas such as the mineralogy and particle shape variables have yet to be written into technical publications. These publications are forthcoming and will be produced in the near future.

PSU14/USBM 4222/5422/2722

Formulation, Evaluation and Verification of Improved Dust Sampling and Analytical Strategies for Use at Surface and Underground Coal Mines

Mutmansky, J. M.; Li, J.

INTRODUCTION

The primary thrust of this project is to research the areas of sampling and analysis technology for use in the sampling and characterization of respirable coal mine dusts. The primary need for sampling and analysis methods comes from the fact that compliance sampling provides a small sample that is unsegregated in size. Such a sample is often not suitable for research work and attempts at providing larger samples are often frustrated by permissibility and other constraints. Within the Generic Technology Center on Respirable Dust, a variety of projects that deal with sampling strategies and analytical methods have increased the knowledge in these areas. Using this knowledge and that of researchers outside the Generic Technology Center, the project personnel will suggest methods of extending the usefulness of sampling and analytical methods for better characterization and use of respirable dust for medical and engineering research purposes.

While emphasizing the sampling and analytical needs, other auxiliary problems will also be pursued. In particular, proper methods of producing, storing and utilizing respirable dusts for research purposes and the effects of other particulates in the mine environment will be considered as part of the research effort. To date, considerable progress has been made in analyzing the production and storage problems of manufactured respirable dusts and work continues on the characteristics of the dust. Particulates like silica and diesel soot are also being considered. The sampling problems that each of these particulates present will be considered as part of the overall research problem.

RATIONALE

Much of the dust research performed in the Generic Mineral Technology Center on Respirable Dust and in research groups throughout the world has been oriented toward the origin, transport and characteristics of respirable coal mine dust. A number of significant sampling and characterization problems exist that tend to limit the characterization activities. This problem is even more acute when permissibility requirements are considered as these requirements further limit the ability to sample the mine environment by adding constraints on the sizes of pumps used for sampling purposed. As a result, proper samples for a variety of analytical procedures are difficult or impossible to obtain. This project is formulating the necessary strategies that will overcome these shortcomings.

Much of this study is oriented toward gathering information from other engineering, medical, industry and government groups involved in related activities associates with respirable dust. The dust sampling and gathering activities of a variety of technical personnel must be analyzed and addressed in a systematic fashion. It is apparent at present that there are a number of important issues that need to be addressed including production and storage of synthesized respirable dusts and the existence of other particulates in the mine environment. These related problems will also be addressed by the project team.

SCOPE OF WORK

The primary goal of this project is to evaluate and assess the sampling and analytical procedures currently used in the coal mining and coal-related research areas to formulate, evaluate and verify improved dust sampling strategies. The major project tasks that have been delineated are as follows:

- Task 1: Evaluation of the data needs for scientific, engineering, medical, regulatory and other pertinent fields related to the problems of respirable coal mine dust.
- Task 2: Assessment of current sampling techniques, their statistical basis and their appropriateness for the specific data needs as defined in Task 1 above.
- Task 3: Review of current equipment used in the sampling and analysis of dust occurrences in both underground and surface mining.
- Task 4: Identification of unsatisfied date requirements, equipment needs, and need for improved analytical methods for R&D and regulatory purposes.
- Task 5: Development of standard procedures for the sampling and analysis of airborne coal mine dust in both underground and surface mines.
- Task 6: Validation of the sampling procedures through application and evaluation in mine environments.

Work on Tasks 1,2 and 3 is moving along toward its terminal stages with a report due out on these aspects of the problem at the end of the year. Task 4 will be completed before the end of the year while Tasks 5 and 6 will be part of the second year's research agenda. Major components of the research accomplished during the first year to date are outlined in the upcoming sections.

INTERACTION WITH EXTERNAL TECHNICAL PERSONNEL

A great deal of effort in the first half year of the project has been expended in gathering project team members together to meet with selected groups of outside technical personnel to gather information on sampling, analytical and related issues and, in particular, on areas where the current technology is deficient. Meetings have been held with personnel from NIOSH, the Bureau of Mines, MSHA, West Virginia

University Medical Center, Hershey Medical Center, the University of Minnesota and the South Dakota School Mines and Technology. The meetings have been very productive to date. Additional meetings have been scheduled with personnel from the EPA, Lovelace Research Institute and the University of Maryland over the next few months.

In the meetings held to date, a number important issues have been addressed. several of which have come up in more than one meeting. A general outline of the more significant topics is listed below:

(1) Sampling needs and concerns
 - (a) High-volume samplers are needed.
 - (b) Diesel particulate samplers and essential.
 - (c) Mini-RAM a problem, need a better portable dust concentration device.
 - (d) Dust sensor for mine-wide monitoring is lacking.

(2) Analytical needs
 - (a) Surface properties of particles need better definition.
 - (b) Effects of fresh versus stale dusts need more research.
 - (c) Effects of free radicals need to be better understood.
 - (d) Need to be able to analyze smaller dust masses or collect larger masses of dust.
 - (e) Need to be able to analytically isolate diesel particulate from mineral dust.

(3) Synergistic effects - need more understanding of the effects on CWP of
 - (a) diesel particulate
 - (b) silica
 - (c) smoking
 - (d) ozone
 - (e) oil mists
 - (f) and fibrous minerals and fiberglass

(4) Synthesizing respirable dust for research purposes
 - (a) Should study the relationships between "natural" and synthesized dusts.
 - (b) Need a detailed definition of fresh and stale dusts.
 - (c) Must have a well-characterized dust for medical research.
 - (d) Should have a detailed study of jet mill versus ball mill dusts.

Many of these suggestions are being followed up as they have significant ramifications on the sampling and analytical procedures that can be used in dust research. Some of these issues will be discussed again in upcoming sections.

PROJECT INTERNAL INVESTIGATIONS

To achieve the project goals in an expedient manner and to provide manageable topics for individual project team members, the individual project technological investigations were organized into subtopics and assigned to individuals on the project team. Each team members is thus pursuing a literature search, an analysis of technology in a specific area and an integration of that technology into the overall goals of the project. An outline of some of the topics being pursued and the activity in those areas follows.

Dust Sampling Strategies. The investigation into dust sampling strategies will include a general study of current technology for personal and area sampling as well as any specialized techniques. The general study has revealed a gap that exists between the sampling techniques that are used for compliance purposes and those used for research purposes. The primary difference is that the mass of dust required for research use may be an order of magnitude greater than that for compliance purposes. In addition, the dust is often split into many size ranges in some research investigations, compounding the problem of a minimum mass requirement.

To counteract these problems, sampling strategies that utilize pumps with relatively high volumes have been investigated. These pumps, if applicable under most sampling situations, will provide the capability of analyzing samples by methods that have been considered to be unuseable before. Of particular interest in the project to date has been the use of the x-ray diffraction method for determining the minerals present in an aerosol powder. The method is of particular interest due to the current difficulty in determining comprehensive mineral identifications on most aerosol samples. Thus it is important to extend our sampling capabilities through the use of improved sampling methods.

Dust Instruments. Dust collecting instruments and related hardware are not a primary province of this research project. However, because of needs that appear in dust sampling and the critical association between sampling and analysis, the development of dust sampling and other specialized dust instruments are of importance in the investigations of this research team. As a result, the team has provided input in other projects where dust instruments are being developed for use in aerosol research by personnel at the University of Minnesota.

The first instrument of interest is a impinger - type sampler that utilizes an animal lung surfactant medium for dust collection. This sampler utilizes a 1.0 lpm flow through a redesigned midget impinger and collects the entire size range of respirable dust. The advantage of such an instrument is the fact that it permits the collection of a respirable dust sample right at the working face much as the human being collects dust. As a result, it appears to have application to critical medical research where the surface chemical properties are important and where a lung surfactant can preserve or stabilize those surface properties. Future work will be performed using dust samples gathered with this instrument to determine the effects on the surface properties after collection.

The second group of instruments that have ramifications within this project are samplers being developed to collect diesel particulate samples from a mine or other working atmosphere where diesels are being utilized. Two classes of instruments are being developed, a personal diesel exhaust monitor and a diesel area sampler. The personal sampler is being developed in 4.0 lpm and 2.0 lpm versions. The devices use cyclone and impactor technology to collect a aerosol which is minus 0.8 µm in aerodynamic diameter. In addition, an area sampling;ing instrument which samples diesel particulate matter is also being studied. These instruments are important here because of the current level of interest in industry and government in the level and effects of diesel particulate on CWP and other health problems.

Analytical Methods. A major emphasis has been placed on this area of investigation in the project. This is an area of technology that keeps advancing due to the widespread demand for methods of analysis throughout the sciences and engineering. Due to the nature of this project, however, more emphasis has been placed on those techniques that pertain to mineral content analysis and characterization of the physical properties of coal mine dusts. Several different types of work are progressing. First, a general gathering of data on a variety of analytical procedures has been gathered. About 36 individual analysis procedures have been identified. Twenty of these have been initially singled out as having potential for usefulness in coal dust analysis. These are as follows:

(1) AAS - Atomic Absorption Spectroscopy
(2) AES - Auger Electron Spectroscopy
(3) DTA - Differential Thermal Analysis
(4) EDX - Energy-Dispersive X-ray Spectrometer
(5) ESCA - Electron Spectroscopy for Chemical Analysis
(6) FT-IR - Fourier-Transform Infrared Spectroscopy
(7) ICP - Inductively Coupled Plasma
(8) IR - Infrared Spectroscopy
(9) ISS - Ion-Scattering Spectroscopy
(10) NAA - Neutron Activation Analysis
(11) PESA - Proton-Elastic Scattering Analysis
(12) PIXE - Proton-Induced X-ray Emission Spectroscopy
(13) RS - Raman Spectroscopy
(14) SEM - Scanning Electron Microscope
(15) SIMS - Secondary Ion Mass Spectroscopy
(16) SSMS - Spark-Source Mass Spectroscopy
(17) TGA - Thermo-Gravimetric Analysis
(18) XPS - X-ray Photoelectron Spectroscopy
(19) XRD - X-ray Diffraction
(20) XRF - X-ray Fluorescence

To date, detailed information on the XRD, PIXE, RA, NAA, SEM and XRF techniques have been gathered. The other analysis techniques are currently being researched.

In addition, specific work under other project funding is ongoing at West Virginia University and at Penn State University into use of an SEM for mineral identification and for particle physical characterization. This is an ongoing effort of general interest in the Generic Mineral Technology Center on Respirable Dust. The primary interests have been centered around identification of minerals on a particle-by-particle basis and the study of particle shapes. In both cases, it is desired to automate the analysis procedure. Because of the general applicability of this method, several project personnel are monitoring the progress in this area.

Supply of Research Dusts. The production of synthesized respirable dusts has become a topic of interest in the Generic Technology Center because of the laboratory need for dusts that are fresh and still retain the properties of in-mine respirable dusts. In addition, it has become of general interest to define fresh versus stale dust for general use in medical and other laboratory experiments. This was accomplished with the help of Dr. Dalal of West Virginia University.

A second major consideration in supplying dusts is the method of producing dusts so that they are as "natural" as possible. A variety of procedures for supplying dusts has been studied:

(1) in-mine recovery of dust using a mine auxiliary fan as a collection system,
(2) in-mine recovery of dust using a surfactant medium,
(3) production of dust in a laboratory using a jet mill, and
(4) production of dust in a laboratory using a ball mill.

To evaluate these alternatives, a comparison will be made by project personnel of the shape characteristics of respirable-size dusts produced from a single coal face by continuous miner, by a jet mill and by a ball mill. Using this as a basic decision variable and considering the other advantages and disadvantages of the different alternatives, the project personnel will make some recommendations to the Generic Mineral Technology Center for Respirable Dust concerning methods for obtaining dust samples for use in laboratory dust research.

Finally, the research team has been investigating methods of storing and distributing coal dusts of respirable size to retain their "freshness" variables for medical and other laboratory tests. The sample production and storage methods of the Penn State Coal Sample Bank have been reviewed and will be considered further when making recommendations to the Center on production, storage and distribution of research dusts.

PROJECT ACCOMPLISHMENTS

At the time of this report, this project is only a little over a half year old and thus major conclusions and recommendations have not yet been formed. However, several important problems and areas where technological improvement is needed have been identified. The major issues and problems that have been targeted within the project are as follows:

(1) There is a strong need for larger sample sizes from scientific dust instruments or analytical techniques that require smaller samples (or both) to extend the usefulness of current sampling techniques.
(2) There is a need to keep synergistic effects in mind in sampling programs. In particular, the effects of silica and diesel particulate are of extreme importance in the thinking of many health and dust specialists.
(3) There is a strong need for a protocol on production, storage and use of coal mine respirable dusts for medical and other laboratory research efforts.

All of these needs are currently being researched by project personnel along with the other general issues addressed in the original proposal. The first need, that of the overlap of sampling and analytical technology, is one of the primary emphases of the project and occupies a significant amount of time on the project because of its importance. Project efforts have been concentrated on looking at improved methods of determining mineral content of dusts on a bulk particle sample or on a particle-by-particle basis. In addition, because the current technology on the bulk particle method requires a rather heavy loading of a filter, methods have been studied for increasing sample masses as well.

The synergistic effects of other aerosols in the coal mine environment is a topic that has arisen in a variety of meetings with the external research groups. Both silica and diesel particulate matter have been mentioned by several groups as being important considerations. While these concerns are peripheral to the primary goals of this project, they are very important as individual topics themselves and also as variables that affect sampling and analysis directly. Thus project personnel are considering the ramifications of these aerosols as a component of the project work.

Finally, the area where the most definitive action has been taken to date has been the area of production, storage and use of respirable dust in research. The project team has worked toward standard procedures for preparing fresh versus stale dust, is studying characteristics of respirable-size dusts produced in the laboratory and is attempting to identify storage methods applicable to respirable dust batches held for research purposes.

CONTINUING WORK

The research outlined for the first year of this project was general in nature with the goals being to perform a comprehensive review of current technology and to assess the needs that exist. Much of this work has been accomplished to date with data needs, sampling techniques and analytical methods being the primary foci of the study. A summary of the findings of this year will be presented in the annual report on the project that will be prepared by October.

The research plan for next year will be concerned with more specific aspects of the technology needs. A meeting of the project team will be held on August 22 with our Technical Project Liaison Officer, Mr. Ken Williams of the Bureau of Mines, to plan our strategy. It is anticipated that the work will center on sampling methodology with as many related topics being studied as are necessary to accomplish our basic goals of providing for sampling and analytical methods for use in respirable dust research.

TECHNOLOGY TRANSFER

During the initial stages of this project, the technology transfer has been primarily from external research organizations to the project team and from other project researchers in the Generic Mineral Technology Center on Respirable Dust to the research team. This has progressed as planned. However, communication between the various projects has increased as a result of this project. The first major effort at technology transfer will be the annual report for the project, due out this fall.

During the upcoming year, it is anticipated that external communications from the project team will increase as the project begins to reach conclusions and make recommendations. At that time, technical papers on dust sampling and analytical methods, synthesis and storage of lab-produced dusts, and use of dusts in research activities will be produced.

WV3/USBM 5043

Measurements and Construction of Dust Distribution Maps for Longwall Faces

Peng, S. S.; Chiang, H. S.

INTRODUCTION

The objective of this project is to construct dust generation/distribution maps for longwall faces under various geological and mining conditions. Specifically, in order to effectiveiy improve dust control technique in the longwall face area, it is necessary to know the dust generation and distribution mechanisms. This project was designed to include the following topics:

1. Field instrumentations of airborne dust concentration distribution and airflow distribution in the longwall face area;

2. Construction of the airborne dust distribution maps, the airflow distribution maps for each surveyed panel;

3. Based on the analyses of the field works, develop the statistical models for predicting the airborne dust distribution and airflow distribution in longwall faces.

RATIONAL

The shearer operation and the support advance are the two major airborne dust sources in the longwall faces. The airborne dust distribution is mainly governed by the velocity and the movement pattern of the airflow in the longwall face area. Due to the complicated time-dependent mining and geological conditions in the face area the airflow distribution is different from mine to mine and face to face. The continuous movement of shearer operation and support advance in a longwall face causes complex ventilation and airborne dust distributions In addition, support advance also causes air leakage to the gob. Moreover, the transportation and diffusion of the dust-laden air depend on the size of dust particulate and its distribution along the travelling way of the dust-laden air. Though dust particles with sizes less than 10 microns could be inhaled, the real destructive portion of the dust is from 1 to 5 microns because only those particles can reach the lungs and be retained there. Those with an equivalent diameter larger than 5 microns will settle on the membranes of the bronchial tubes while those with diameter less than 1 micron can either be exhaled from the lungs or the settled quantity is so insignificant that it does very little harm to the lungs. In the transportation process, the finer dust will be carried farther away from the source than the coarser ones before settled down. Thus once the fine dust is generated and become airborne, it will spread out to a large area.

It is important, from the view point of airborne dust control, to be able to predict the dust distribution (both dust concentration and size distribution) in the longwall face area, given the characteristics of the dust sources and the ventilation conditions, the field measurements and the statistical modeling were proposed.

INSTRUMENTATION

Underground dust instrumentation was carried out in five longwall faces in four different coal seams. 7,650 measurements using GCA RAMs and 360 respirable dust samples using gravimetric samplers by both mobile and stationary methods were obtained. The analyses of the four highly productive longwall panels showed that, among a total of 3,077 RAM readings, 65% had dust concentrations less than 2 mg/m^3, 15% between 2 to 3 mg/m^3, and 20% greater than 3 mg/m^3 . Furthermore, the studies condusted under this project also showed that the shearer operation and the support advance are the two major dust sources, and that the distributions of the airflow velocity in the face area control the distributions of airborne dust. However, within a certain range of the shearer or advancing support, the distribution of the airborne dust concentration changes constantly.

The amount of airborne dust generated by the support advance depends on the immediate roof conditions and varies with the support advancing operation (i.e., leg lowering, support advancing, and leg rising). Under the combined influence of shearer operation and support advancing, the airborne dust concentration along the walkway was usually twice as high as when only the shearer was cutting or cleaning. In addition, the instantaneous readings with RAMs showed that during coal sloughing, the airborne dust concentration increased rapidly from 5 to 12 mg/m^3. Although it appeared for only a short time, the dusty air moved directly toward the shearer because coal sloughing was severe during shearer cutting and cleaning.

The airborne dust distribution maps are shown as Figs. 1--9.

When the shearer is cutting upwind, the dust concentration at the leading operator is higher. It decreases continuously on the downwind side (even at the rear operator's position) and reaches the lowest level at two support distance downwind from the rear drum. It then increases gradually away from the shearer.

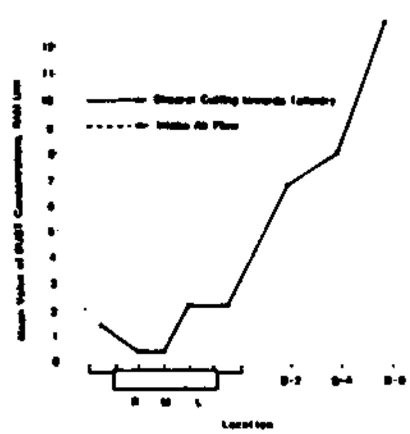


Figure 1. Dust distribution around the shearer.

When the shearer is cutting downwind, dust concentration increases rapidly on the downwind side beginning with the leading drum. Within the shearer, the lowest level occurres near the rear operator's position (approximately 50-60% lower than that around the leading operator's position). It increases on both directions, i.e. both toward the rear drum and leading drum.

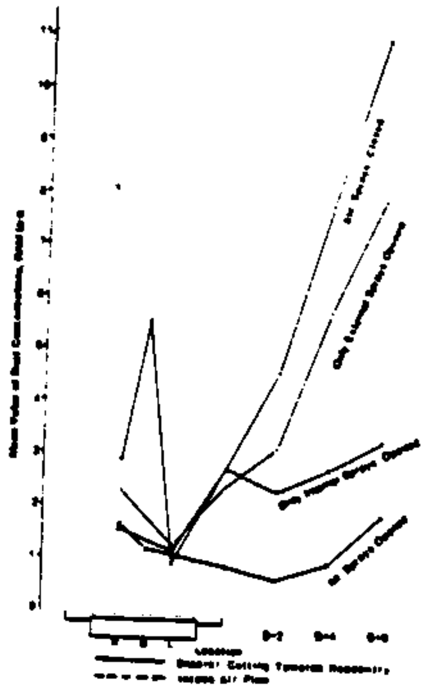


Figure 2. Dust distribution around the shearer.

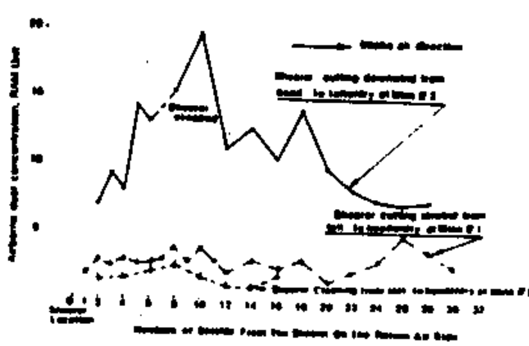


Figure 3. Dust distribution at various distance from the shearer.

After the low concentration area in the return side of the shearer, the dust concentration increased gradually until it reaches the highest level which is generally 2-3 times higher than that around the leading drum operator. Beyond that point, dust concentration decreases away from the shearer. The higher is the airborne dust concentration and the lower is the air velocity, the shorter is the distance between the point of the highest dust level and the shearer.

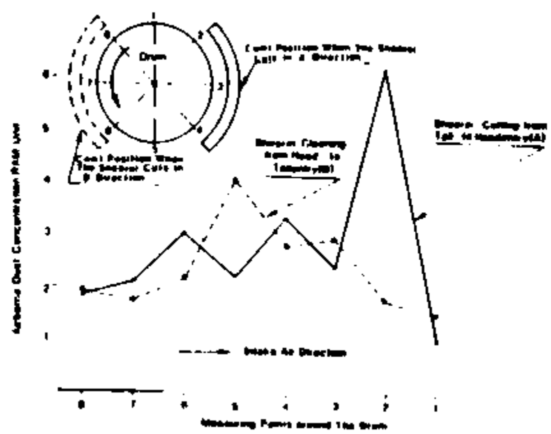


Figure 4. Dust distribution around the leading drum.

The higher dust concentration occurs near the top side of the leading drum during cutting while during the cleaning trip, the higher concentration always occurs near the bottom of the drum.

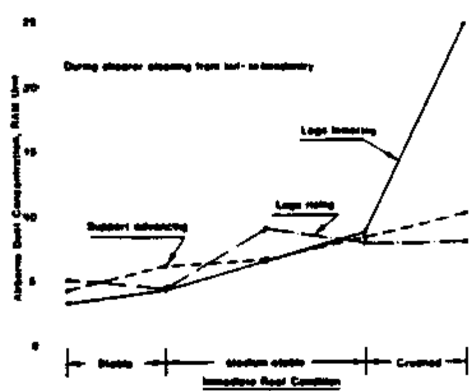


Figure 5. Dust concentration generated by support advance on the return air side.

The airborne dust concentration during support advance is rather high, sometimes up to 20-25 mg/m^3 under the crushed immediate roof. This is very signficant, even though its contribution to the dust generation is only for a short period of time.

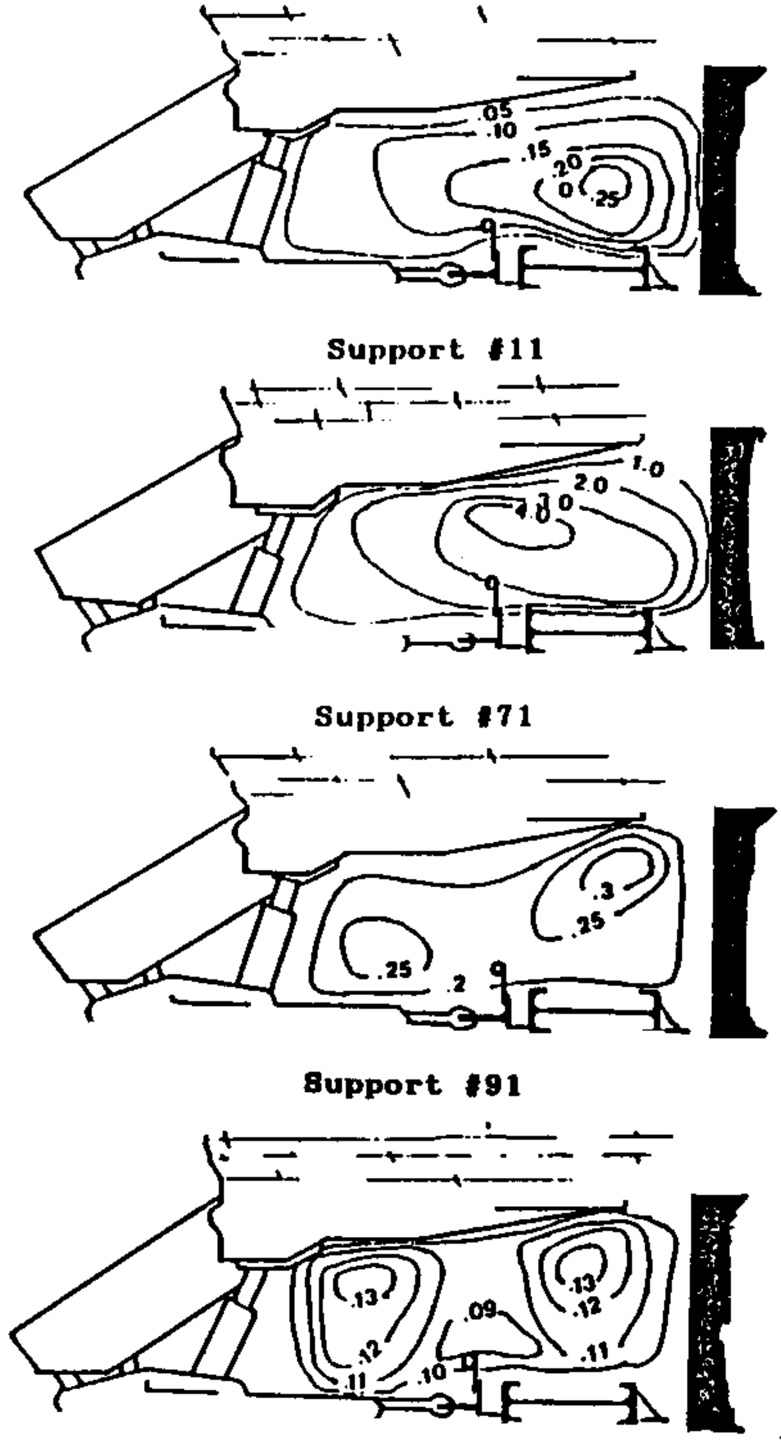


Figure 6. Actual dust concentration for various cross-sections along the longwall face.

The pattern of dust distribution with which the dust emanates from the shearer as the major dust source and the major influence zone of the shearer. The high dust concentration zones follow the panline of the AFC while the walkway is in the low concentration zone with dust level less than 2 mg/m^3 along most of the face except for that portion about 20 supports in and around the shearer.

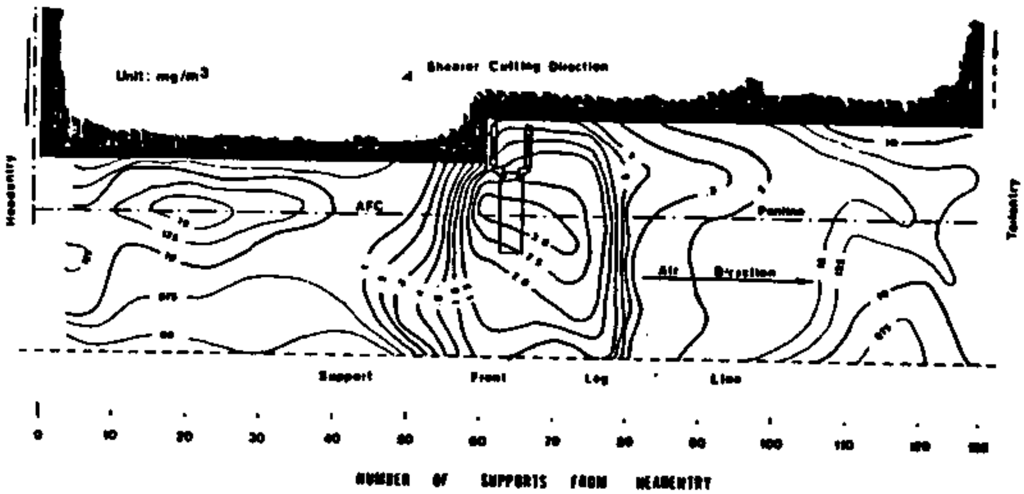
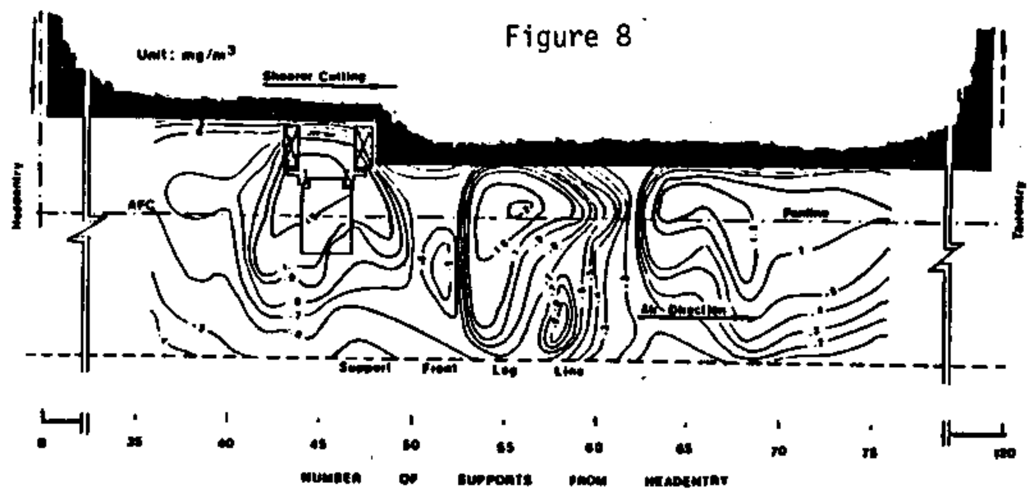
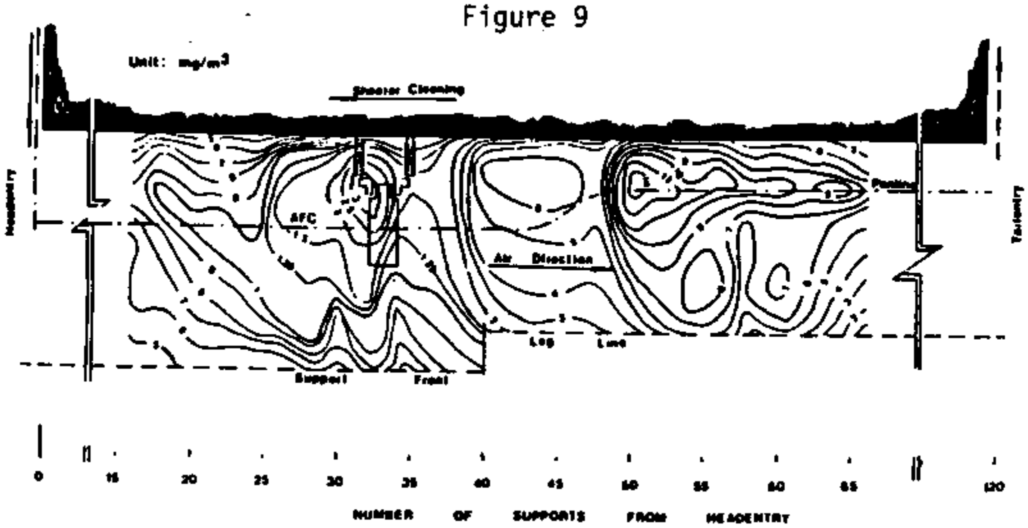


Figure 7. Dust distribution map on a horizontal plane approximately 3 feet above the floor.



Figures 8 and 9. Dust distribution on a horizontal plane where the crew breathe during shearer cutting and cleaning.

Figure 9



Both in the cutting and cleaning trips, the high dust concentration zones are located on the face side of the panline. During cutting, the dust concentration level on the walkway is well below the regulatory limit of 2 mg/m^3. During cleaning, although the dust level on the walkway is well above the limit after the 40th shield, the level on the intake air side of the shearer and within five-support distance behind the shearer on the return air side is still below the regulatory limit. This situation is very favorable to the shearer operators. If the trailing distance of the support advance is kept within five supports behind the shearer on the return side, the shieldmen are still exposed to airflow of lower dust concentration.

The dust samples collected from longwall faces were analyzed by the Coulter Counter's method. The results obtained showed that the size distribution curves, at any location along the face, skew heavily toward the fine dust range. The portion of fine dust (1 to 5 microns in size) is more than 70% of the total airborne dust.

Field studies also identified the two major factors that greatly affect the air velocity distribution and the airborne dust distribution: (1) changes in the cross-sectional area, and (2) water sprays mounted on the shearer.

Changes in the cross-sectional area. The continuous movement of the shearer followed by the advancing supports significantly changes the cross-sectional area for the ventilation. This in turn contributes to the change in the air velocity and its distribution. As a result, the airflow redistributes constantly near the shearer and advancing supports. In addition, the support advance also causes air leakage to the gob. For these reasons, in the area close to the shearer and the advancing supports, the distributions of airflow and, consequently, the airborne dust become very complicated. Their distributions vary with the location along the face. It would be interesting to study the dynamic airflow pattern and its controlling factors in detail so that proper operational procedures can be developed to control the airflow distribution. In particular, the optimal distance between the advancing supports and the shearer should be studied.

Water sprays. The water sprays mounted on the shearer not only suppress the airborne dust but also redirect the airflow pattern. Once the water spray on the shearer is completely turned off during cutting, the dust concentration increases suddenly. Fig. 2 shows the effectiveness of the water spraying in four different situations. However, the effects of water sprays on the distribution of the airflow at and near the shearer have not been studied in detail.

DEVELOPMENT OF COMPUTER MODELS

A computer model was developed to plot the airborne dust distribution maps. In addition, the statistical models for each surveyed panel were also developed for prediction of airflow distribution in the longwall face area. Due to the complicated time-dependent mining and geological conditions in the face area, the relationship between the airflow and airborne dust distributions could not be established within the two year project period.

CONCLUSIONS

The field measurements showed that about one-third of the measurements exceeded 2 mg/m^3 limit. Shearer operation and support advance are the two major dust sources and also the major factors for airflow and airborne dust distributions. The airborne dust distribution maps show that there exist some positions with repect to the shearer where the dust exposure to the shearer operators and the shieldmen is the lowest. This will be the ideal location for shearer operators and shieldmen. According to the analyses of numerous dust samples obtained at the intake and return sides of the shearer, the quartz content in each dust sample was mainly generated by the support advance, instead of the shearer operation as normally perceived. At present, the most effective technique of airborne dust control is the water spray system mounted on the shearer. However, based on the studies in this project, controlling the airflow distribution will be beneficial to reduce the airborne dust exposure to the workers. A more in-depth study of airflow distribution is needed for better prediction of the dust distribution.

CONTINUING WORK

This project have been completed and continued by project USBM 5410/WV11 in 1986.

TECH TRANSFER

Two symposium papers, two published papers, two presentations and one thesis have resulted from this project. The continuing research in project USBM5410/WV11 is expected to result in one more paper from this study.

WV6/USBM 5406

Correlations of Respirable Dust Characteristics to Coal Seams, Worker Positions, and Mining Methods

Stobbe, T. J.; Plummer, R. W.; Grayson, R. L.; Pavlovic, A.; Andre, R.; Simonyi, T.; Kim, H. W.; Zhao, L. J.

INTRODUCTION

This research has been dedicated to finding the coal "rank factor(s)" that exist in the occurrence of coal workers' pneumoconiosis but have not yet been discovered. Since the biochemical mechanism of CWP occurs on a lung cell-dust particle level, it is hypothesized that dust particle analysis will eventually give the desired answers, which have been unattainable with bulk analysis techniques. The major emphasis has been placed on the characterization of mineral particles in the dust. This was done because the role of minerals, such as quartz and various clays, in disease development is contradictory at present.

The research on this project has been primarily directed toward achievement of the following specific objectives:

1. Develop a methodology for a size-based mineralogical characterization of respirable coal mine dusts on a particle-by-particle basis.
2. Define mineralogical and size fractional variations of mine dusts by worker location on a longwall panel and by coal seam.
3. Determine the relative purity of respirable mineral species, and especially quartz.
4. Investigate respirable-sized mineral particles for shape and angularity differences.
5. Determine correlations among respirable coal mine dust characteristics and worker locations, coal seams and mining methods.

The results presented here focus on characterizing properties of respirable coal mine dusts collected from longwall panels operating in West Virginia and Virginia. Longwall panels were selected for analysis because the respirable dust in the coal face areas is largely uncontaminated by rock dust and, hence, analysis of the dust yields results unconfounded by minerals existing in contaminants.

RATIONALE

The search for the cause or causes of coal workers' pneumoconiosis continues notwithstanding the vast amount of research that has been undertaken over the past thirty to forty years. Good correlations between the mass of dust inhaled over workers' lifetimes and incidence of the disease has led to development of effective environmental standards, we believe, and establishment of good procedures for control of dust generation and dispersion in the working place. Research has only begun, however, to uncover the mechanisms involved in initiating and perpetuating the disease.

Correlation between the rank of the coal seam in which miners worked and disease incidence is also high, but the agents in the higher rank seams which cause CWP are still unknown. We know the basic compositions of the coal seams, mineralogically and elementally on a bulk basis, but the way in which they interact with human pulmonary cells is still a mystery.

The process of disease development is a biochemical one which depends on characteristics of the pulmonary cells and their immediate environment and the characteristics of the invading respirable coal mine dust particles, probably both physical and chemical in nature. The cell-particle relationship must yet be defined, but, in order to do this, cells and particles must first be characterized according to properties that potentially are involved in disease development.

Following such characterization, specific respirable dusts from different coal seams, which appear to have different effects on coal workers, must be obtained or constructed, analyzed to ensure they possess the characteristics that are attributed to them, and used in experiments designed to determine dust toxicity or the response of animals exposed to the dusts.

Although a majority of studies on the role of quartz in CWP suggest a relationship does exist, some researchers have found contradictory evidence. A relationship between the amount of quartz existing in the respirable dust and disease incidence or progression is too simple to be meaningful and, it appears, not causative.

Interaction of quartz with other minerals may be a factor in reducing the influence of quartz in the disease process. One study showed that mineral matter in coal inhibited the fibrogenic effect of quartz on experimental rats, suggesting that the surface characteristics of quartz particles were modified, thereby reducing their fibrogenic response. Other studies suggested that mineral matter other than quartz may play a protective role. This project proposes that the reduction of the fibrogenic response of quartz occurs because of contamination of quartz particles rather than because of an interaction between other minerals (clays) and quartz on a bulk basis.

This project hypothesizes that quartz itself is generally not pure (i.e., found strictly as SiO_2) in coal seams and that the incidence of CWP varies according to the relative purity of quartz occurring in a coal seam. Thus quartz particles in higher rank coal seams, where higher incidences of CWP are proven, will be more pure than those found in lower rank coal seams.

Figure 1

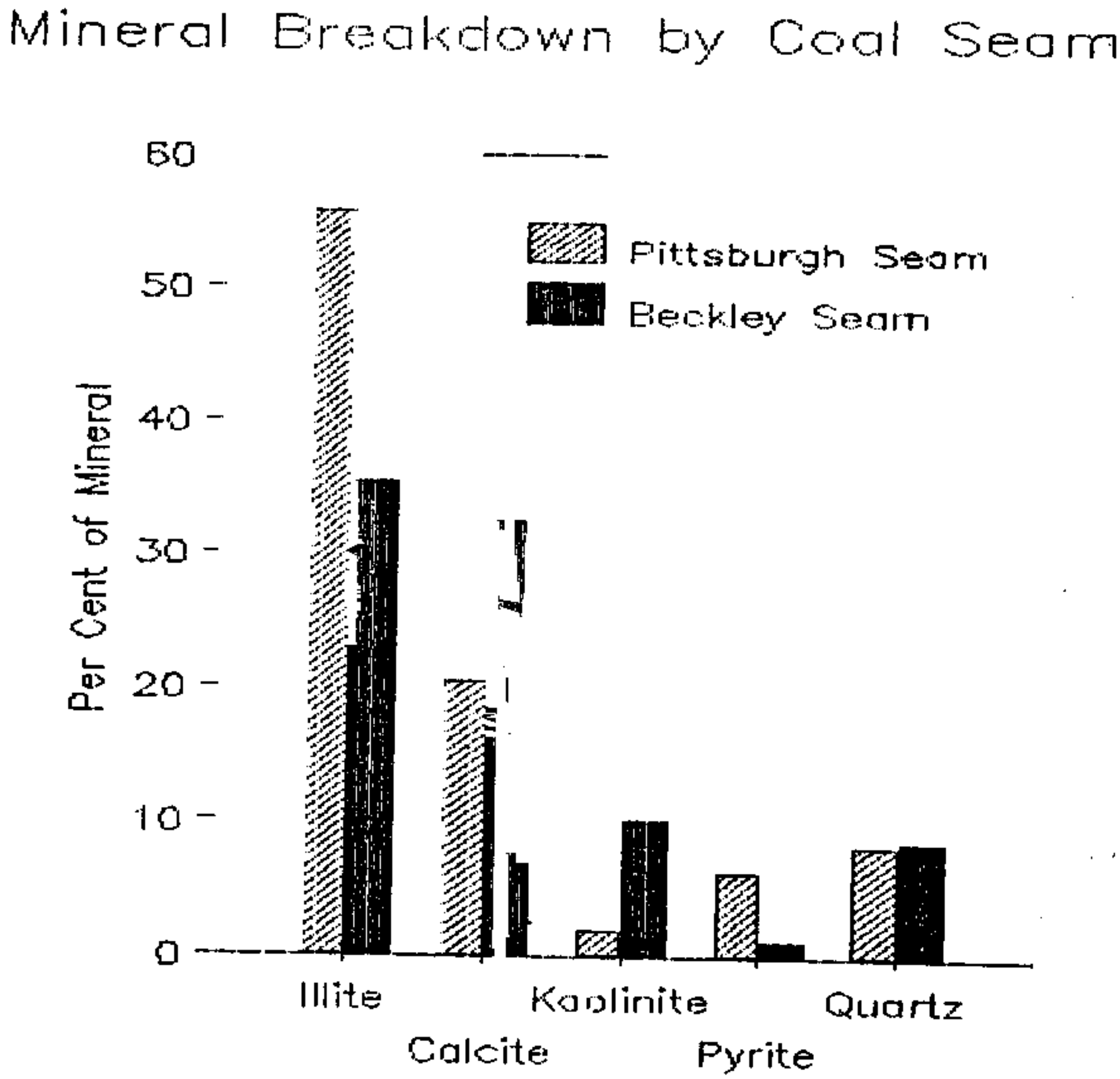


Figure 1. Mineral breakdown by coal seam.

SCOPE OF WORK

The research in this project was designed to determine correlations between respirable dust characteristics and worker locations on four different longwall panels, between respirable dust characteristics and four different coal seams, and between respirable dust characteristics and two different longwall mining methods (plow and shearer). Full shift, gravimetric, compliance samples were taken on each longwall panel at multiple locations and on multiple shifts to obtain the respirable dust to be analyzed.

Using the SEM/EDX technique, dust particles were sized, given shape and angularity index numbers, and analyzed for constituent elements, yielding their mineralogy. The procedure was very slow since it was done manually. Only one sample could be analyzed per week, giving characterization of 100 mineral particles out of approximately 1000 dust particles (mineral and coal). Now, however, a state-of-the-art SEM/EDX instrument has been obtained, and the procedure has been automated to a large degree. The respirable dust samples from two longwall panels will be analyzed using this new method, while obtaining the same characteristics for particles. Presently, both coal and mineral particles can be analyzed and our plans are to analyze 2000 particles per sample. Since three samples were obtained for each worker location, 6000 particles will be analyzed for each of seven or nine locations on the remaining two longwall panels.

Major accomplishments in the previous years include:

1. We developed a procedure for a size-based mineralogical characterization of respirable dust particles.
2. We demonstrated mineralogical and size fractional variations of respirable mine dusts by worker location on a longwall panel and by coal seam.
3. We demonstrated a major difference in the relative purity of respirable mineral particles by coal seam, revealing that the higher rank coal seam generated twice as many pure quartz particles.
4. We pinpointed the common elements that contaminate mineral particles in respirable coal mine dust.
5. We determined significant differences in the geometric mean size of different mineral particles generated on a longwall panel.
6. We determined that the shape and angularity of mineral particles do not vary significantly by worker location on a longwall panel or by coal seam.
7. We determined correlations among certain respirable dust characteristics and worker locations on a longwall panel.
8. We determined a CWP risk index for miners working in various West Virginia coal seams that increases with increasing rank of a coal seam.

Specific results for some of these accomplishments will be presented next as conclusions.

Figure 2

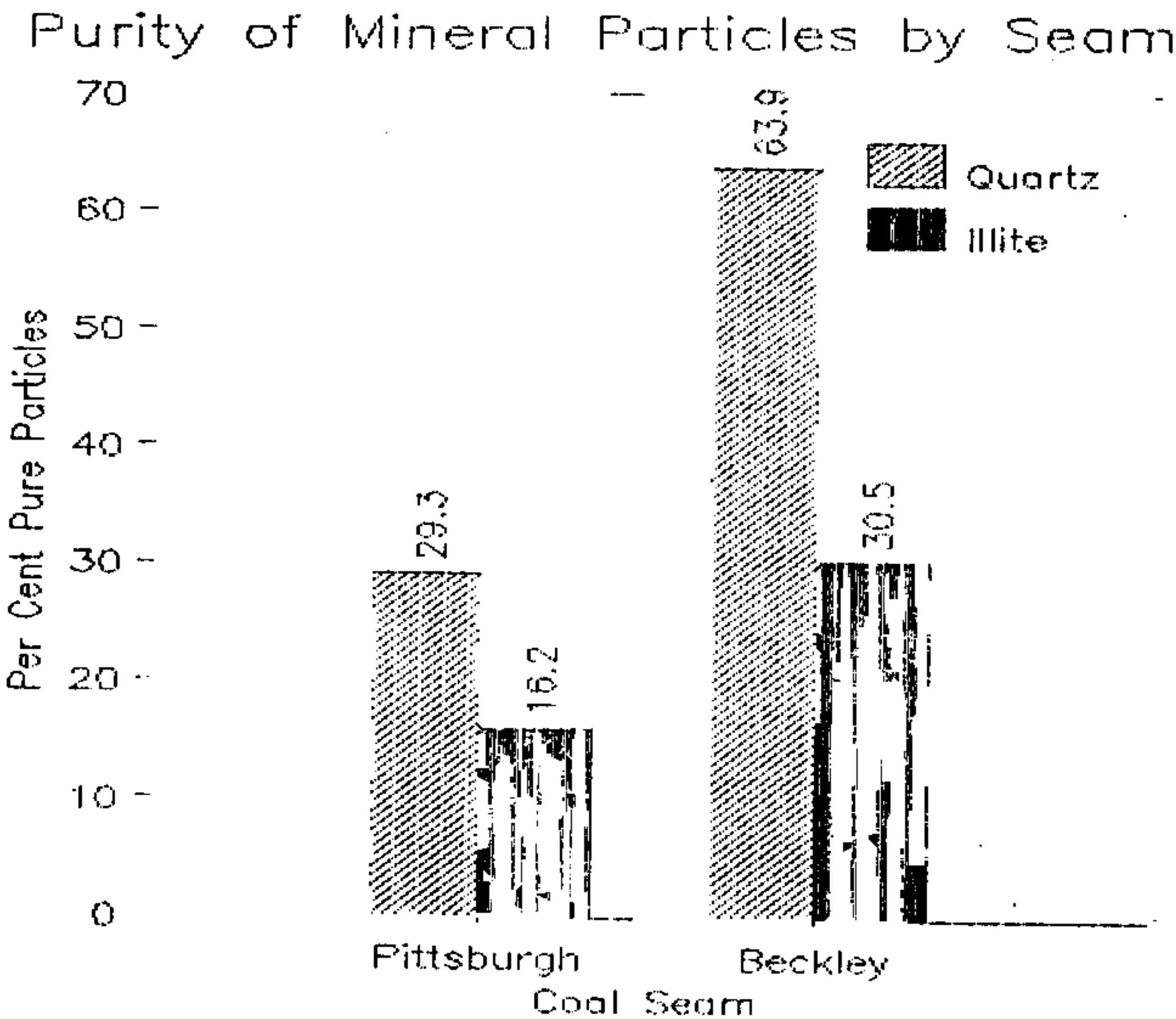


Figure 2. Purity of mineral particles by seam.

CONCLUSIONS

Figure 1 shows the variation of the mineralogy of dust particles by coal seam. The Beckley seam is a higher rank seam. The procedure used brings out the fact that illite and pyrite exist in a larger amount in the Pittsburgh seam while calcite and kaolinite dominate in the Beckley seam. The percentage of quartz was nearly the same for both seams. Variations such as these were detected by worker locations within a longwall panel (seam) as well.

Figure 2 reveals that both illite and quartz particles are nearly twice as pure (that is, contain only stoichiometric elements) in the higher rank Beckley seam than in the Pittsburgh seam. Of course, quartz particles are of special concern because of their toxicity. If they are not pure, then their toxicity may be greatly reduced.

Figure 3 shows the non-stoichiometric elements occurring in quartz particles in the Pittsburgh seam. The high frequency of aluminum and potassium indicate that inclusions of clay minerals (and especially of illite) are found in the quartz particles.

Size fractional breakdowns are also available, but will not be displayed here, to indicate that the per cent quartz decreases with particle size in the Pittsburgh seam while it hold fairly constant among size fractions in the Beckley seam. The purity of quartz particles holds nearly constant for all size fractions in both seams, albeit the per cent of pure particles differs significantly.

Table 1 gives the calculated CWP risk indices for miners working in different coal seams and the related ranks of the coal seams involved. These indices were calculated as the ratio of the per cent of HSAC "Dust Diseases of the Lung" cases occurring to miners within a seam (over the period 1980-1985) to the volume of coal mined in that seam over the past 25 years. A correlation of 0.85 was obtained between the risk index and the rank of the coal seam.

Some other significant correlations were obtained relating dust characteristics to worker location and some physical conditions existing on a longwall panel; for example, the angularity of dust particles decreases as the cutting speed of the shearer increases and the number of angular particles decrease as the number of particles smaller than one micrometer increase (i.e., smaller particles are less angular).

APPLICATIONS OF RESEARCH RESULTS

The results of this research can be used to determine which coal mine dusts should be used in animal exposure experiments and in toxicity tests. Also, before the experiments are run, the researcher should have a complete characterization of the dust to be used for exposing animals. Knowing the purity of quartz particles in the dust can give the researcher an idea of its potential fibrogencity, whereas knowing the per cent of quartz in the dust can not. The size distribution of the dust particles and the concentration of minerals within size fractions need to be duplicated to match the dust which would be generated under specific mining conditions. The results of this research can be used to determine how dusts to be used in experiments should be constructed.

CONTINUING WORK

Continuing work is focussed on analyzing coal particles as well as mineral particles. Possibly some relationship between the constituents of coal particles

Figure 3

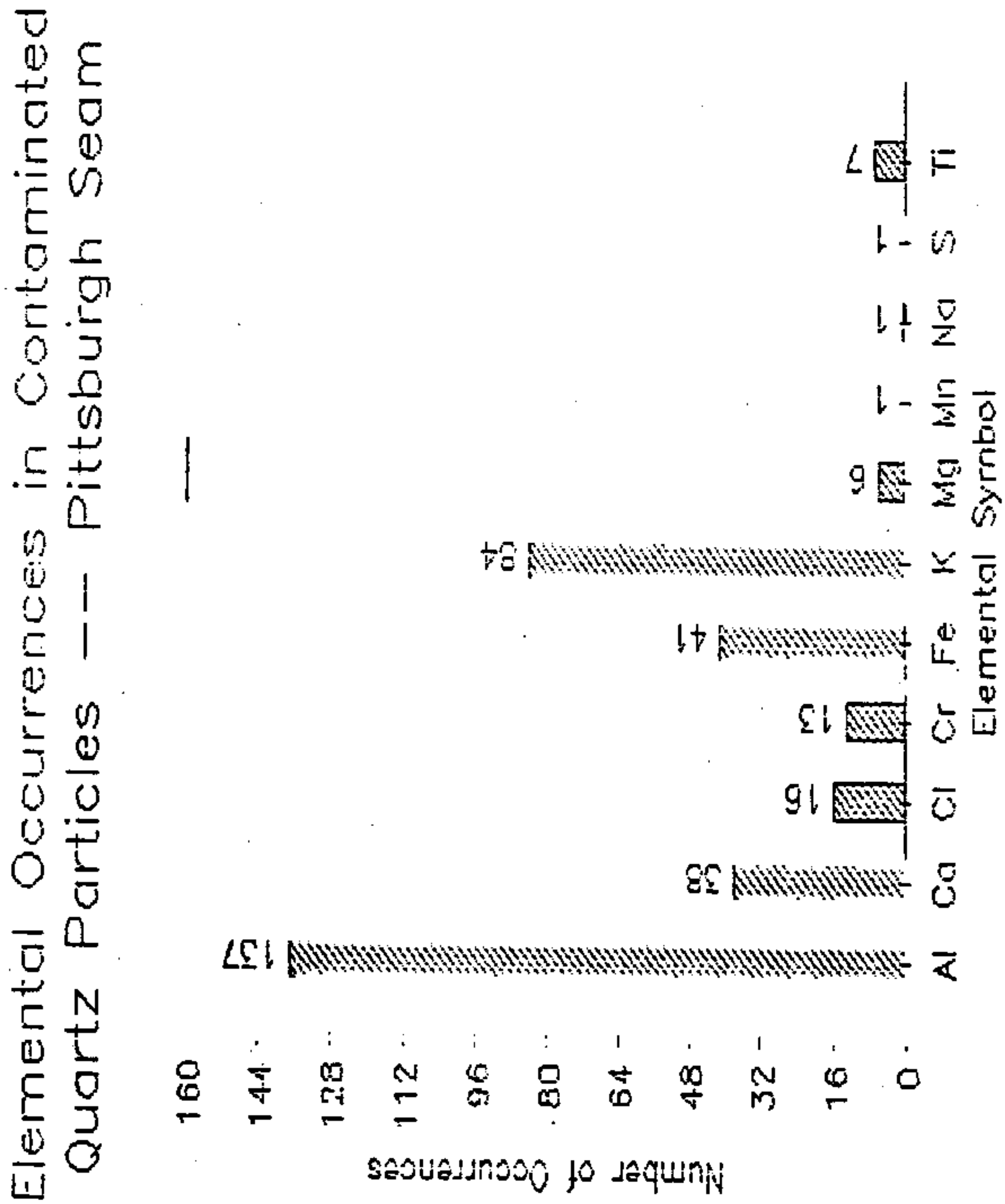


Figure 3. Elemental occurrences in contaminated quartz particles--Pittsburgh Seam.

and the rank of the host coal seam can be pinpointed. Also, accurate information is needed on the size distribution of coal particles versus the size distribution of mineral particles and the overall size distribution of coal mine dusts. The samples from the remaining two longwall panels will be analyzed in this way.

In the future, this methodology should be used to characterize the respirable dust from many more coal seams, including anthracite seams, to further test the hypothesis that the purity of quartz particles is related to the rank of the coal seam and plays a key role in the development of CWP.

TECH TRANSFER

Four publications have resulted from this work thus far. Two graduate students were supported during the course of this research, thus far resulting in one thesis. Numerous conversations with personnel interested in this approach have occurred. Interestingly, researchers in West Germany are about to embark on a nationwide study that will focus on analysis of dust particles, also looking for the rank factor(s).

		Rank Factors	
Seam	R_{IS}	BTU/lb	%VM
Pocahontas	3.02	14,670	17.9
Sewell	1.50	14,640	23.7
Eagle	2.13	14,420	32.8
No. 2 Gas	0.94	14,200	34.7
Cedar Grove	0.61	13,940	35.8
Pittsburgh	0.45	13,660	39.7

Note: Increasing BTU value and decreasing percent volatile matter (VM) positively correlate with increasing rank of a coal seam.

Table 1. Risk index and tank by coal seam in West Virginia.

MTU1/USBM 2601

Quantitative Analysis of Diesel Particulate Matter in Respirable Coal Dust by Raman Spectroscopy

Johnson, J. H.; **Cornilsen**, B. C.; **Carlson**, D. H.

INTRODUCTION

The Laser Raman Quantitative Analysis (LRQA) method is used to determine the fractions of diesel and coal in airborne particulate matter, as collected in a diesel underground coal mine. This method has not previously been tested using samples collected in an actual underground, diesel-powered coal mine. Michigan Technological University is cooperating with the University of Minnesota to make simultaneous measurements using the LRQA method and their size-selective sampling method.

RATIONALE

Several coal mining companies have found that mobile diesel-powered vehicles improve both safety and productivity, thereby lowering the cost of mining. However the health effects of diesel exhaust, especially particulate, are a concern in the underground workplace. The principle objection of organizations such as the UMW to the introduction of diesels underground has focused on the presence of measurable concentrations of diesel particulate in the mine air. The composition of airborne particulate in a diesel underground coal mine is roughly half diesel particulate matter and half coal dust. While coal dust has been an important health concern for a number of years, the concern about Diesel Particulate Matter (DPM) is more recent. DPM consists mainly of insoluble carbonaceous particle agglomerates, adsorbed or condensed soluble organic compounds, and small concentrations of sulfate and trace metals. Many of the compounds are mutagenic and some are known carcinogens.

Air in U.S. underground coal mines is usually monitored for dust and methane and, when diesel equipment is used, for CO, NO and NO_2. A knowledge of the causes of high concentrations of these pollutants is required to provide effective control to reduce concentrations. Furthermore, there is no fully-proven method to distinguish between diesel and coal particulate.

A systematic approach to monitoring diesel emissions for control of mine air quality was developed by Michigan Technological University (MTU) in earlier Bureau of Mines sponsored research. This approach has provided a means to relate air quality measurements to engineering controls (such as the diesel particulate filters). The method involves simultaneous mine ambient air pollutant and CO_2 concentration measurements and relating the concentrations of the different pollutants and CO_2 mathematically and graphically. The CO_2 concentration is in turn related to the fuel consumption and airflow per unit of diesel power used. The effectiveness of engineering air quality controls can thereby be determined. A portable mine air quality monitoring instrument package has been assembled and the combined system of simultaneous measurements and data analysis using the relationships developed has been used in several production underground mines in both the U.S. and Canada to evaluate air quality control devices.

The methodology and instrumentation package add a new dimension to mine air quality control. However, much work on both the instrumentation and measurement techniques is still needed to improve accuracy and reliability. Areas which need to first be addressed are establishment of 1) a proven method to distinguish between airborne diesel and coal particulate, 2) a safe and effective means to control diesel mine vehicle tailpipe emissions, and 3) a proven method to measure diesel tailpipe particulate emissions.

Figure 1 is a schematic diagram of the LRQA instrumentation used in this research. In the early 1980s, MTU successfully demonstrated the LRQA method to distinguish between diesel and coal particulate. The demonstration involved the analysis of laboratory-prepared samples only, which contained known compositions of diesel and coal particulate matter. This earlier work found that a well-defined relationship existed between spectral peak ratio and the diesel/coal composition (Figures 2 & 3). Therefore, a chemical technique was shown to be viable if diesel-only and coal-only reference samples could be collected in the mine. Samples had to be rotated to prevent decomposition in the laser beam.

SCOPE OF WORK

Research this year, Michigan Tech's first year as part of the Generic Dust Center, emphasized the development of the LRQA method. An important feature of this method is the use of particulate samples that are collected by gravimetric personal samplers as used by U.S. mines to determine the airborne respirable coal dust concentrations. The LRQA method avoids the main difficulties associated with most other methods. Thus with the LRQA method 1) new sampling instruments and techniques are not required, 2) transferring the sample from the collection substrate to an analysis substrate is not required, and 3) the sample is not destroyed by the analysis so other analyses can be made on the sample.

The LRQA method is now being verified using samples of real mine air particulate collected in a U.S. underground coal mine. One week of underground air sampling work was completed during August of 1987. The analyses to date indicate that going from laboratory to mine samples requires refinement of both sampling and LRQA procedures to maximize precision and accuracy.

This years research also compared this LRQA method with the size-selective sampling method being developed by the Bureau of Mines Twin Cities Research Center and the University of Minnesota. In comparing the two methods, airborne respirable diesel/coal particulate mixtures for the LRQA and size-selective methods are collected simultaneously, side by side.

The LRQA method requires that diesel-only and coal-only samples be collected as reference materials for accurate analysis. A portable tailpipe emissions measurement apparatus (EMA), developed by Michigan Tech. in earlier Bureau of Mines sponsored research, has been used to collect the diesel-only particulate samples (Figure 4). The undiluted exhaust emissions concentrations of DPM, CO_2, and CO were measured by the EMA. The engine load when collecting this tailpipe sample is created by holding the accelerator pedal to the floor with the transmission engaged and the brake on. The EMA is the only portable apparatus designed to collect tailpipe emissions diluted in a manner that is similar to their being exhausted into the mine air.

CONCLUSIONS

During this first year of research, we have accomplished the following.

1. In-mine particulate samples with sufficient particulate loading for LRQA were obtained.

2. Diesel-only samples for the LRQA were successfully collected (Figure 2) .

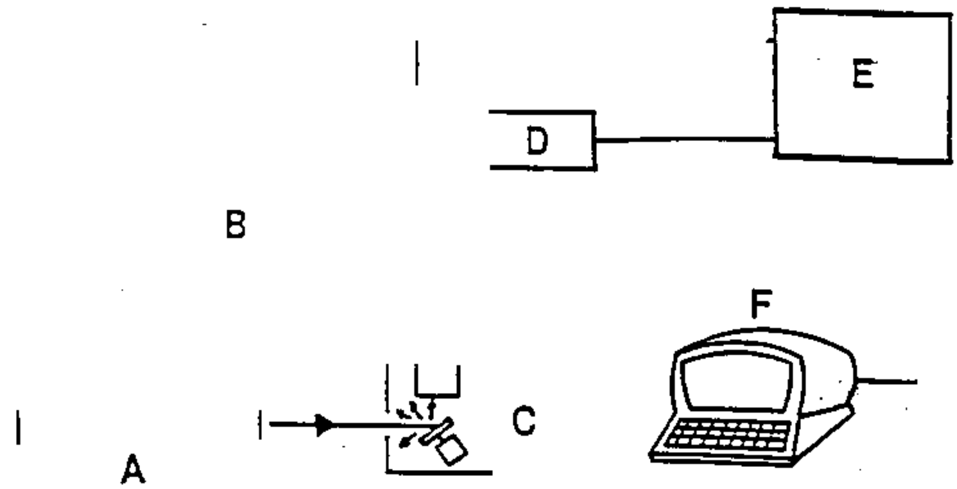


Figure 1. Schematic diagram of Raman instrumentation used to collect coal/diesel particulate spectra

a) laser
b) spectrometer
c) sample chamber with spinning sample holder
d) photomultiplier tube
e) interface between spectrometer and computer
f) computer - graphical spectral analysis and spectrometer control

3. A method was developed to sample airborne coal-only reference particulate samples (Figure 2).

4. Diesel/coal particulate mixture samples for the LRQA were collected underground at the following locations: 1) near the feeder-breaker (dump point), 2) on haulage vehicles, and 3) in the returns.

5. The laboratory preparation of a 50/50 "reference mixture" or "standard" from samples containing coal-only particulate and diesel-only particulate has been successful. This standard is required to define the relative scattering efficiencies of the two components, making the method quantitative.

6. The LRQA and size-selective sampling results have been compared for samples collected at 2 locations in an underground diesel coal mine. Reasonable agreement has been found.

APPLICATIONS OF RESEARCH RESULTS

Satisfactory development of the LRQA method will have the following applications: 1) it will make possible the separate measurement of diesel particulate and coal dust on the samples that are currently collected to enforce Federal regulations limiting a miner's exposure to airborne

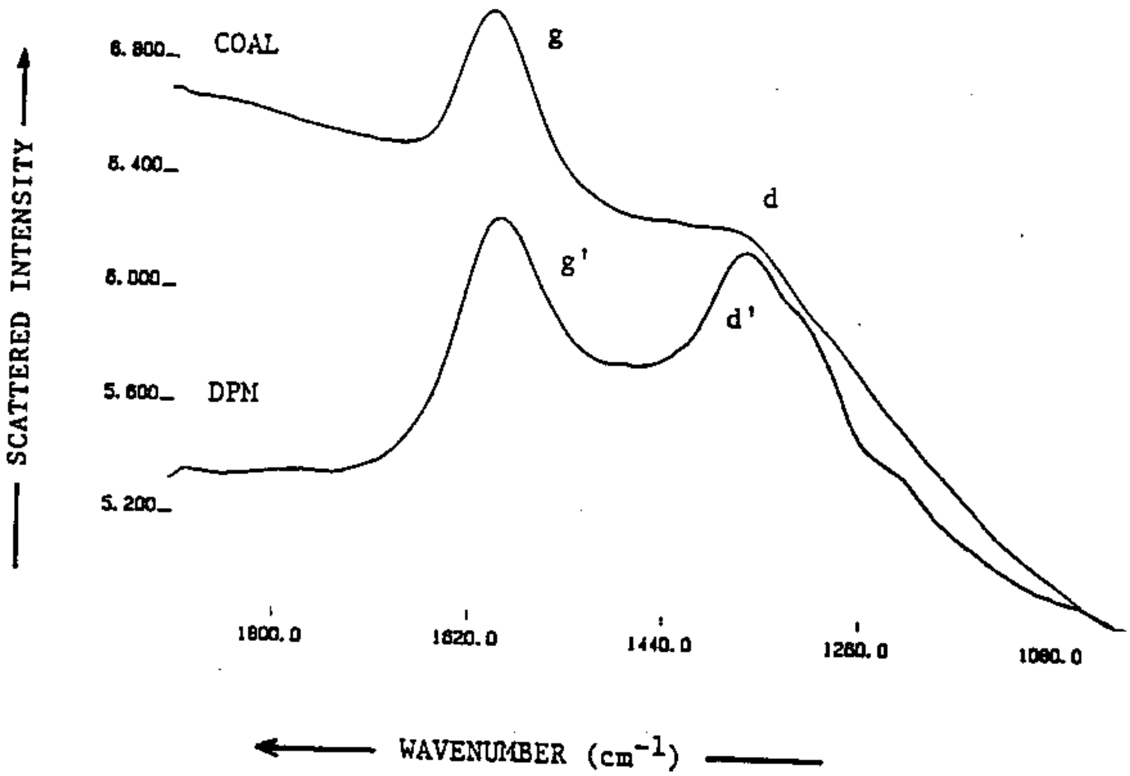


Figure 2. Raman spectra of coal and diesel particulate matter (DPM), showing the difference in peak intensities (d'/g' > d/g). A mixture will exhibit an intensity ratio (D/G) between these two extremes (see Figure 2).

respirable coal dust, 2) it will make possible the adaptation of a separate standard for diesel particulate based upon its particular health effects rather than considering the diesel particulate as part of the coal dust.

CONTINUING WORK

Detailed analyses of precision and accuracy of LRQA measurements on the samples collected in August of 1987 is continuing. Continued development of the LRQA is focusing on refinements in the sample collection and analytical methodology. We have identified sources of analytical variability and have already made a number of refinements which should greatly improve precision and accuracy. These changes are being incorporated into the sample collection procedures used in the Trail Mountain Mine monitoring program and in the laser Raman analysis of these samples. These and other tests are expected to demonstrate the accuracy and usefulness of the LRQA method. This research will lay the groundwork for developing a Laser Raman instrument designed

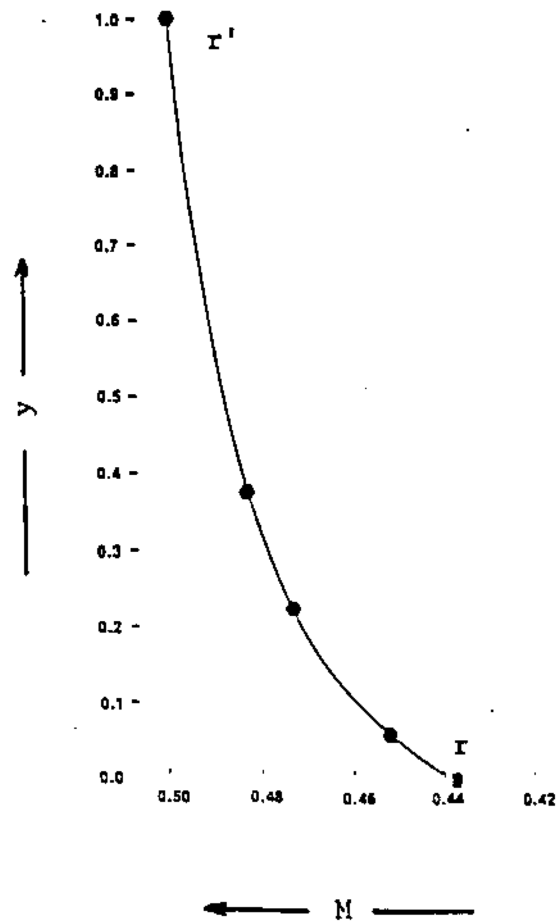


Figure 3. This graph is used to obtain filter composition, % DPM (y), from the experimental mixture ratios (M). The solid line is calculated using the coal-only (r) and diesel-only (r') reference sample.

specifically for coal/diesel particulate analysis. Such a design will make low cost, routine and efficient coal/diesel particulate composition analyses possible.

Future work will include continued joint underground research with the Bureau of Mines and the Colorado Mining association in evaluating other diesel particulate control devices as they become sufficiently developed to warrant underground testing and evaluation.

TECHNOLOGY TRANSFER

A draft report has been prepared. The results have also been refined and summarized for publication. A paper on the year one research was presented at the VIIth International Pneumoconioses Conference held in Pittsburgh on August 23-26, 1988.

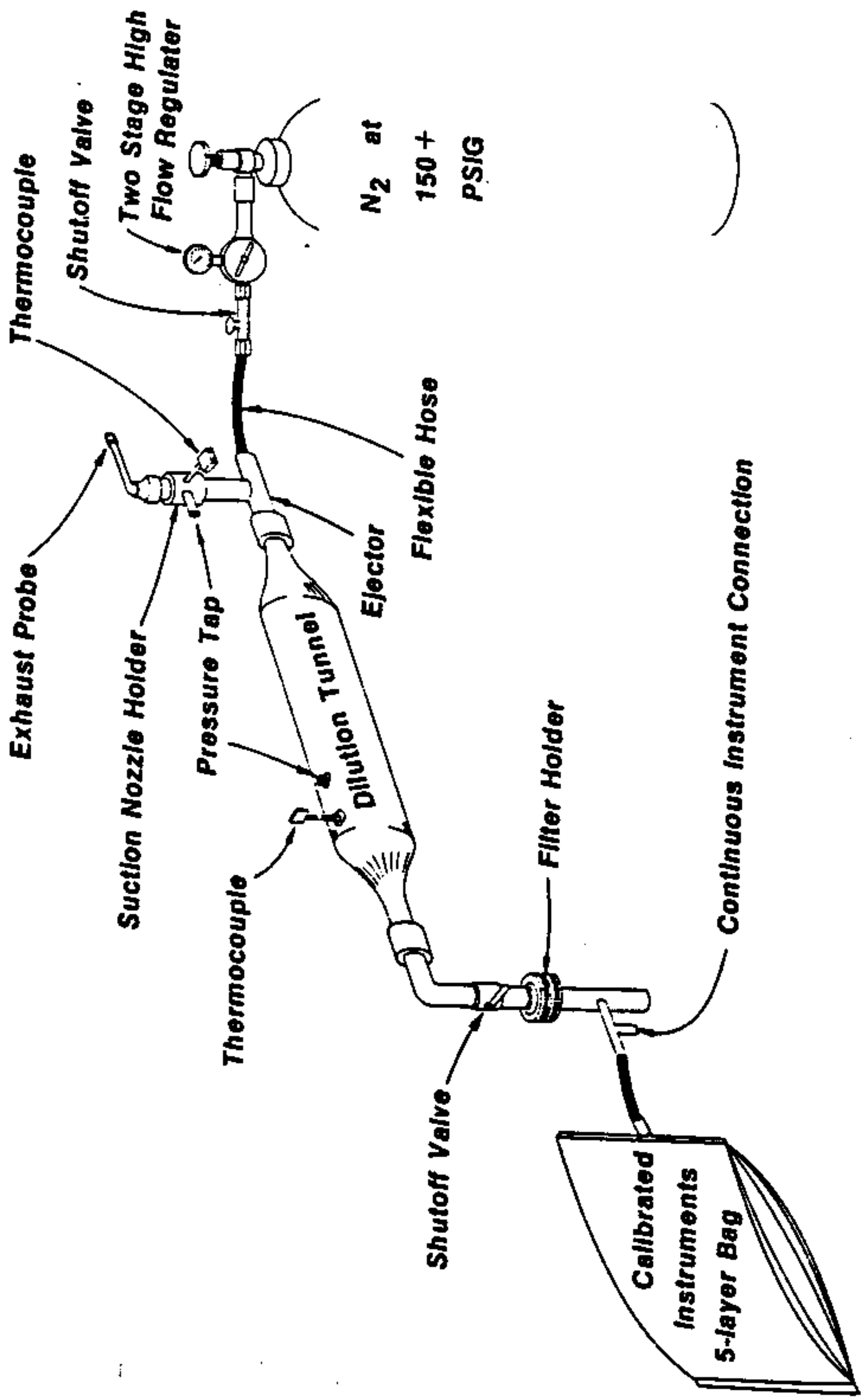


Figure 4. Apparatus used to collect diesel-only tailpipe samples for laser Raman quantitative analysis of coal/diesel particulate mixtures.

MTU2/USBM 2621

Improved Methods for Monitoring and Control of Diesel Particulate in an Underground Mine

Johnson, J. H.; **Cornilsen**, B. C.; **Carlson**, D. H.

INTRODUCTION

This research involves: 1) evaluation of the Pyroban dry-type explosion-proof safety system (Dry System) and diesel particulate filter (DPF) package, which earlier Bureau of Mines sponsored and in-house research has found to be the most advanced of the methods being developed to reduce the exposure of underground miners to diesel particulate matter (DPM) and 2) development of the Laser Raman Quantitative Analysis (LRQA) method for determination of the fractions of diesel and coal in airborne particulate matter, as collected in a diesel underground coal mine. Michigan Technological University is cooperating with the Bureau of Mines Twin Cities Research Center (TCRC), the University of Minnesota, and the Colorado Mining Association in the current evaluation of the Dry System/DPF, and with the University of Minnesota in simultaneous size-selective and Raman analyses of the diesel particulate content of dust.

RATIONALE

Several coal mining companies have found that mobile diesel-powered vehicles improve both safety and productivity, thereby lowering the cost of mining. However the health effects of diesel exhaust, especially particulate, are a concern in the underground workplace. The principle objection of organizations such as the UMW to the introduction of diesels underground has focused on the presence of measurable concentrations of diesel particulate in the mine air. The composition of airborne particulate in a diesel underground coal mine is roughly half diesel particulate matter and half coal dust. While coal dust has been an important health concern for a number of years, the concern about diesel particulate matter (DPM) is more recent. DPM consists mainly of insoluble carbonaceous particle agglomerates, adsorbed or condensed soluble organic compounds, and small concentrations of sulfate and trace metals. Many of the compounds are mutagenic and some are known carcinogens.

Air in U.S. underground coal mines is usually monitored for dust and methane and, when diesel equipment is used, for CO, NO and NO_2. A knowledge of the causes of high concentrations of these pollutants is required to provide effective control to reduce concentrations. However, well-developed, easy-to-apply technology is not available for mining companies to determine the conditions that are associated with high concentrations. Furthermore, there is no fully-proven method to distinguish between diesel and coal particulate.

A systematic approach to monitoring diesel emissions for control of mine air quality was developed by Michigan Technological University in earlier Bureau of Mines sponsored research. This approach has provided a means to relate air quality measurements to engineering controls (such as the DPFs). The method involves simultaneous mine ambient air pollutant and CO_2 concentration measurements and relating the concentrations of the different pollutants and CO_2 mathematically and graphically. The CO_2 concentration is in turn related to the fuel consumption and airflow per unit of diesel power used. The effectiveness of engineering air quality controls can thereby be determined. A portable mine air quality monitoring instrument package has been assembled and the combined system of simultaneous measurements and data analysis using the relationships developed has been used in several production underground mines in both the U.S. and Canada to evaluate air quality control devices.

The methodology and instrumentation package add a new dimension to mine air quality control. However, much work on both the instrumentation and measurement techniques is still needed to improve accuracy and reliability. Areas which need to first be addressed are establishment of 1) a proven method to distinguish between airborne diesel and coal particulate, 2) a safe and effective means to control diesel mine vehicle tailpipe emissions, and 3) a proven method to measure diesel tailpipe particulate emissions.

In the early 1980s, Michigan Technological University successfully demonstrated the LRGA method to distinguish between diesel and coal particulate. The demonstration involved the analysis of laboratory-prepared samples only, which contained known compositions of diesel and coal particulate matter. This earlier work found that a well-defined relationship existed between spectral peak ratio and the diesel/coal composition. Therefore, a chemical technique was shown to be viable if diesel-only and coal-only reference samples could be collected in the mine.

A number of diesel mine vehicle particulate control devices have been assembled and tested. In recent years the emphasis has been primarily on ceramic element particulate filters. Most of the work was sponsored by the Bureau of Mines and CANMET. CANMET was also involved in providing the devices to be tested. Ontario Research Foundation performed laboratory tests on the devices, and Michigan Technological University performed the underground mine evaluation of the devices in its Underground Laboratory under a Bureau of Mines contract. This joint research proved the ceramic element DPF to be the most advanced of the various methods under development.

The internal workings of the DPF are shown schematically in Figure 1. This device is not compatable with the ordinary wet scrubber through which diesel emissions must be passed before exhausting them into the air in a U.S. underground coal mine. Application of the DPF therefore requires that the wet scrubber which cools the exhaust and acts as a flame arrestor be replaced with a dry type explosion-proof safety package. One such system known as the Dry System, which is under development in Canada, has been evaluated in the Bureau of Mines TCRC laboratories. Figure 2 is a schematic illustration of the combined dry system and DPF showing their locations relative to each other and to the diesel engine.

The TCRC laboratory research on the Dry System indicated that the dry system needed modifications to reduce the back pressure to levels that were acceptable to the diesel engine manufacturer. A second prototype which reduced the back pressure effect was sent to the Mine Safety and Health Administration Certification and Approval Laboratory in Triadelphia, West Virginia. Underground research is now planned to test the safety, durability, and effectiveness of the system on a diesel-powered haulage vehicle. Baseline data were collected in the Trail Mountain Mine during August of 1988.

A portable tailpipe emissions measurement apparatus (EMA) was also developed by Michigan Technological University in the earlier Bureau of Mines sponsored research. This device is illustrated schematically in the report for Project M101. The undiluted exhaust emissions concentrations of DPM, CO_2, CO, NO, and NO_2 are measured by the EMA. The engine load is created by holding the accelerator pedal to the floor with the transmission engaged and the brake on. The EMA is the only portable apparatus designed to collect tailpipe emissions diluted in a manner that is similar to their being exhausted into the mine air. However, this portable apparatus needs to be fully-proven by comparison of the measurements to accepted laboratory instrumentation and techniques. This calibration work is scheduled for FY 89.

SCOPE OF WORK

The above sequence of events has set the stage for the current research program. Michigan Technological University's involvement in the Generic Dust Center began early in 1987. The first years research emphasized the

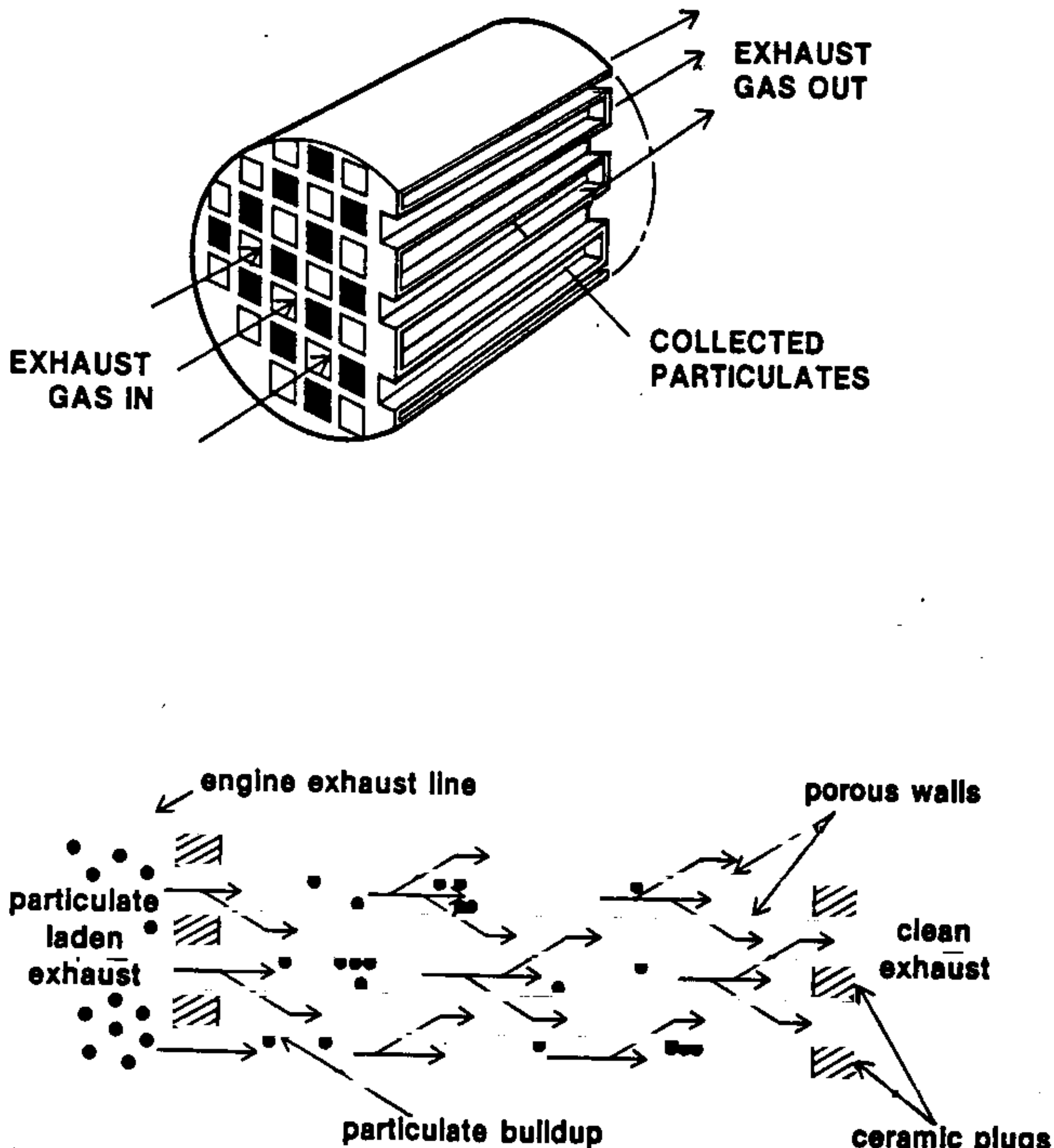


Figure 1. Schematic illustration showing how ceramic monolith diesel particulate filter works.

development of the LRQA method. An important feature of this method is the use of particulate samples that are collected by gravimetric personal samplers as used by U.S. mines to determine the airborne respirable coal dust concentrations. The LRQA method avoids the main difficulties associated with most other methods. Thus with the LRQA method 1) new sampling instruments and techniques are not required, 2) transferring the sample from the collection substrate to an analysis substrate is not required, and 3) the sample is not destroyed by the analysis so other analyses can be made on the sample.

During this fiscal year, more extensive testing of the LRQA method is being conducted to verify the methodology. The analyses to date indicate that going from laboratory to mine samples requires refinement of both sampling and LRQA procedures to maximize precision and accuracy.

The underground mine vehicle evaluation of the Dry System is being conducted in the Trail Mountain Mine. Michigan Technological University is participating with the Bureau of Mines and the University of Minnesota. One week of baseline mine air diesel pollutant concentration measurements were conducted in August 1988. The dry system/DPF will be mounted on a Jeffrey Ram Car coal haulage vehicle owned by Mountain Coal. Particulate samples for gravimetric respirable dust concentration and LRQA are being collected. In addition to particulate, Michigan Technological University is measuring the mine air concentrations of CO, CO_2, NO, NO_2, SO_2. and SO_4. Tailpipe measurements for the same pollutants are also being made on a number of diesel powered mine haulage vehicles.

After the dry system is mounted, the mine air measurements will be repeated to determine the effect of the dry system on the air quality along with the safety and durability of the system. During both of these 1-week measurement periods, simultaneous mine air particulate matter samples will be collected for the LRQA and the size-selective particulate analysis methods. The samples will be analyzed with the objectives of comparing the LRQA and size-selective methods and of determining the effects of the dry system/DPF on the airborne diesel particulate matter concentrations.

APPLICATIONS OF RESEARCH RESULTS

Dry System/DPF Evaluation - Once the dry system/DPF combination is found to be safe, durable, and effective in the underground coal mine application, the mines can use it to reduce the concentration of diesel particulate by upward of 90 %. The main benefit will be a more healthful environment for coal miners as a result of making it practical to enforce lower mine air diesel particulate concentration standards. An immediate benefit to the mine operators will be to make it easier for them to meet the current coal dust standard since the diesel particulate which is presently considered to be coal dust will be almost entirely eliminated.

Emissions Measurement Apparatus - Development of a satisfactory, proven tailpipe emissions measurement apparatus will make it possible for mine operators to determine, on a vehicle by vehicle basis, how each contributes particulate and gaseous pollutants to the mine air. Such a knowledge will provide a means to determine when the various mine vehicle particulate/gaseous pollutant control systems are no longer effective and require maintenance. The EMA also provides diesel-only samples for the LRQA analysis.

LRQA Method - Development of the LRQA method will have the following applications: 1) it will make possible the measurement of diesel particulate and coal dust separately on the samples that are presently collected to enforce Federal regulations limiting a miner's exposure to airborne respirable coal dust, 2) it will make possible the adaptation of a separate standard for diesel particulate based upon its particular health effects rather than considering the diesel particulate as part of the coal dust.

CONTINUING WORK

Detailed analyses of precision and accuracy of LRQA measurements on the samples collected in August of 1987 is continuing. Continued development of the LRQA is focusing on refinements in the sample collection and analytical methodology. We have identified sources of analytical variability and have made refinements which should greatly improve precision and accuracy. Refinements have been incorporated into the sample collection procedures we used in the Trail Mountain Mine monitoring program to eliminate radial heterogeneity on the filters. Other refinements will be made in the laser Raman analysis of these samples. These and other tests are expected to demonstrate the accuracy and usefulness of the LRQA method. This research will lay the groundwork for developing a laser Raman instrument designed specifically for coal/diesel particulate analysis. Such a design will make low cost, routine and efficient coal/diesel particulate composition analyses possible.

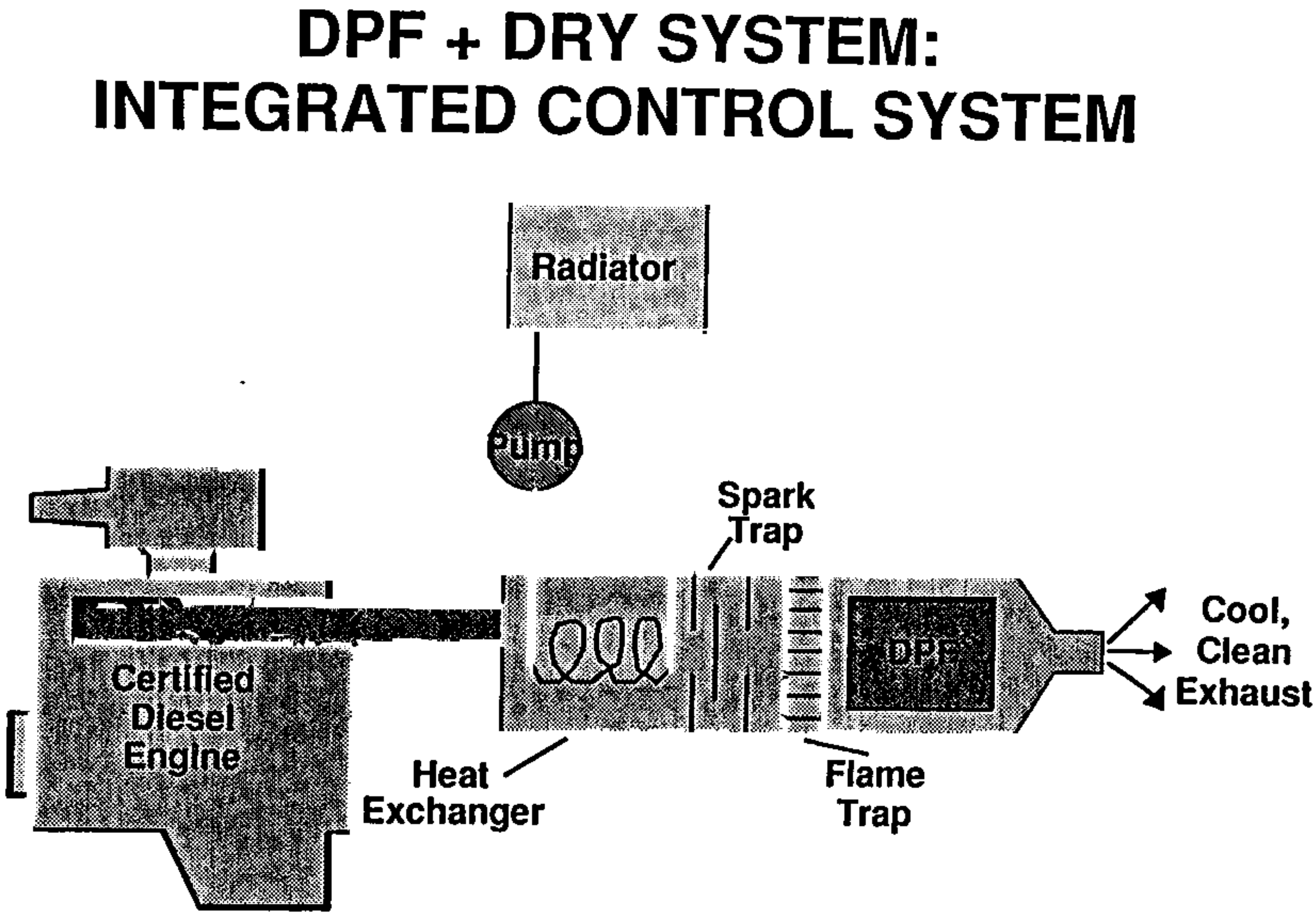
Future work will include continued joint underground research with the Bureau of Mines and the Colorado Mining association in evaluating other diesel particulate control devices as they become sufficiently developed to warrant underground testing and evaluation.

The calibration of and perhaps refinement of the diesel tailpipe emissions measurement apparatus is scheduled for FY 89. The laboratory comparison will be made at the Bureau's Twin Cities Research Center which has excellent facilities for analysis of diesel emissions.

TECHNOLOGY TRANSFER

When the research is complete, a draft report will be prepared and the results will be refined and summarized for publication.

Figure 2. DPF + DRY system: integrated control system.



4.4

Dilution, Dispersion and Collection in Mine Airways

PS2/USBM 4202

Prediction of Ambient Dust Concentration in Mine Atmospheres

Ramani, R. V. and Shankar, S.

INTRODUCTION

The major thrust of this project is directed towards a better understanding of the behavior of airborne dust particles in underground mine airways. Specifically, for effective dust control in mines, it is necessary to analyze and match the characteristics of the dust control measures with those of the dust generation and transport mechanisms. Such an analysis is also essential for identifying potential methods to control both the amount of airborne dust and the exposure of miners to these dusts. This study required an understanding and analysis of the following:

(i) system characteristics such as mining machine, dust generation potential, type of ventilation, velocity of flow, turbulence and dispersivity.

(ii) particle characteristics such as dynamic size distribution, depositional propensities, mass and density.

The research in this project has encompassed the following: (i) development of a mathematical model for predicting airborne concentration as a function of dust sources, and airflow and airway characteristics; (ii) experimental studies to develop data sets for validation of the model and its components; and (iii) comparative analysis of model predictions with data from controlled mine experiments and experiments in operating mines. Applications of the model to dust control in mines include prediction of airborne concentrations and size distributions in existing or new mining systems and planning systems and equipment for reduction in airborne dust.

RATIONALE

Mining as a process essentially consists of breaking in-situ materials and transporting them out of the mine. Therefore, the generation of fine particles cannot be completely eliminated. In underground coal mining, fine coal dust, in addition to being a nuisance factor obscuring visibility, is associated with sudden catastrophic incidences of explosions. Furthermore, it is associated with the slow appearing and long enduring diseases of the lungs. The control of fine coal dust and of the exposure of workers to high concentrations is essential for improved health and safety.

An airborne dust cloud is a complex system containing particles of varied size, density, shape and state of aggregation. The behavior of the particles is dependent on a number of complex physical mechanisms, often opposing in nature. The net interaction results in the ambient concentration. Since the passage of the Coal Mine Health and Safety Act in 1969, considerable progress has been achieved in the control of dust in mine atmospheres to mandated dust standards through research and development by the U.S. Bureau of Mines, other agencies and industry. However, the literature on the transportation and deposition of dust in mines is scant. Theoretical and fundamental studies on spatial and temporal characteristics of dust flow in mine airways are very few in number. Experimental results have shown great variabilities and only limited effort has been spent on correlating theoretical studies with experimental observations. In fact, a committee of the National Academy of Sciences on the measurement and control of dust stated that this lack of understanding of the formation and behavior of clouds of respirable dust constrains the introduction of more productive methods in the coal mining industry. Clearly, this research into the spatial and temporal characteristics of airborne coal dust is important from the health, safety and productivity aspects of the Nation's coal industry.

SCOPE OF WORK

The research performed under the project has been defined and developed so as to ensure co-ordinated research flowing from theoretical considerations in model development to experimental design and performance of field experiments. The research is divided into four distinct areas (1) theoretical studies, (2) experimental studies, (3) comparison of model and experimental results, and (4) the analysis of model parameters and components to enhance the performance of the model.

Theoretical Studies

A mathematical model was developed to study the dispersion and transport of dust in a mine airway. A schematic of the model is presented in Figure 1. The model included the following: Diffusional deposition, both Brownian and turbulent deposition, of dust on the roof, sides and floor of an airway were determined and included as a sink term. Convection and diffusion rates used in the model were obtained from studies into dispersion of contaminants in mine airways; and sedimentation was considered as a major mechanism of deposition on mine floors. Due to the non-linear nature of the sedimentation rate equation, the dust size distribution was discretized into several size classes and appropriate sedimentation equations were applied. A discretized form of the Smoluchowski equation was used to determine addition and disappearance of particles from various size classes. The one-dimensional convection-diffusion equation was used to determine concentration. The equation incorporated the various source and sink terms. Initial and boundary conditions appropriate to the case under study were selected and the equation was solved using finite difference techniques. The model was programmed for a computer-oriented solution.

Experimental Studies

The need for examining model assumptions and model predicted behavior through carefully designed experiments was identified as a necessary part of this research project. Therefore, a set of experiments were performed in mine environments to understand dust transport phenomenon. The first set of experiments were designed so as to acquire data under varied but controlled experimental conditions. To aid in a better understanding of respirable dust behavior in these experiments, dust of the superfine variety (-25 microns) which had a significant percentage in the respirable range was dispersed. The controlled experiments were followed by in-mine experiments in two coal mines. The design of experiments under controlled conditions was initiated after a detailed examination of the data needs. Essentially, two types of data -- ambient concentration and deposition -- were considered necessary. The Lake Lynn Laboratory mine of the U.S. Bureau of Mines was selected as the location to perform controlled tests. The experimental design for data collection involved specifications of the methods of dispersing dust, the number of sampling points, the location of the sampling points and the method of sampling for determining airborne dust concentrations and floor depositions (Figure 2). An arrangement of the sampling device for airborne dust concentration is shown in Figure 3. Specifically, the following data were collected:

(1) ambient dust concentration in the total size range;
(2) ambient dust concentration in the respirable size range;
(3) deposition of dust in the total size range;
(4) deposition of dust in the respirable size range; and
(5) cross-section sampling at several points, along with center-line sampling in the same sections.

To relate the theoretical results and data obtained from controlled experiments with data from operating mines, two experiments were carried out in the return airway of producing mine sections. Instantaneous data were also collected using real-time aerosol monitors (RAM-1) and data loggers.

The samples collected in the experiments were analyzed for size distribution of source dust, density of source dust, mass concentration of ambient dust cloud at various points, size distribution of the ambient dust cloud, deposition rate of dust deposited on the floor of the airway, and size distribution of deposited dust. These data were used for determination of ambient concentration and deposition; change in concentration and deposition along the length of the airway; the relation between center point concentration and average concentration across a cross-section; change in size distribution as the dust cloud traverses the airway; and influence of velocity and density of deposition, concentration, and size distribution. Selected results are presented in Figures 4 and 5.

Comparative Analysis

For the purpose of a comparative analysis, the experimental conditions were simulated in the mathematical model, and the model results were compared with the experimental results. Input values for model testing were derived from field data. Known differences between field conditions and model assumptions were identified and removed by either through adjustment to the model input, or to the field data to have the same basis for comparison. Also a number of assumptions were made in the derivation of the model. An attempt was made to verify some of these assumptions. For example, the dispersion coefficient assumed in the model was compared with that obtained from experimental data.

Model and experimental results were compared for the following aspects:

(1) ambient concentration of airborne dust in both the "total" and "respirable" size ranges along the length of the mine airway,

(2) deposition of dust in the total and respirable size ranges along the length of the airway,

(3) deposition rate of airborne dust under varying conditions of the experiments (the deposition rate for various size classes are determined), and

(4) change in size distribution of the dust cloud as it traverses an airway (this also includes an examination of the velocity effect on size distribution)

Selected results of the comparative analysis are presented in Figures 6 and 7. Some variations between the model assumptions and experimental results were noticed. In general, the model tracked the concentration and deposition pattern fairly well.

CONCLUSIONS

A general conclusion of this research study is that the mathematical model for predicting the behavior of dust clouds in mine airways under the action of steady flow is useful to study dust deposition and concentration patterns in sensitivity in a straight section of a roadway. Sensitivity analyses on model input parameters can reveal the importance of the various factors for dust control in mines.

Experimental Results

Several conclusions were drawn from the controlled and in-mine experiments in the areas of concentration, deposition, size distribution, cross-sectional concentration, and the effect of velocity.

(1) A sharp decline in dust concentration occurs within the first 100 m (300 ft) of the source. After 300 m (1000 ft), the dust concentration tends to assume an asymptotic form.

(2) The respirable fraction of the airborne dust increases with distance from the source due to lower deposition rates for small size particles.

(3) Deposition rate per unit concentration increases for particles less than one micron with decrease in size.

(4) The in-mine data collected over a length of 1000 m (3280 ft) show a formation of the asymptotic form for concentration, with little change in the total and respirable dust concentration after some distance from the source.

(5) Deposition for total dust is rapid at the first few stations after which it tends to assume an asymptotic form. The decrease is relatively uniform for the respirable size range.

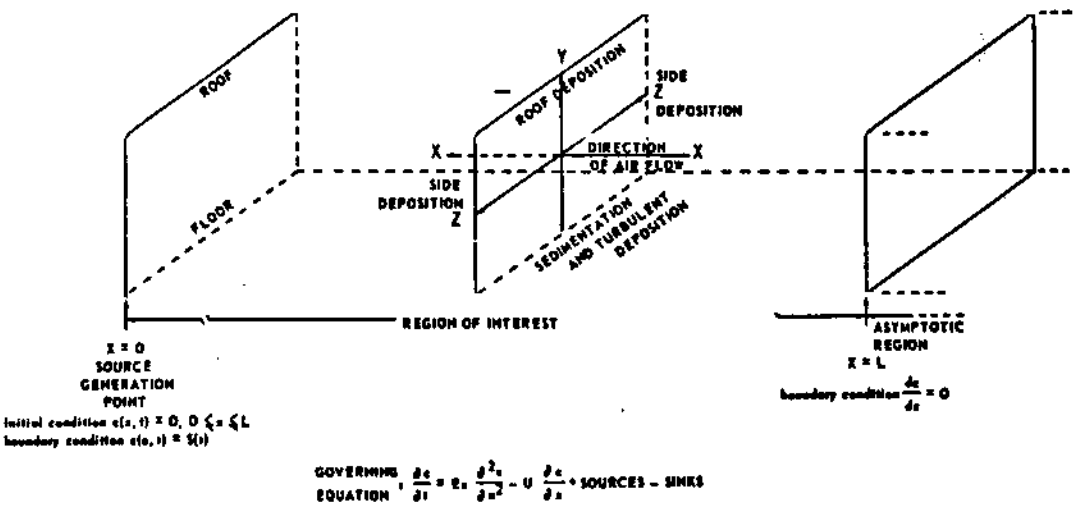


Figure 1. Schematic of dust flow in mine airway.

Comparative Analyses

The comparative analyses show that deposition, both in the total and respirable range, is predicted by the model in almost all the controlled experiments especially at distances beyond 100 meters. Also, the model tends to predict concentration better at lower flow velocities than at higher velocities. Total concentration appears to be better predicted than respirable concentration. It appears that the difference between the model predictions and experimental results for total concentration is primarily due to the differences between predicted and experimental respirable concentration.

Due to the non-linear interactive nature of the components of the model, simple history matching with deposition and concentration data is not adequate. Therefore, in the validation processes, reasonableness of the assumptions were evaluated with the following conclusions:

(1) It appears that the deposition rate is a function of concentration. At higher concentrations near the source, the deposition rate is high, which results in large amounts of particles being deposited close to the source.

(2) There exists a variation in dust concentration across a mine airway cross-section. The concentration of dust increases from the roof to the floor.

(3) No definite statement can be made about the value of the dispersion coefficient from the in-mine experiments due to both the very limited amount and coarseness of data. However, the value calculated from real-time data is in the same order of magnitude as the model assumed dispersion coefficient.

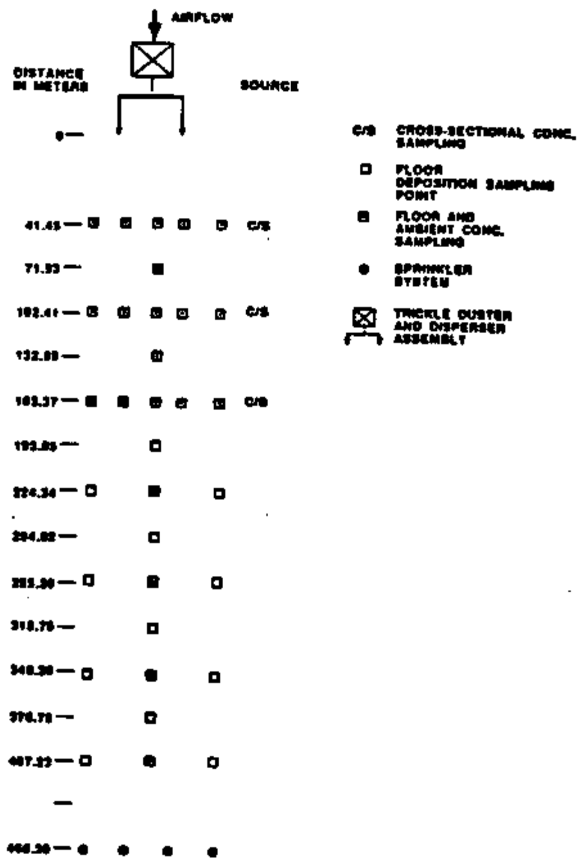


Figure 2. Schematic of the airway showing locations of the sampling points (Experiment 6).

APPLICATIONS OF RESEARCH RESULTS

The mathematical model in its present form is applicable to dust flow analyses in straight airway sections. The following is a list of the potential applications.

(1) Prediction of ambient dust concentrations and deposition in a mine airway. Both spatial and temporal concentrations can be predicted.

(2) Rock dusting programs. The model can be used to predict the amount of coal dust that is deposited in the return airways. The amount of rock dust that needs to be sprinkled to obtain the necessary inertness in dust samples from mine airways can be calculated.

(3) Recirculation of air. In situations where recirculation of air is permissible, the model can be used to predict the dust concentration in the recirculated air, as well as its size distribution.

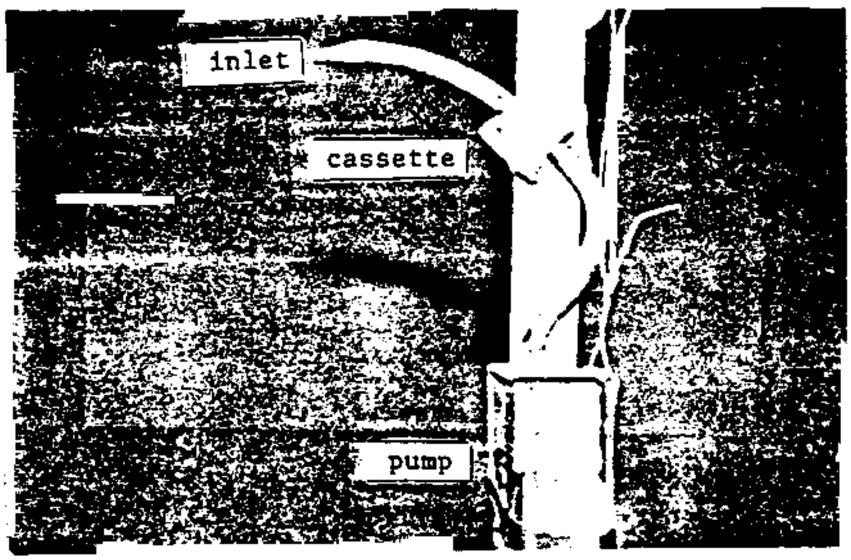
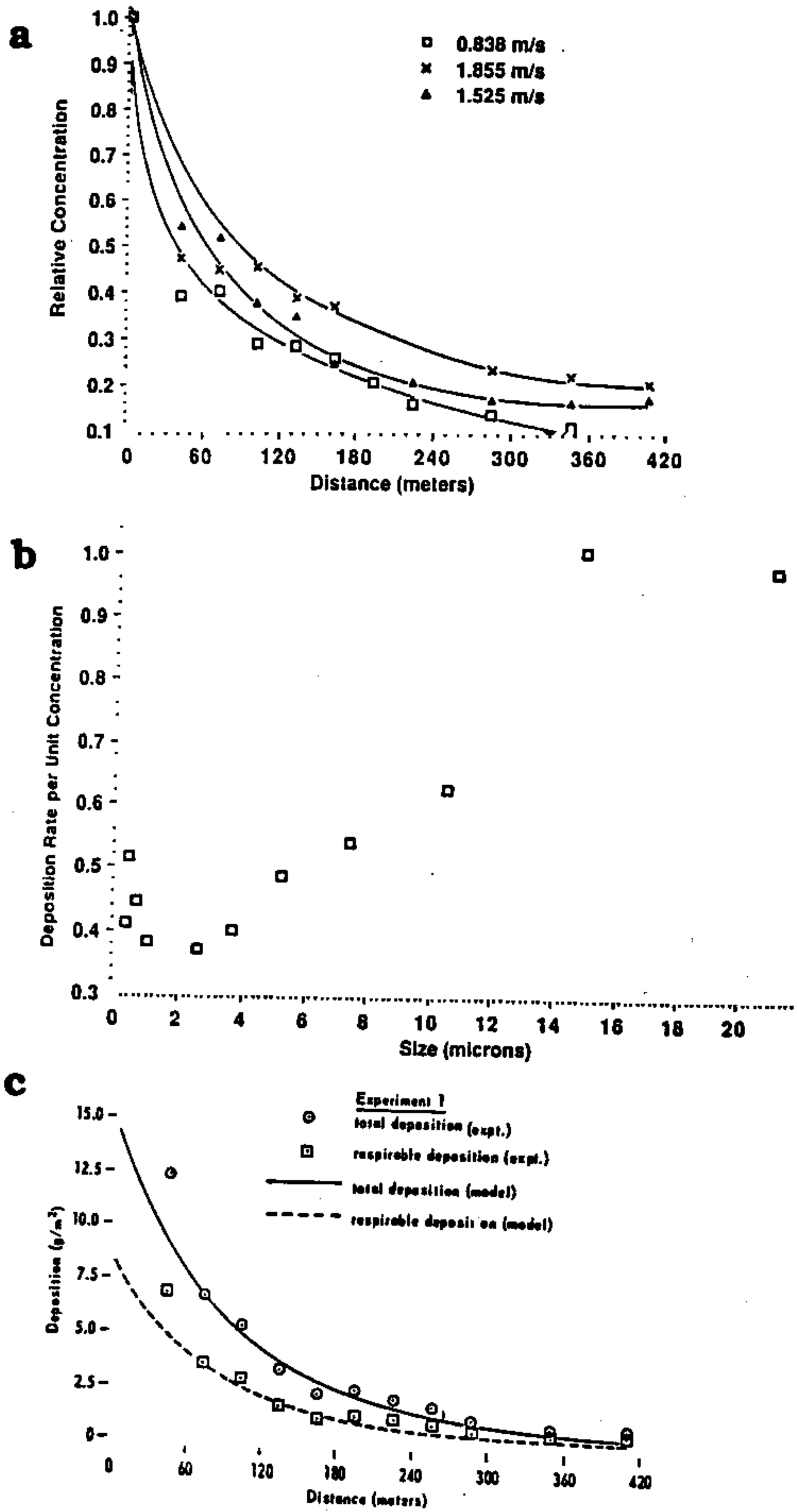


Figure 3. Assembly for ambient concentration sampling.

(4) Equipment planning. On the development of a data base of the dust generating characteristics of various equipment, the model can be used to predict which equipment are appropriate for a given set of conditions.

(5) The effect of dust in the intake air on the dust concentration at the face can be studied using the model. By examining the type and size distribution of the dust, the impact of the various sources on the intake concentration and size distribution can be evaluated.


a
0.838 m/s
1.855 m/s
1.525 m/s
Relative Concentration
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
60
120
180
240
300
360
420
Distance (meters)
b
Deposition Rate per Unit Concentration
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
2
4
6
8
10
12
14
16
18
20
Size (microns)
c
Experiment 1
total deposition (expt.)
respirable deposition (expt.)
total deposition (model)
respirable deposition (model)
Deposition (g/m³)
15.0
12.5
10.0
7.5
5.0
2.5
0
0
60
120
180
240
300
360
420
Distance (meters)

d

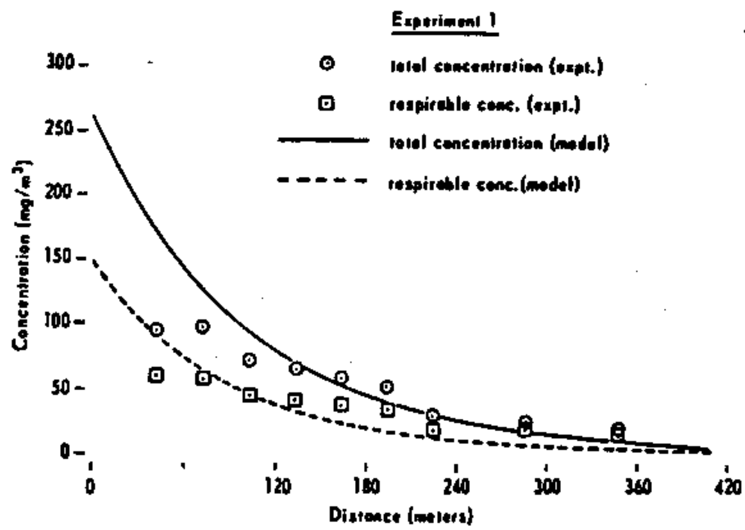


Figure 4. Theoretical and experimental results.

a) Effect of velocity on total airborne dust concentrations (semi-anthracite).
b) Deposition rates for various particle sizes (Controlled Experiment 1).
c) Comparison of model predicted floor deposition with experimental data.
d) Comparison of model predicted concentration with experimental data.

CONTINUING WORK

Continuing work is focussed on experimental and theoretical studies for predicting reentrainment rates as a function of size, density, velocity and other parameters relevant to the reentrainment process. Experimental studies have been planned both in the laboratory and in mine airways.

Dispersion rate and deposition rates were identified as components of the dust transport and dispersion model that needed further research. These areas have been approved for research under the Generic Mineral Technology Center for Respirable Dust and work is expected to begin in October 1988.

TECH TRANSFER

Several publications and useful discussions with personnel from other research institutes have resulted from this work. A total of two refereed papers, four symposium papers, two thesis and two presentations have resulted from this study. One more paper is under review by referees. The continuing research is expected to result in one more thesis.

PS7/USBM 4206

Computer Modeling of Longwall Face Ventilation

Ramani, R. V. and Qin, J.

INTRODUCTION

The major objective of this on-going project is to contribute to a better understanding of longwall ventilation schemes with particular reference to dust concentrations. Specifically, in longwall mining systems, large amounts of dust are generated by the cutting action of the shearer. It is necessary to study both dust generation in longwall faces and the transport behavior of dust clouds along the longwall face. This study is important for evaluating and developing alternative ventilation and operational strategies, because, the miners may have to work in the air that has passed over the shearer and therefore, may be exposed to large amounts of airborne dust. This study has required analysis of the following:

(i) characteristics of longwall system such as real-time behavior of dust with respect to shearer operations, leakage of air along the face, resistance factors and velocity of flow.
(ii) characteristics of dust along the longwall face, such as the dust release rate of the shearer, size distribution of the dust source, and dust concentrations along the face.

The workplan for this project consists of the following: (i) literature survey on longwall mine dust control, characteristics of longwall ventilation system, and dust concentration models; (ii) design and conduct of underground experiments to provide data necessary to construct and validate a mathematical and computer model of longwall face ventilation; (iii) development of the mathematical and computer model for describing and predicting airborne dust concentration along a longwall face as a function of airflow velocity, leakage of air, resistance of longwall face, and moving dust source; and (iv) comparative analysis of model predictions with data from experiments in operating longwall faces.

RATIONALE

Longwall mining is generally recognized as more productive, safer and economic as compared to room and pillar underground coal mining. While the concentration of production operations is an aid in ventilation planning, longwalls present a significantly higher difficulty problem with regard to maintaining the airborne dust concentrations to below the mandated levels. Furthermore, miners may have to work in the return air of the shearer. The exposure of workers to high dust concentrations is to be avoided through improved dust control as well as longwall operating procedures.

Part of the dust problem in the longwall face has been the difficulty in getting a high quantity of air due to the length of the face, the length of the panels, and the significant leakage of air through the gob. High face velocity, however, tends to increase dust concentration mainly due to higher entrainment and reduced settling of dust along the longwall face. Aimed at reducing worker exposure to dust, the U.S. Bureau of Mines and its contractor's have conducted comprehensive research programs addressing the dust reduction methods and have focussed on improving the ventilation system at the face and at equipment. Models for describing the dust concentrations along a longwall face based on the contributions of dust from various sources and the position of worker and exposure time have been proposed. Some of these models are macro in nature and do not consider the fundamental behavior of the airborne dust cloud which is a complex aerosol system containing particles of varied size, density, shape and state of aggregation. A model based on the fundamental mechanisms and basic longwall parameters is currently not available.

SCOPE OF WORK

The overall scope of work for this research has been broken down into four phases as follows:

Phase I: Preliminary Experimental Studies

Phase II: Design of Controlled Experiments

Phase III: Derivation of Model Parameters

Phase IV: Model Verification and Validation

PHASE I: Preliminary Experimental Studies

In contrast to the large amount of work on engineering control of dust, little information is available on the fundamental aspects of dust flow along the longwall face. Before building a mathematical and computer model, there is a need to develop data on the parameters which affect the dust flow along a longwall face. The need for deriving model parameters and validating the model through carefully designed experiments was considered as a necessary part of this research project. Three sets of experiments were performed in operating longwall faces in three different mines. A typical sampling scheme on longwall face is shown in Figure 1. Three types of data - ambient concentration along the longwall face, mine data, and time study data - were collected. Specifically, the following data were collected along the longwall face:

(i) airborne dust concentration in the respirable size range;

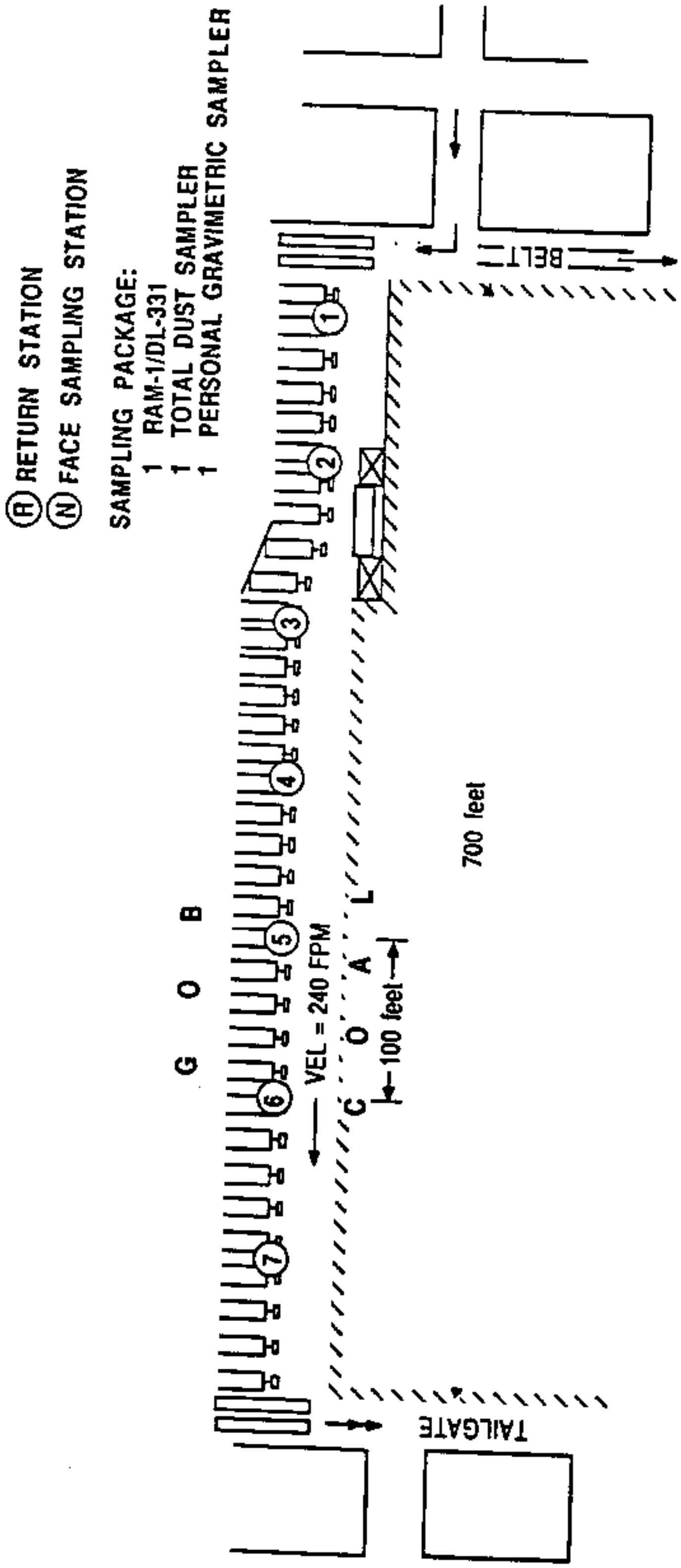


Figure 1. Longwall face airborne dust sampling plan.

(ii) airborne dust concentration in the total size range;

(iii) real-time aerosol data in different stations;

(iv) loss and re-entry patterns of dust laden air into and from gob; and

(v) time study data with regard to location of dust source (or position at shearer) as a function of time.

The airborne respirable and total dust samples were collected using gravimetric personal sampler. These samples give the average concentration for the entire sampling time (usually 3-5 hours). The instantaneous dust concentrations were collected using real-time aerosol monitors (RAM-1) attached with data loggers. The instantaneous data have to be analyzed with time study data which recorded the activities of the shearer during sampling time. One example output of RAM-1 data and time study results are shown in Figure 2. As expected, the dust concentration is higher when shearer cuts in the direction of airflow than against airflow. Higher levels of airborne dust are generated when shearer cuts near the headgate. Examples of dust concentrations along longwall face are given in Figures 3 and 4. These are the average concentrations over the entire sampling period. The distribution of air quantity along the longwall face is shown in Figure 5. It is clear that significant amounts of air leak into the gob near the headgate and some air enters the face, often near the tailgate.

PHASE II: Design of Controlled Mine Experiments

In order to get more accurate information about dust flow along a longwall face, experiments under controlled conditions were desired. The Lake Lynn Laboratory Mine of the U.S. Bureau of Mines was selected to perform controlled underground experiments. After a detailed examination of the data needed for the research and of the results from the preliminary experiment in operating mines, a design of controlled experiments and sampling plan was developed. The sampling plan is shown in Figure 6. The experimental design involves specifications of the methods of moving the dust source and dispersing dust, air leakage control, sampling stations along the face and method of sampling for determining airborne dust concentrations. These controlled experiments are scheduled for the summer of 1988.

PHASE III: Derivation of Model Parameters

Based on the results from the preliminary experiments and literature survey, the factors which need to be considered in the model are:

(1) longwall ventilation parameters, such as face velocity, air leakage into gob, and face resistance;

(2) characteristics of dust source, such as the partial size distributions, dust release rate, directions and velocity of moving dust source; and

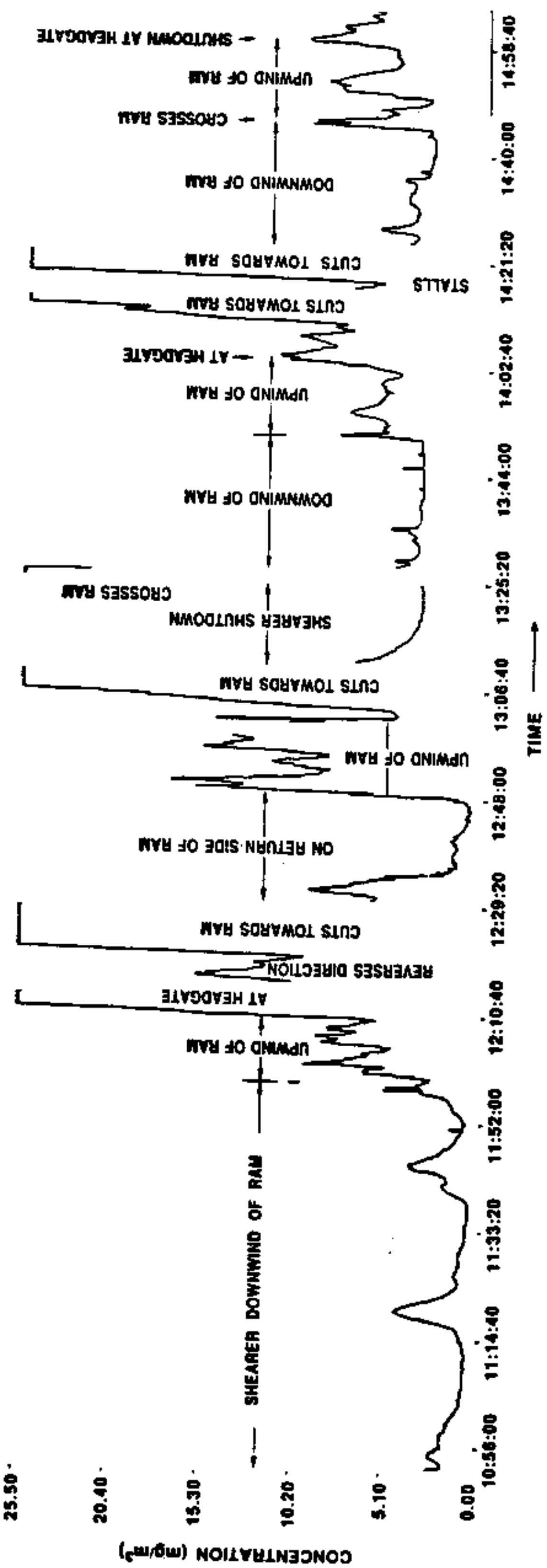


Figure 2. RAM-1 output of dust concentration along longwall face.

(3) dust dispersion, transport, deposition, and coagulation. Most of those factors will be studied under controlled conditions in Lake Lynn Laboratory mine. Values for some of the parameters, such as face resistance and air leakage into gob, have to be selected from data from operating mines.

PHASE IV: Model Verification and Validation

This part of the project will be scheduled when the controlled mine experiments have been completed and the development of a computer model is complete. Such a model will be validated by comparing the model results with the experimental results. The data needed for the model testing will be obtained from specially designed experiments in operating mines. The assumptions for the model will be tested.

CONCLUSIONS:

Longwall dust cloud, which is generated by the shearer cutting process, is a very complex aerosol system. For a better understanding of longwall dust problems, a model is needed for describing and predicting airborne dust concentrations along longwall face. This is an ongoing project and the conclusions drawn here are based on the first two phases of the project, which are literature review and preliminary experiments in the mines:

(i) high levels of airborne dust are generated when shearer cuts near headgate;

(ii) the cumulative effect on dust level along longwall face is significant when the movement of shearer is in the same direction as the air flow, dust level is relatively lower when the shearer cuts are in the direction against air flow;

(iii) there is, however, no clearly recognizable pattern of dust concentrations in the observations due to several interpretation to the production process. Secondary dust sources, such as, movement of shield, and falling roof are visible from the RAM-1 results; and

(iv) significant amount of air leaks into the gob. Air leakage has to be considered in the computer modeling.

CONTINUING WORK

Work is continuing on Phases II, III, and IV. The controlled experiments in Lake Lynn Laboratory Mine are on-going and will be completed in summer 1988. These experiments will provide valuable information for deriving model parameters and the model itself. A mathematical and computer model is in the process of being developed.

The project has already supported one graduate student and one research engineer. Presently, one graduate student is working towards a doctoral degree on the project.

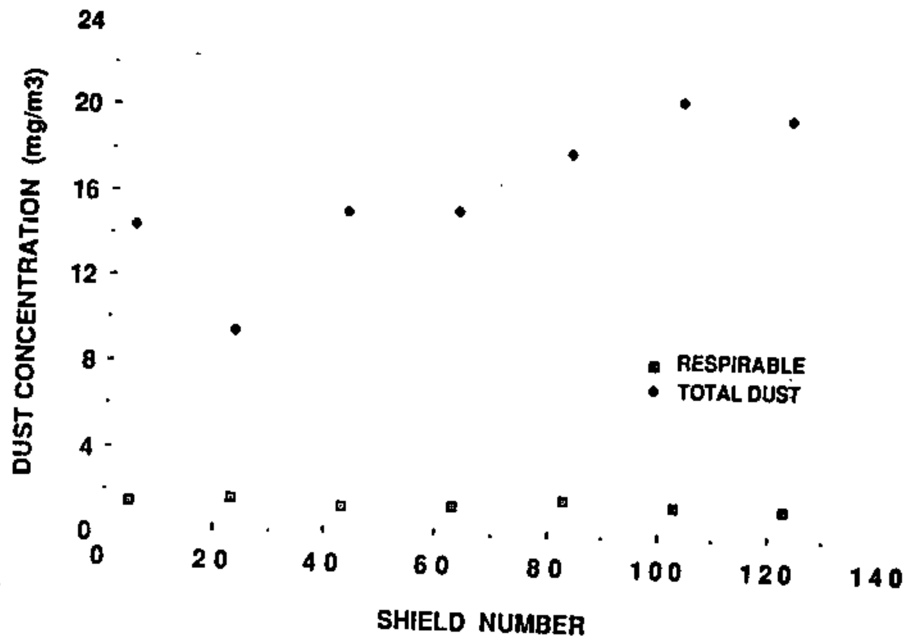


Figure 3. Dust distribution along longwall face (Mine C, Experiment 1).

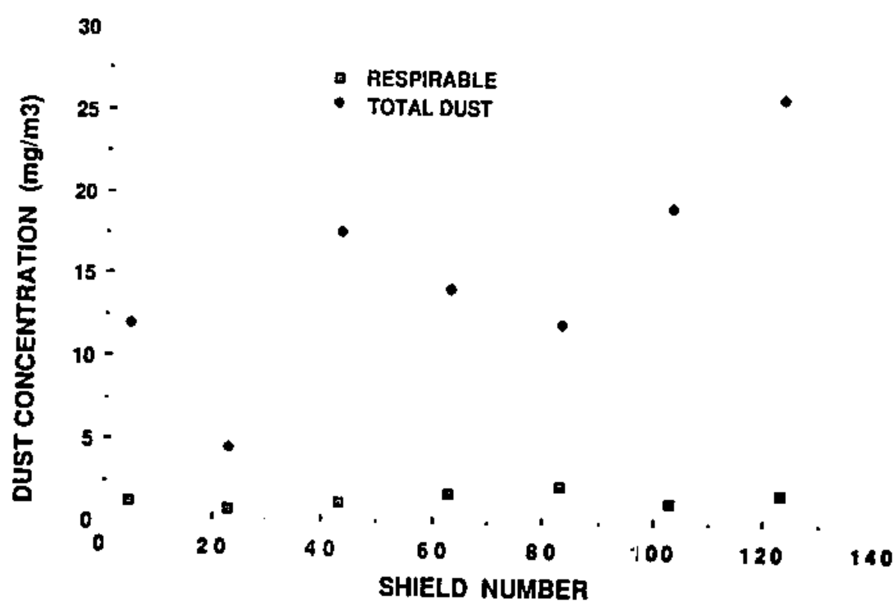


Figure 4. Dust distribution along longwall face (Mine C, Experiment 2).

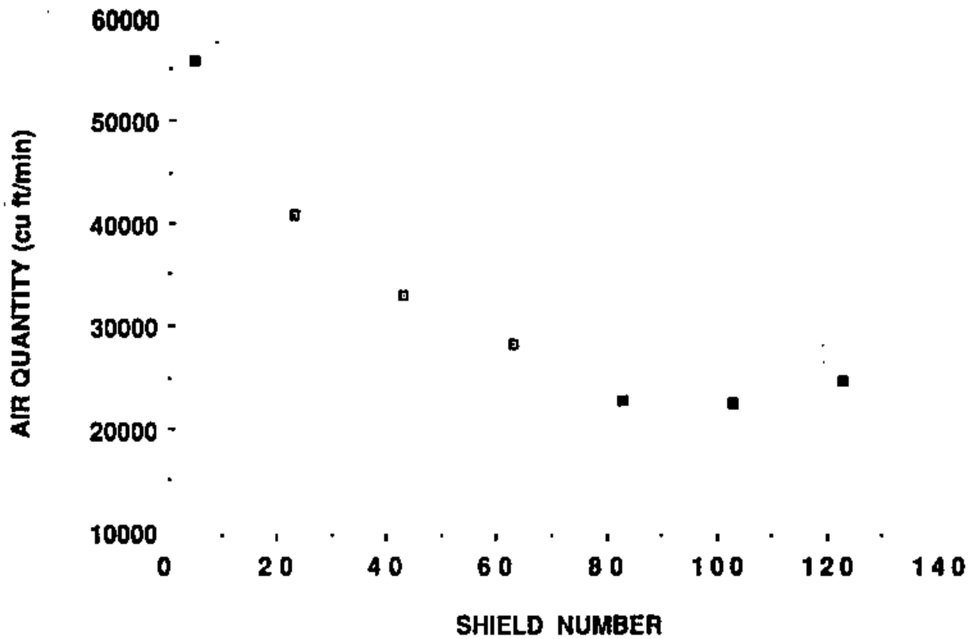


Figure 5. Air quantity along longwall face (Mine C, Experiment 2).

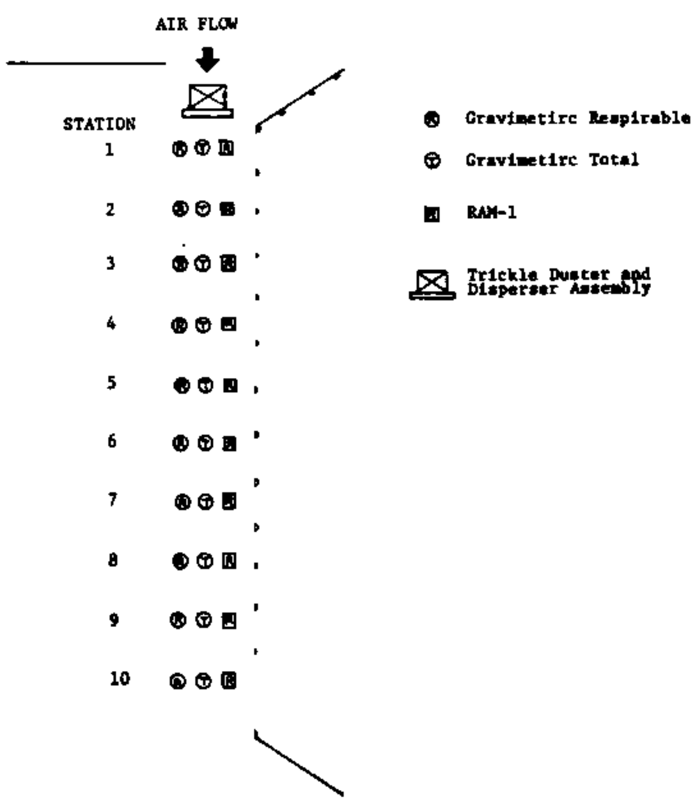


Figure 6. Sampling plan of controlled mine experiments.

PS13/USBM 4221

A Knowledge Based Expert System for Planning Mine Ventilation Systems

Ramani, R. V.; Prasad, K. V. K. and Swaminathan, M.

Introduction

The design of mine ventilation systems is an engineering problem requiring both **insight** and **precision**. The insight required to solve the problem takes several forms. In some cases, insight into the problem solving process is needed in order to organize and codify any given problem scenario into a solvable form. In other cases, insight is required to interpret computed results from which meaningful alternatives can be generated and useful conclusions drawn. In yet other cases, apprentice users need guidance and counselling to make proper utilization of existing programs to arrive at rational and acceptable design schemes. Hitherto most computer programs for mine ventilation (these include network analysis programs, coal dust, methane and diesel exhaust flow models) have focussed on the precision aspect and not much on these insights. The existing programs have provided the user with accurate numerical results and in many cases have reduced the time complexity of arriving at the results by employing efficient computational algorithms.

A complete mathematical model of a situation, implemented as an algorithmic computer program, by itself is not enough for many tasks especially mine ventilation system design. For these programs to be used effectively, the user must be able to a) **analyze** a physical problem situation and idealize it into a form solvable by some algorithmic program and b) **interpret** the program output. The knowledge needed to perform effective analysis and interpretation is qualitative in nature and involves judgement and experience. The mine ventilation design procedure involves substantial use of both numerical computing and qualitative reasoning aspects. A typical design exercise would consist of switching back and forth between the algorithmic computations and the qualitative analysis and interpretation phases. Therefore, to arrive at better mine ventilation designs, a combination or coupling of these quantitative and qualitative aspects is desirable. While the numerical computing aspect of the problem has reached a high level of maturity in mine ventilation (as evidenced by the large number of such programs currently available) the incorporation of qualitative and judgemental information has only recently been made possible through the expert systems approach. In an expert system the the judgemental and experience based knowledge of recognized experts in the field is acquired and represented in computer programs in the form of IF...THEN rules in a symbolic computer language such as LISP and/or PROLOG. Currently several expert system packages (also called shells in ES parlance) are available in the market which permit quick development of expert systems. These shells are typically written in a language such as LISP, PROLOG or C as it is easier to represent symbolic and uncertain information in these languages. The algorithmic programs for mine ventilation are, without exception, written in FORTRAN for better computational efficiency. The objective of this project is to develop an expert system which would incorporate the necessary qualitative and heuristic information for the analysis and interpretation activities and interface and integrate it with an algorithmic program (PSUMVS) The development of this system would contribute to the improved planning of mine ventilation systems from the dust control perspective in particular and the mine environment in general.

Rationale

Among the several methods of achieving health and safety standards in underground atmospheric environment for dust control, the most important ones are, in order of preference: i) Prevention or reduction of formation ii) Removal before becoming airborne such as with dust extractors on roof bolters and scrubbers on miners iii) Suppression using water sprays iv) Isolation as practiced in keeping the mine workers away from dust either by remote control or diversion of dust by spray fans and shearer-clearer systems and v) Dilution by main ventilation airstream and by local auxiliary ventilation. These methods are also generally applicable to the control of gaseous contaminants as well as diesel exhausts. The first four methods have great potential, either singly or in combination, under selected and special circumstances. However, the reduction in ambient concentration of all pollutants is most commonly achieved through dilution by the main ventilating airstream. The importance of this overall ventilation in dust control and environmental planning has been highlighted by the National Academy of Sciences report on 'Measurement and Control of Respirable Dust'. In fact for the effectiveness of dust control methods such as spray fans and shearer-clearer systems, there must be adequate flowing air directed over the machine by the jetting effect of the water sprays. In the same way, for the operation of diesel equipment in coal mines, the quantity of ventilating air is specified for the splits on which these engines will be working. In summary, planning and design of mine ventilation systems so as to ensure adequate main ventilation air streams in all the working areas cannot be overemphasized.

Although the importance of mine ventilation has been recognized from the earliest days of mineral extraction, ventilation planning is, even today, more commonly considered an art rather than a science. In fact, the application of digital computers to solve the pressure quantity problem associated with mine ventilation systems began to make an impact only two decades ago. For scientists and engineers, the two important advantages of computer applications are the increased scientific reasoning and the forced quantitative thinking embedded in computer-oriented models. Their combination has the potential to expand the interpretation capabilities of the analyst and to the generation of a number of alternatives to solve the same problem. It is important to stress that the solution of the pressure quantity problem is only one step in the total planning process. There are important analysis steps prior to this 'solution' stage and even more important interpretation steps after the 'solution' stage. Considerable intuition, experience and judgement are needed during both the analysis and interpretation phases to arrive at good ventilation designs.

Mine ventilation system design is an engineering design problem whose solution requires the steps of perception, idealization, modeling, interpretation, implementation, feedback and control. During the analysis phase, since ventilation system design is a part of the overall mine design, consideration must be given to the interrelationships which exist between the mine infrastructure and mine ventilation system. The adequacy of the input data and their reliabilities are also of paramount importance. In the interpretation phase, an objective analysis of the output is necessary. The step may identify weak areas in the definition of the problem, in which case, redefinition of the problem may be in order. The solution may have undesirable elements or maybe infeasible to implement leading to questions on the design or the data. Also, the solutions, when properly analyzed and interpreted, can lead to better definition of the problems, or superior alternatives to the problem. The design process can be visualized as an iterative process leading to improved perception, idealization, definition and solution of the problem. Since the analysis and interpretation phases require considerable expertise and background in mine ventilation systems and mining engineering, often many of the benefits of computer-aided analysis are not realized in practice. In fact, the complexity of some mine ventilation design problems has grown to such an extent that, user's manuals notwithstanding, it takes a considerable amount of time for the engineer to effectively use computer programs, if at all. Even if the engineer can execute a program, very often the expertise required for the tasks of analyzing a real world problem in terms of the model and interpreting the model output in terms of the overall design objectives and constraints is often lacking. However, there are many recognized ventilation 'experts' --- individuals with expertise, high quality knowledge, and excellent reasoning capability --- who perform the analysis and interpretation tasks with great competence and relative ease.

In recent years, advancements in the field of Artificial Intelligence (AI), particularly knowledge based systems (KBS), have made significant contributions in bringing the knowledge of 'experts' to bear upon the problems of users in such fields as medicine (MYCIN, PUFF etc.), mineral exploration (PROSPECTOR), chemical structure identification (DENDRAL), and structural engineering (SACON), by capturing and coding the knowledge of experts as a set of rules and heuristics through knowledge engineering.

Concurrent with the advancements in capturing expertise through knowledge engineering, there have also been advances in exploration and data acquisition systems for improved characterization of coal seams prior to the development and extraction phases. These advancements provide important ventilation data on variables such as dustiness, methane emissivity, entry stability and hydrological conditions. The establishment of air quantity requirements in underground workings is largely dependent on the methane emission rate. A direct method of analysis can be used on coal cores obtained during exploration to estimate methane emissivity. Another important data item is the stability of entries (expressed as expected stand-up time) used for air coursing. The stability dictates useful life of these entries, flow resistance and leakage. Hydrological conditions in the mine area significantly influence the location of shafts, and heat and humidity conditions in the mine. Important information on water inflow can be obtained during the exploration program. In the past, very qualitative knowledge was used to make ventilation decisions and this resulted in wide variation of encountered conditions from predicted ones. A somewhat more quantified knowledge based on site specific conditions needs to be used.

In view of the above discussion, it is believed that significant advances can be made to ventilation planning and design by incorporating developments in i) data collection activities ii) mathematical, empirical and qualitative knowledge on the system variables such as methane emission, hydrological conditions, dust generation potential, diesel exhaust emissions etc. iii) mine planning and design including ventilation network analysis and iv) expert systems. Therefore, the objective of the proposed work is to contribute to the improved planning of mine ventilation systems, primarily for dust control but also for other mine atmospheric environmental issues, by providing Expert Systems interface to a computer-oriented ventilation planning model.

Scope of Work

The essential elements of an integrated knowledge based mine ventilation system design environment are shown in Figure 1. The highlighted portions in the diagram show items directly relevant to the scope of work in the proposed project.

There are three major interacting elements in the integrated system. 1) the expert system and its input-output interfaces to the design and analysis program (DAP). 2) the design and analysis programs consisting of a ventilation data base and ventilation programs and 3) the actual mine system which is operated on by natural (mine location, seam characteristics, methane etc.) and cultural factors (equipment characteristics, fan operation etc.) resulting in dust, gas, heat and humidity etc. and from which data can be collected on a real time basis. The expert system element is the prime mover of the whole system.

In the design of mine ventilation systems, the first item is the analysis step. Analysis involves the major task of planning and idealization of the given problem situation to make it amenable to engineering analysis. In this step, decisions have to be made regarding some of the following factors:

a) What is the problem to be addressed? Is it dust generation? Is it lack of requisite air quantities? Is it the excessive liberation of methane? Is it a combination of the above?
b) Interrelationships of the problem with other mine design aspects e.g. ground control, mining method and extraction, hydrology, regulations etc. have to be identified.
c) Since an engineering problem is rarely amenable to engineering analysis as is, the problem has to be idealized with simplifying assumptions. A major decision has to be made regarding the relevant assumptions to make so as not to sacrifice the purpose of the analysis.
d) From an actual mine map the mine ventilation network geometry has to be set up.
e) An appropriate model will have to be hypothesized e.g. the gradient transport theory of mass transfer.
f) An appropriate design and analysis program will have to be selected commensurate with the availability and quality of the input data and desired accuracy of results and
g) The data necessary for the model has to be developed.

Following the analysis step, the selected DAP is executed and after this solution stage, interpretation of the output will have to be done. In the interpretation stage the model results will have to be interpreted and any discrepancies diagnosed in terms of the overall design objectives. Among the questions arising at this stage are the following:

a) What do the flow directions, air quantity, dust and methane concentration values mean and imply?
b) What are the fan operating conditions? Are they realistic?
c) Are the conditions critical in any branch of the network?
d) If so what could be the possible reasons?
e) Are the model results realistic?
f) How sensitive is the solution?
g) Is the hypothesized model a valid idealization of the problem situation?
h) What are the refinements which can be made? OR What other model alternatives can we choose from?
i) Which one of the available options should be chosen?

Most of the knowledge involved in answering these questions and making these decisions is judgemental, intuitive and heuristic. The knowledge base of the expert system will be designed to incorporate this judgemental knowledge. Knowledge will be acquired from public domain sources (USBM RIs and ICs on mine ventilation, relevant journal articles, ventilation engineering textbooks etc.) and from recognized mine ventilation experts in USBM, MSHA, industry and the academic community.

The inference engine consists of the control strategy to apply the knowledge in the knowledge base to aid analysis and interpretation and will invoke the design and analysis programs (as and when required) through the input interface and obtain the relevant results through its output interface to the DAP.

The DAPs consist of a ventilation data base and ventilation programs. The data base consists of two parts 1) a static part which contains problem specific information such as fan characteristics, airway resistances, network geometry and 2) dynamic part receiving synthesized and reduced time varying data from the mine monitoring system on variables such as air quantity, methane concentrations, dust concentrations. The ventilation programs part contains detailed algorithmic programs relating to ventilation network analysis (PSUMVS), dust flow, diesel emissions programs etc.

The mine monitoring system, in addition to feeding time varying data to the dynamic data base, also permits direct operations management control of the mine system.

The thrust of the proposed project is in the area of ventilation design and not in ventilation system control. Towards this end the project will consist of the following three major phases:

PHASE I: Evaluation of AI/ES tools and their application to the planning problem (October 1, 1987 -- September 30, 1988).
PHASE II: Development of the analysis and interpretation knowledge bases for the expert system (October 1, 1988 -- September 30, 1989).
PHASE III: Application Demonstration (October 1, 1989 -- September 30, 1990).

The three phases represent a continuum, and the various aspects of evaluation, development and application (Phase III) will continue throughout the project. In fact, validation and demonstration of the work in each of the phases will be an on-going activity. A more detailed discussion of the work elements in each of the phases follows.

PHASE I (October 1. 1987 -- September 30. 1988).

The overall objective of this phase is to select an appropriate ES shell for the knowledge based system development and to develop input output interfaces for this shell with DAPs. Specifically, this will involve the following tasks:

TASK 1: Evaluation of ES shells: The evaluation will be done on the shells currently available in the market to determine overall suitability for the ventilation problem. Factors such as versatality of the inference engine, ease of knowledge coding and modification, capability for uncertain reasoning, friendliness of the user interface (if available), size capability and ease of developing interfaces will form important dimensions along which the evaluation will be carried out. Since the developed system is intended to be widely distributed, more attention will be given to mini or microcomputer based shells.

TASK 2: ES-PSUMVS input output interface development: This task will involve revising the input and output options of PSU/MVS to facilitate its easy invoking from the ES. The first step would involve reducing the raw input data to PSUMVS to the essential minimum and generation of dependent information through an input generation routine. Likewise, the output options will be modified to suppress passing back of unnecessary output from the program to the ES. In other words, the output will be made selective. The second step is to a) develop a consultative input interface routines which will be called by the ES to help the user create the input data file for PSUMVS and transform the ES data objects into appropriate PSUMVS function arguments and 2) develop an output interface to transfer the PSUMVS output back to the ES by converting the output values to ES data objects.

TASK 3: Literature review of a) Knowledge on mine ventilation system (MVS) design and b) Heuristics and guidelines set by USBM. MSHA. industry : This task will involve a thorough review of literature available in the public domain relating to MVS design. There is a wealth of information in USBM ICs and RIs, MSHA guidelines, published journal articles and textbooks on ventilation engineering.

TASK 4: Development of a Ventilation. Dust. Gas. Diesel exhaust model library: This task will involve a compilation of all existing computer models relating to the design of MVS to form the 'ventilation programs' part of the Design and Analysis Programs section in Figure 1. The library will initially consist of PSUMVS, dust generation and flow model, methane model and diesel exhaust model. PSUMVS is the most widely used ventilation simulation model in the industry.

PHASE II (October 1. 1988 -- September 30. 1989).

The objective of this phase is to build the knowledge base for the ES to aid the analysis and interpretation stages of the MVS design process.

TASK 1: Development of analysis knowledge base: This task will draw on the information gathered in Phase I Task 3 to derive facts and rules relevant to the analysis stage. Causal associations will be established between the rules to account for the various interrelated factors in MVS design. These facts and rules will help the user i) instantiate the problem situation correctly into an appropriate model and ii) develop input data for the algorithmic program through an interactive dialog consistent with the protocols of the ES-PSUMVS input interface. The input parameters specified by the user might be uncertain which will be accounted for by attaching an index of reliability to each data item.

TASK 2: Development of interpretation knowledge base: This task is similar to Task 1 but will involve knowledge for the interpretation stage. Rules will be derived from the information in Phase I Task 3 so that the user is aided in developing alternatives for consideration and also in modification and redefinition of the idealized model based on the output from PSUMVS.

TASK 3: Interview of experts: This task will involve selection and interviewing of recognized MVS design experts in industry, USBM, MSHA and other institutions for obtaining heuristic knowledge. The motive is to elicit basic strategies which the experts use for MVS design -- which facts are established first by the experts, do experts make initial guesses based on tentative information, what questions do experts ask to redefine the guess, in what order do the experts pursue each of the subtasks etc..

TASK 4: Execution of the ES-PSUMVS knowledge based system: This task will involve the execution of simple (not trivial, not too complex) ventilation systems design examples on the developed system. The system will be evaluated for consistency -- by comparing the results from the various examples and by checking any inadvertant contradictions in the knowledge base rules and heuristics -- and efficiency -- by evaluating the reasoning chain for each problem.

Work in this phase will draw on recent USBM work in mine ventilation related expert systems viz. continuous miner and longwall section dust control and methane control expert systems, and past work on expert systems for emergency management and ventilation control.

PHASE III (October 1. 1989 -- September 30. 1990).

This will be a validation and demonstration phase where the system will be first validated and then demonstrated to users in the industry and government (USBM,MSHA). In addition to demonstration, the system will also be evaluated by obtaining feedback from the users.

TASK 1: Validation of the developed Knowledge Based Expert System: In this task the performance of the system will be validated by taking example problems and comparing the conclusions given by the system with the experts' conclusions. While the conclusions of the system and the experts might be same it is also necessary to compare the reasoning process of the system with that of the experts to ensure that the system is using the right rules to derive the conclusions. In particular, the KBES will be validated by considering questions such as i) Is the knowledge base consistent and complete or does it need to be extended? ii) Is the system coming up with the right answers for the right reasons? iii) Is the embedded knowledge consistent with the experts? This will help in identifying any inadequacies and/or inconsistencies in the system and in fine tuning the system to conform to experts' line of reasoning. In this task, use will be made of the techniques used in the validation of the USBM developed expert systems.

TASK 2: Modifications and refinements on the basis of validation: This task will depend on the ouput and feedback generated in Task 1 and, if necessary, will involve a restructuring and modification of the knowledge base. There might be several iterations between Tasks 2 and 1 in the validation process until the system is satisfactory.

TASK 3: Application Demonstration: In this task the developed system will be demonstrated to users in the industry and government to obtain feedback for further evolution of the system. In particular, issues relating to the user interface and 'friendliness' of the system in guiding a user through the analysis and interpretation tasks will be gauged from user response.

TASK 4: User's Manual and Final Report: This task will involve the preparation of a user's manual with case examples to acquaint a new user to the capabilities and running of the system. A final report will also be prepared detailing the procedures used in various stages of the the system development lifecycle and recommendations.

Progress to Date

1) Evaluation of expert system shells and environments. Major criteria for evaluation:

Forward and backward chaining
Interactive transfer of data to external FORTRAN programs
Scheme for handling uncertainty in data and rules
Explanation and justification procedures

Over 30 shell vendors and research institutions have been contacted. In addition to technical information, demonstration copies of the shells have been acquired and evaluated whenever possible. People in industry and universities having experience with coupled systems have also been contacted.

2) The PC version of PSUMVS has been modified for SI unit input and output. This same version is being used for the development of interactive natural language type input and output routines.

3) Literature review for public domain sources of heurisitic information relating to mine ventilation system design is in progress.

4) Development of a program library consisting of ventilation, diesel and dust programs and other expert systems available is also in progress. Expert systems

dealing with dust and methane control in coal mines have been acquired from the Bureau of Mines.

Application of Research Results

In the design of mine ventilation systems, the integration of algorithmic programs with expert systems for analysis and interpretation would be a major step in enhancing design capability of mine ventilation engineers. The benefits accruing from a knowledge based approach are:

a) Permanent availability of timely, high quality and diverse expertise for analysis and interpretation.

b) Assistance in good characterization of the ventilation problem situation and proper consideration of relevant (and critical) factors.

c) Avoidance of misinterpretation of program outputs and assistance in faster convergence of the iterative design process towards the goal.

d) Ability to solve ventilation problems where incomplete or uncertain data only is available.

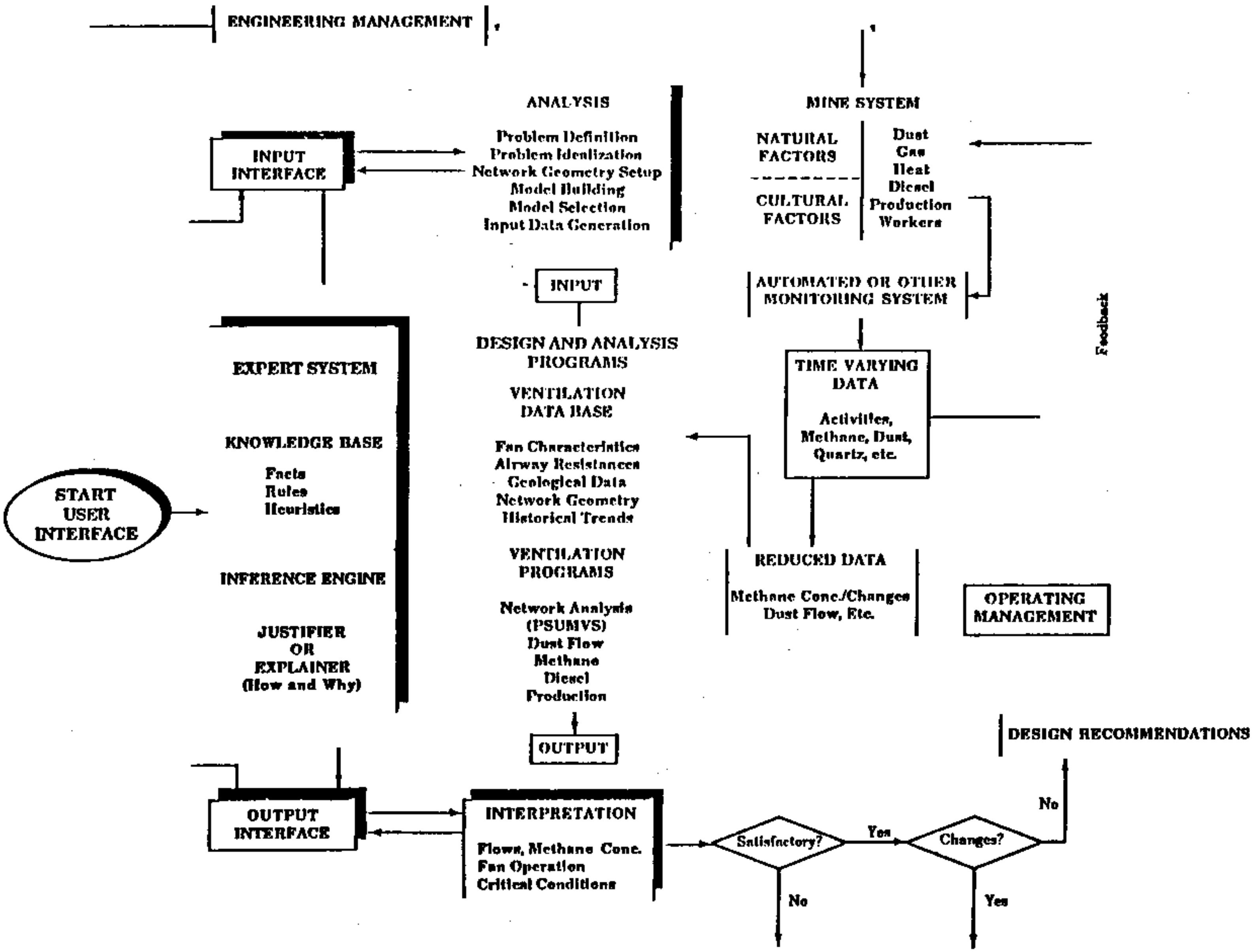
e) Enhanced training of new engineers and analysts.

f) Increased productivity and better ventilation designs.

Technology Transfer

The developed system is intended to be made available in a PC environment with runtime versions of the expert system. This would permit easy distribution of the system and reduce some of the hardware dependence of mainframe applications. A paper has been published discussing the broad theme of expert systems and areas in mining engineering where they may have fruitful applications. The annual reports and the final project report will highlight the different stages of the system development process which could help ES development in other areas of mine engineering and design and also suggest pitfalls to avoid in the development process.

Figure 1. A logic flow diagram of a knowledge based system for planning mine ventilation systems.



WV11/USBM 5410

Development of Mine Dust Distribution Models For Working Faces

Wang, Y. J.; **Chiang**, H. S.; Tsang, P. and Ueng, H. S.

INTRODUCTION

The objective of this project is to develop a mathematical model for dust distribution at working faces, integrating the results of field measurements. This project was designed to include the following topics: (1) field instrumentation of airborne dust concentration, size distribution, and airflow distribution in the longwall face area; (2) development of a mathematical model for predicting airborne dust distribution, based on the characteristics of dust sources, airflow distribution, and mining conditions; and (3) model validation.

Since the velocity profile function obtained from field measurements is one dimensional and does not provide sufficient information, it has been decided to numerically solve for the air velocity and pressure distributions assuming an isothermal incompressible turbulent flow in the area simulation working-face geometry.

RATIONALE

The continuous movement of shearer operation and support advancement in a longwall face causes not only the ventilation (or airflow) condition but also the dust distribution very complex. It is important, from a view point of dust control, to be able to predict the dust distribution along a longwall face, given the characteristics of dust sources and the ventilation condition. To improve the technique of prediction the dust distribution in a longwall working face, field measurements and mathematical modeling were proposed.

INSTRUMENTATION

Underground dust instrumentation was carried out in five longwall faces. In addition to 7,650 measurements using GCA RAMs, 360 respirable dust samples of gravimetric samplers were obtained by both mobile and stationary methods. Recent analyses of four highly productive longwall panels showed that, among a total of 3,077 RAM readings, 65% had dust concentrations less than 2 mg/m^3, 15% between 2 to 3 mg/m^3, and 20% greater than 3 mg/m^3. Furthermore, the studies conducted under this project also showed that the shearer operation and the support advance are the two major dust sources. The distribution of the airflow velocity in the face controls that of the airborne dust; however, within a certain range of the shearer or advancing support, the distribution of airborne dust concentration changes constantly.

The amount of airborne dust generated by the support advance depends on the immediate roof conditions and varies with the support advancing operation (i.e., leg lowering, support advancing, and leg rising). Under the combined influence of shearer operation and support advancing, the airborne dust concentration along the walkway was usually twice as high as when only the shearer was cutting or cleaning. In addition, the instant sampling with RAMs showed that during coal sloughing, the airborne dust concentration increased rapidly from 5 to 12 mg/m³. Although it appeared for only a short time, the dusty air moved directly toward the shearer because coal sloughing was severe during shearer cutting and cleaning.

The dust samples collected from the longwall faces were analyzed by the Coulter Counter's method. The results obtained show that the size distribution curves, at any location along the face, skew heavily toward the fine dust range. The portion of the fine dust (1 to 5 microns in size) is more than 70% of the total airborne dust.

The field studies also identified the two major factors that greatly affect the air velocity distribution: (1) changes in the cross-sectional area, and (2) water sprays mounted on the shearer.

Changes in the cross-sectional area. The continuous movement of the shearer followed by the advancing supports significantly changes the cross-sectional area for the ventilation. This in tern contributes to the change in the air velocity and its distribution. As a result, the airflow redistributes constantly near the shearer and advancing supports. In addition, the support advance also causes the air leakage to the gob. For these reasons, in the area close to the shearer and the advancing support, the distributions of air velocity and, consequently, the airborne dust become very complicated. Their distributions vary with the location in the face. It would be interesting to study the dynamic airflow pattern and its controlling factors in detail so that proper operational procedures can be developed to control the airflow distribution. In particular, the optimal distance between the advancing supports and the shearer should be studied.

Water sprays. The water sprays mounted on the shearer not only suppress the airborne dust but also redirect the airflow pattern. However, the effects of water sprays on the distribution of the air velocity at and near the shearer have not been studied in detail.

DEVELOPMENT OF MATHEMATICAL MODEL

An explicit form of finite-difference equations for turbulence dispersion of incompressible flow were derived to model the dust distribution in the working area. Based on the finite-difference equations, a FORTRAN 77 coding for predicting the dust concentration was completed and tested. The input includes airway dimensions, airflow profile function, dust size distribution coefficients, and dust dispersion coefficients.

Since the velocity profile function obtained from the field measurements was one-dimensional, the numerical result obtained was less than desirable. The development of a computer program for solving the air velocity and pressure distributions, assuming an isothermal incompressible turbulent flow, is in progress.

CONCLUSIONS

The field measurements showed that about one-third of the measurements exceeded 2 mg/m^3 limit. The fine dust (under 5 microns) was generally over 70% of the total airborne dust. Shearer movement and support advance are the major dust sources and also the major factors for airflow and dust distributions.

A more in-depth study of airflow distribution is needed for better predicting dust distribution.

CONTINUING WORK

Continuing work is focussed on refining the dust dispersion model and completing the air velocity model.

TECH TRANSFER

One paper has resulted from the field studies. Two more papers are expected from the modeling and numerical computations.

MN2/USBM 2702

Experimental and Theoretical Aerodynamic Diameter Analysis of Coal Dust

Marple, V. A.; **Rubow**, K. L.; Zhang, X. and Ananth, G.

INTRODUCTION

The primary objective of this project is to devise methods to determine experimentally and theoretically the aerodynamic diameter of irregular shaped particles. The aerodynamic diameter was chosen as the most important parameter in defining the particle size since it defines where the particles will deposit in the respiratory tract. Therefore, this is an important parameter when studying particles that could cause Coal Workers' Pneumoconiosis.

The theoretical study involved the numerical solution of the Navier-Stokes equations, the governing equations for fluid flow, to determine the flow field around the particle. This technique has been widely used for determining the flow field within instruments and then for determining the trajectory of particles within the flow field. In the work here, the grid was made much smaller than the particle and the details of the flow field around the particle were calculated. From the details of the flow field, it is possible to determine the drag on the particle, and hence, its aerodynamic diameter.

The experimental work involved collecting particles in a centrifuge classifier and inspecting the particles in a scanning electron microscope (SEM) to determine the details of their irregular shape. The aerodynamic diameter was then calculated using the numerical methods and the results compared to the aerodynamic diameter as determined in the classifier.

This project has led to important advances in two areas of aerosols science:

1. A theoretical technique has been developed by which the aerodynamic diameter of any regular or irregular shaped particle can be determined as a function of the particle's orientation or as an average over all particle orientations.

2. A technique of examining irregular shaped particles in an SEM after the particles are shadowed in two orthogonal directions has been developed. In the course of this development, it has been found that inspecting a particle in an SEM or any type of microscope where only one two-dimensional view of the particle can be seen, can lead to drastically erroneous conclusions about the particle size and shape. A far more detailed view of the particle is obtained by looking at the shadows of the particles in two orthogonal directions as well as the plane view of the particle. Comparison of the conclusions that could be drawn by looking at the particles in only two dimensions and the particles with shadowing, reveals that the shadowing technique is a far superior method for particle size and shape analysis.

RATIONALE

It is commonly understood that aerosol particles may be injurious to human health if they are of a size that enables them to enter the respiratory tract. Coal Workers' Pneumoconiosis (CWP) is one disease known to be caused by coal mining related particles.

The location in the respiratory tract where the particles are deposited is primarily a function of the equivalent aerodynamic diameter (EAD) of the particle. The equivalent aerodynamic diameter is the diameter of a spherical particle with a density of 1.0 gm/cm^3 with the same falling speed as the particle in question. For a spherical particle the calculation is rather simple in that the equivalent aerodynamic diameter is simply the diameter of the particle in question multiplied by the square root of the density of the particle. For irregularly shaped particles, such as coal particles, there is no simple way to make the EAD calculation and, therefore, their deposition locations in the respiratory tract, is difficult to estimate.

The normal method for determining the aerodynamic diameter of particles has been to experimentally measure the size of the particles in a settling chamber or with an inertial classifier such as an impactor, cyclone or a centrifuge, since inertial classifiers have the property of classifying the particles according to their aerodynamic diameters. However, these devices can only give limited information on the EAD of a single particle with a specific shape. Impactors and cyclones, for example, collect particles in size ranges and not at a specific size, so the determination of the EAD of a specific particle is not possible. A centrifuge, on the other hand, can measure the EAD of a specific particle, but the equipment is costly and procedure laborious, and it may not be possible to disperse a particle of a specific shape into the centrifuge. The centrifuge can be used to determine the EAD of clusters of spheres in various arrays, but introducing particles of a specific irregular shape may not be feasible. Furthermore, the EAD is a function of the orientation of an irregularly shaped particle and the orientation of a particle in an inertial classifier is unknown. The orientation may also vary as the particle passes through the classifier.

Because of the difficulty in experimentally determining the EAD of an irregular shaped particle, a technique is needed to theoretically calculate the EAD of any shape particle. A numerical technique using finite difference methods to calculate the flow around the particle appears currently to be a viable method to achieve these goals.

SCOPE OF WORK

The starting point of this work is computer programs which numerically solve the Navier-Stokes equations to determine flow fields. These programs have been used in our laboratory to determine the flow fields through sampling instruments. Once the flow field is known, particle trajectories can be traced through the flow field by solving particle motion equations. This has been very successful in determining the sampling characteristics of inertial classifiers such as impactors, cyclones and virtual impactors. In this work, the numerical programs are to be used to determine a flow field around single particles, thus leading to the calculation of the aerodynamic drag and, subsequently, its aerodynamic diameter.

Before the technique can be applied to irregular shaped particles however, the technique must first be proven by being able to predict the correct aerodynamic drag on regular shaped particles such as spheres, cylinders, and discs: particles for which there are known drag values. If the program can be demonstrated to accurately predict these drag coefficients, then it can be applied to irregular shaped particles. To further substantiate the accuracy of the technique to determine the EAD of irregular shaped particles, the calculated aerodynamic diameter of irregular shaped particles is to be compared to those determined experimentally. If this final check is satisfactory, a technique will have been developed for theoretically determining the aerodynamic diameter of any irregular shaped particle in any orientation. Details of applying the technique to regular and irregular shaped particles are described below.

Application to Regular Shaped Particles

The two-dimensional analysis has been applied to single spherical particles, cylinders in cross flow, disk shape particles and spherical particles connected in

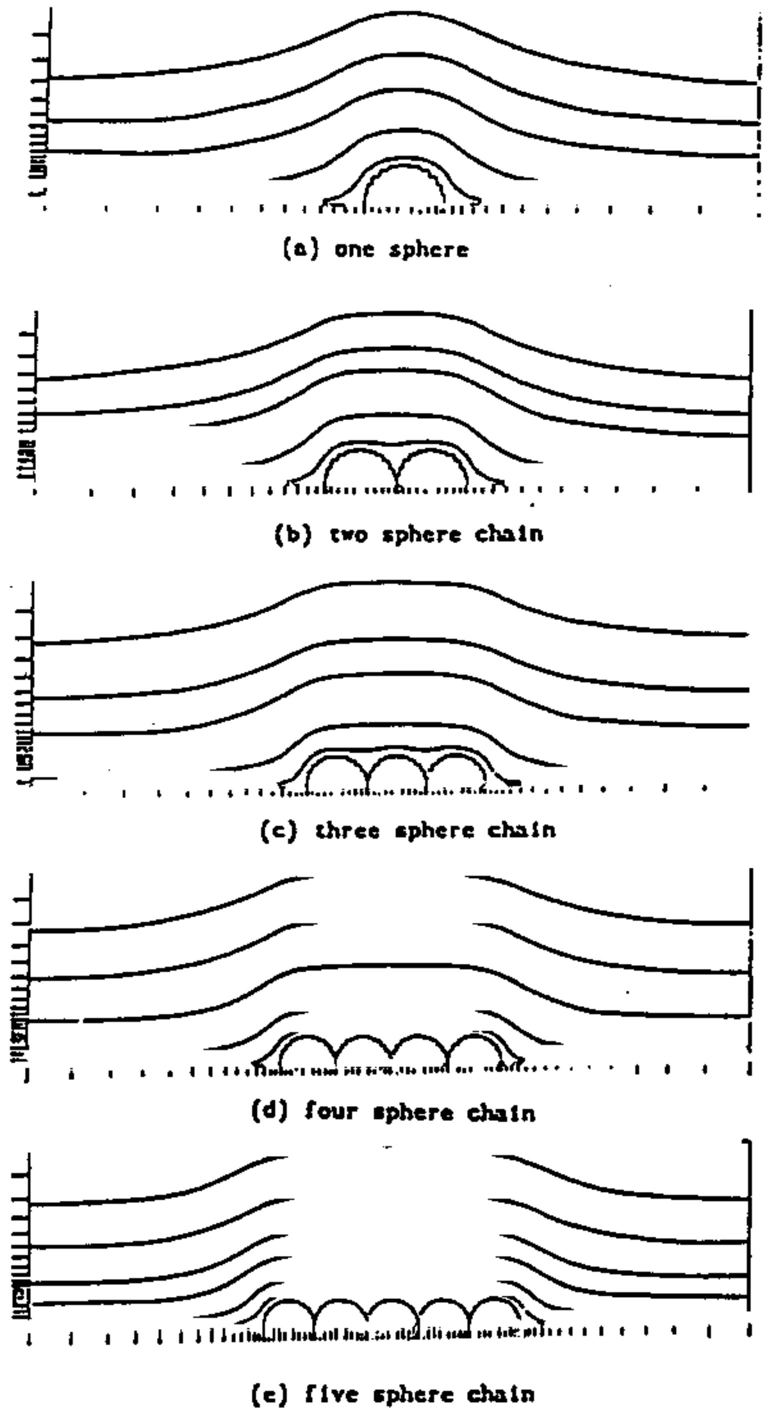


Figure 1. A logic flow diagram of a knowledge based system for planning mine ventilation systems.

chains. In all cases the shapes were selected because there was a prior analytical or experimental determination of the drag force on the particle by other investigators, since it was the object of this portion of the project to gain confidence in a numerical technique.

For the single spherical particle, the drag force from the numerical solution was compared to the drag force predicted by Stokes law. In general, it was found that the calculation of the drag force on a particle agreed within four percent of that determined by Stokes law. This was believed to be quite good since the number of node points defining the particle was only approximately 40 in all cases. The sphere is approximated by 11 stacked cylinders, creating steps along the surface of the particle. As the number of grid points (cylinders) increases, the size of the steps will decrease and more closely approximate the sphere.

For the case of cylinder in cross flow, which utilized rectangular coordinates, only one case was analyzed (10 μm diameter) and compared to the analytical solution. There was good agreement between the two techniques with a difference of only 2.5%. Again, the cylinder was defined by about 40 node points.

The next configuration studied was the disk in cross flow which again utilized cylindrical coordinates. In the case of the disk the analysis was run for several values of the Reynolds Number. The error in the drag forces increased with decreasing Reynolds Number from approximately 1.5% at a Reynolds Number of 0.13 to about 6% at a Reynolds Number of .00326.

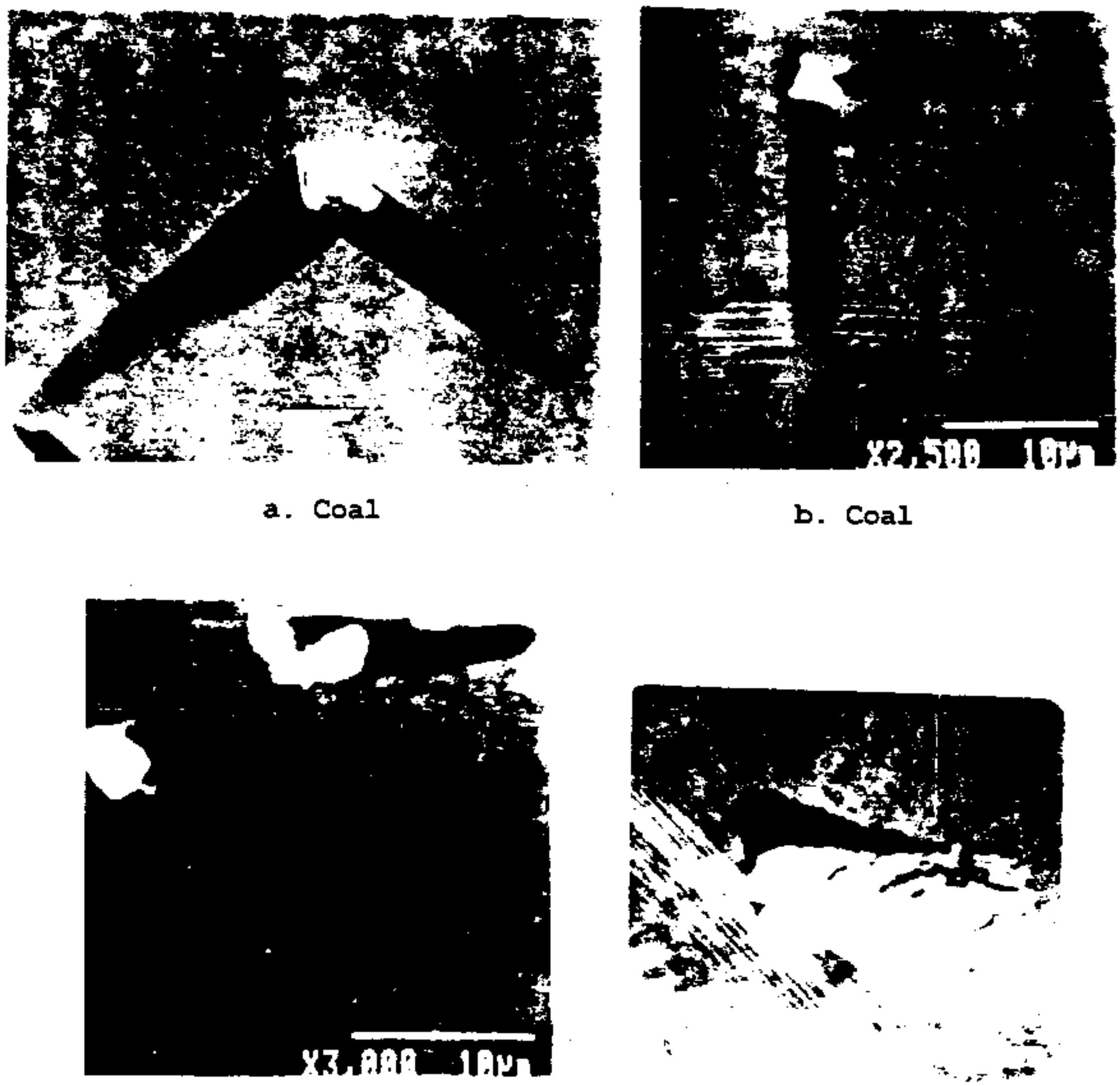
The final test of the numerical analysis technique was to study spherical straight chain agglomerates. Figure 1 shows the flow field around the chains containing from one to five spheres. In this case the dynamic shape factor of the straight chains was calculated and compared to those values reported from experiments performed using a centrifuge to determine the shape factor. The numerical technique was performed on primary spheres of sizes 0.4, 1, 4 and 10μm diameter and compared with the experimental results which used latex spheres of several particle sizes on the order of 1 μm diameter.

Application to Irregular Shaped Particles

In this step of the project, the numerical program was expressed in three dimensions since an irregular shaped particle does not have a plane of symmetry. To verify that the program will yield the correct results, it was decided to apply the technique to analyzing irregular shaped particles collected in a centrifuge. Since the centrifuge can provide a measure of the aerodynamic diameter of the particle, the comparison can be made between the aerodynamic diameter calculated with the numerical technique to that determined by the centrifuge.

In cooperation with the Lovelace Inhalation Toxicology Research Institute, test particles were collected on TEM grids placed along a metal foil in a centrifuge. The particles were then analyzed within the SEM. At this point, a problem was encountered in that the SEM only provides a two-dimensional view of the particles and it is necessary to know the three-dimensional shape of the particles as an input to the numerical solution technique. Therefore, a technique was developed whereby the particles were shadowed with a gold film in two orthogonal directions prior to inspection with the SEM. For the shape of the two shadows plus the shape of the plane view of the particle it was possible to reconstruct the three-dimensional shape of the particle.

Four examples of this technique are shown in Figures 2 and 3. In these figures it should be noted that the shadows indicate the shape of a particle can be substantially different than what may have been inferred from the two-dimensional view of the particle. In fact, in some cases, the three-dimensional shape is dramatically different from that observed in the two-dimensional view. It is now recommended that the shadowing technique be used in all cases where particles are studied by SEM analysis. Figure 3 shows the digitized particles that have been inferred from the SEM photographs in Figure 2. Note that the shape of the particles must be built from cubes and, thus, the particles are approximated by a set of parallel planes of various shapes. Also shown in the Figure 3 are the numerical and experimental results of the aerodynamic diameters of the particle.



a. Coal

b. Coal

c. Coal

d. Talc

Figure 2. Photomicrographs of coal and talc particles shadowed in two orthogonal directions.

Since the particles are of irregular shape, the aerodynamic diameter is dependent upon the fluid drag on the particle. Thus, the orientation to the direction of the airflow will have an influence on its aerodynamic diameter. To investigate this phenomenon, two particles were analyzed in three orthogonal directions to determine the effect of orientation on the calculated aerodynamic diameter. These results, shown in Figure 4, indicate that the orientation does have an influence on the

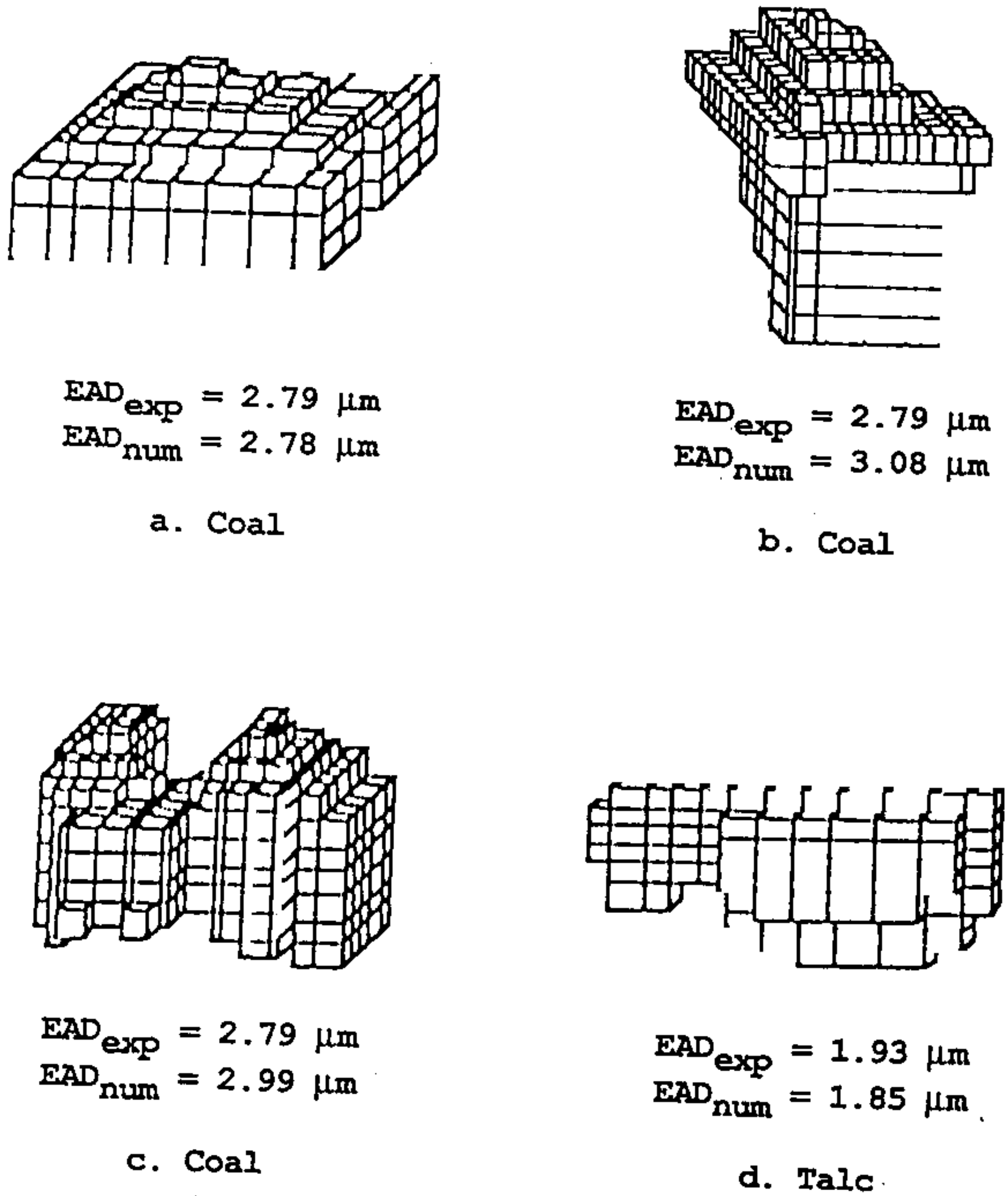


Figure 3. Digitized three-dimensional representations of particles in Figure 2 and a comparison of the numerically and experimentally determined EAD's.

aerodynamic diameter. However, the influence is not as large as may be expected. Also, shown in this figure is the experimental aerodynamic diameter which can be compared to the calculated aerodynamic diameter for the orientation of the particle as found upon the centrifuge foil. It must be realized, however, that the particle could have tumbled as it was deposited on a foil and the orientation of the collected particle may not be an indication of the particle's orientation as it approached the foil. However, there is good agreement between the experimental and calculated aerodynamic diameter for the same orientation assuming that the particle was not tumbling.

CONCLUSIONS

Theoretical calculations of the flow around particles by numerical methods has led to an important technique for determining the aerodynamic diameter of an individual irregular shaped particle that may be of interest to researchers. For example, if the aerodynamic diameter of a particle (or particles) are desired, the particles can be shadowed in two orthogonal directions and inspected in an SEM. The shape and size of the particle revealed by the SEM is input to a numerical computer program which calculates the aerodynamic diameter as a function of orientation or, if desired, the average aerodynamic diameter can be calculated. This is the first time that it has been possible to determine the aerodynamic diameter of any individual irregular shaped particle that may be of interest.

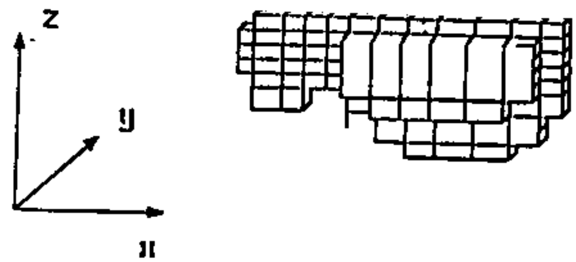
APPLICATIONS OF RESEARCH RESULTS

There are two applications of the numerical technique for determining the aerodynamic diameter of irregular shaped particles. One application is to determine the shape factors of a variety of standard shapes. For example, the shape factors for a variety of classes of particles with various aspect ratios could be determined and tabulated in a catalog. These shapes would include rectangular shaped particles, flake-like particles, sphere-like particles, elipsoid shaped particles or other standard geometrical forms. Most particles could be compared to one of these standard shapes with the appropriate aspect ratios and a close approximation to its shape factor obtained. However, if more information on a particular particle is required, the second application of the numerical technique would be to digitize the shape of the particle and determine its aerodynamic diameter as a function of orientation.

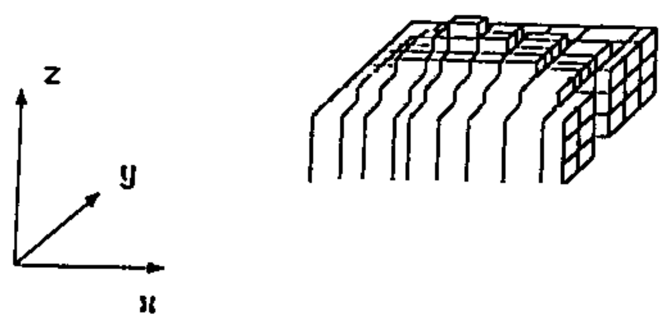
Future Work

The ability to theoretically determine the details of flow around a particle and a subsequent calculation of its aerodynamic drag, pressure distribution around the particle and the aerodynamic forces at various points on the particle is a powerful analytical tool. It will now be possible to place the particle into a flow field that is nonuniform, such as in the boundary layer close to a surface, and determine if the particle will have a tendency to tumble, be lifted from the surface, or move towards the surface. This is important in determining the deposition of particles in pipes, or in airways of the lungs.

The technique can also be applied to determining what orientation the particle will take as it falls through still air, or in air where the velocity is nonuniform, such as in a boundary layer. This can be accomplished by analyzing the aerodynamic forces on various parts of the particle as dictated by the digitized portions of the particle and examine the torque about the center of gravity of the particle. For example, if a particle is falling in still air the orientation of the particle will be such that the summation of the drag vectors on all portions of the particle will be in line but opposite direction as the force due to the center of mass as influenced by gravity.



Direction of the flow	K	Do (μm)	Experimental Results
x	1.26	2.17	----
y *	1.74	1.85	Do=1.93 μm
z	1.34	2.10	----



Direction of the flow	K	Do (μm)	Experimental Results
x	1.17	2.89	----
y	1.154	2.92	----
z*	1.27	2.78	Do=2.79 μm

* Direction of the particle settling

Figure 4. Comparison of the numerically determined EAD's for three orthogonal orientations of a talc and coal particle.

TECH TRANSFER

This work has been the presented at two conferences and published in two conference proceedings. Currently, three journal articles are being prepared for publication. Additional results will be reported at conferences during the next year

REFERENCES

Marple, V. A., Z. Zhang and B. Y. H. Liu, "Numerical Technique for Calculating the Equivalent Aerodynamic Diameter of Particles", Proc. of the Int. Symposium on Respirable Dust in the Mineral Industries, University Park, PA, Oct 14-16, (1986).

Marple, V. A., K. L. Rubow and Z. Zhang, "Experimental and Theoretical Measurement of the Aerodynamic Diameter of Irregular Shaped Particles", Proc. of the VIIth Int. Pneumoconioses Conf., Pittsburgh, PA, Aug., (1988).

4.5
Control of Dust Particle Generation

PS 1/USBM 4201

A Fracture Mechanics Study of Crack Propagation Mechanism in Coal

Bieniawski, Z.T. and Zipf, Jr., R.Karl

Direct costs of dust induced illnesses from coal mining exceed $1 billion per year, yet fundamental mechanical knowledge of particle generation is meager. This research utilizes fracture mechanics theory, experiment and application to explain how fine coal fragments (respirable dust) are generated during coal cutting.

The following four step mechanism is proposed: 1) development of a crush zone, 2) macrocrack propagation, 3) shear movement along macrocracks and 4) additional fragmentation from shear. The cutting tool interacts with coal material and its inherent flaw structure producing fine coal fragments near the tool grading into coarser fragments further away. Two fine fragment sources exist: the crush zone and the rough fracture surfaces. Fine particle creation is controlled in part by fracture toughness and also the inherent flaw geometry. Basic relationships are developed between the flaw geometry and fine fragment generation.

Experimentation centers on extensive mixed mode fracture toughness testing. The system developed herein provides a record 117 measurements concluding that K_{Ic} is a reliable material property despite coals' enormous heterogeneity. Strain energy density theory adequately describes the onset and direction of crack growth under mixed mode loading conditions. Tentative relations exist between K_{Ic} and fracture surface roughness and fracture velocity.

Fracture toughness values are applied in crush zone size calculations with a boundary element program containing a failure criteria based on strain energy density theory. From postulates about the role of inherent flaws in fragmentation, the crushing extent is the locus of active 10 micron flaws. The calculations demonstrate the effect of attack angle and tool geometry on crushing extent and fine fragment formation. Future research must measure the fracture toughness of coal constituents at a microscopic scale and quantitatively describe their inherent flaw structure.

Fracture Mechanics Study of Crack Propagation in Coal

Research Objectives

The major aim of this research is to develop a fundamental understanding of how fine fragments of coal (respirable dust) are generated during a fracture process based on the most up-to-date scientific principles of fracture mechanics. Present knowledge of the basic mechanics of this process is meager at best. Therefore, the first objective is to develop a hypothesis that sequentially describes the mechanics of fine fragment formation during a generic coal material/coal cutting tool interaction. This hypothesis incorporates current understanding of mixed mode fracture mechanics and the micromechanics of crack growth that leads to fragmentation at a microscopic scale. Furthermore, it is consistent with existing empirical relationships that describe the production of fine fragments.

The hypothesis provides the basis for the second objective which is to conduct experimentation that collects reliable basic fracture mechanics data on various coals. The experimentation seeks to verify the applicability of the strain energy density theory and observe the micromechanical details of fracture that can lead to the production of fine fragments in coal. The third and last research objective is to develop a mathematical model that quantifies the production of fine fragments during a key event in the hypothesis. This model provides limited confirmation of the hypothesis by describing fragmentation in the crush zone with the strain energy density theory of mixed mode fracture.

Scope of Project

There are basically four major tasks that the research has completed. The first is a thorough review of current available literature aimed at assessing present knowledge of dust formation mechanics, discussing applicable topics in fracture mechanics and identifying research needs to improve the fundamental knowledge of the fine fragment formation mechanism. The review provides an up-to-date survey of mixed mode fracture mechanics, inherent flaws in materials, crack branching mechanisms, fragmentation mechanics, fracture toughness studies of coal and other related topics that have a direct influence on the mechanics leading to fine fragment formation.

The second task is the development of a hypothesis for the mechanics of fine fragment formation that describes the sequence of mechanical events occurring during a generic coal/tool interaction and leading to the formation of fine fragments. The hypothesis contains four essential steps that include: 1) the nucleation and growth of microcracks leading to the development of a crush zone under the tool tip; 2) the coalescence of microcracks resulting in macrocrack formation and the generation of fine fragments near the tool tip and larger fragments further away; 3) the development of relative displacements between the larger fragments leading to shear movement along macrocracks, and 4) the formation of additional fine fragments resulting from shear fracturing along the macrocracks. The major experimental requirements of this hypothesis are: 1) observation of the inherent flaw structure; 2) verification of the mixed mode fracture behavior of coal, and 3) characterization of newly created fracture surfaces.

The third major task is execution of a fracture mechanics test program that quantifies key elements of the fine fragment formation hypothesis. This program studies the behavior of coal subjected to various mixed mode fracture loads, different starter crack orientations and three different loading rates in order to test the applicability of the strain energy density theory to coal. Such mixed mode fracture toughness testing is required since the initial and subsequent crack growth resulting from coal/tool interaction is best described as a complex mixed mode fracture problem. Strain energy density theory was selected from several possible mixed mode fracture theories; although, none of these theories have ever been extensively tested or applied to coal. In conjunction with studying the behavior of mixed mode cracks in coals, the testing also provides a suite of fresh macrocrack surfaces created under known loading conditions. Microscopic observations of these macrocracks serve two additional experimental purposes. First, direct observation of the inherent flaw structure can be conducted that is so crucial to the initial development of fine fragmentation. Second, the degree of surface roughness and the amount of subsurface material damage can be studies which are essential for quantifying the additional fine fragmentation due to shear fracturing.

The last major task is to develop a model that can quantify a key aspect of the fine fragment formation hypothesis. This model utilizes the strain energy density theory and an estimate of the inherent flaw distribution of the coal material to calculate the crush zone size under the tool tip. Within that region, the coal material has been reduced to fragments 10 microns or less in size. The boundary of the crush zone is based on relationships between the inherent flaw structure and the production of fine fragments. It is conservatively estimated that the region is bounded by the locus where 10 micron flaws of some orientation can grow unstably.

Fine Fragment Formation Mechanism

Examination of current literature on the formation of fine fragments in coal shows that most of the work conducted to date has focused on deriving empirical relations between the formation of fine fragments as measured in the atmosphere near a cutting tool and a variety of machine operating parameters like depth of cut, rotational speed and tool geometry. Many useful relations have emanated from this empirical work; however, very little of that work has led to any conclusive understanding of the fundamental mechanics that govern the creation of undesirable fine fragments (Cook, et al., 1982).

Figure 1 shows the proposed four step mechanism for fine fragment formation. In the first step, the tool makes initial contact with the coal and load increases. Microcracks begin to nucleate and grow within the vicinity of the tool tip forming a crush zone as soon as the cutting tool first contacts the coal. The size of this crush zone increases proportionately with the tool load, and it is controlled by the fracture toughness of the nearby coal material and the coal's flaw structure.

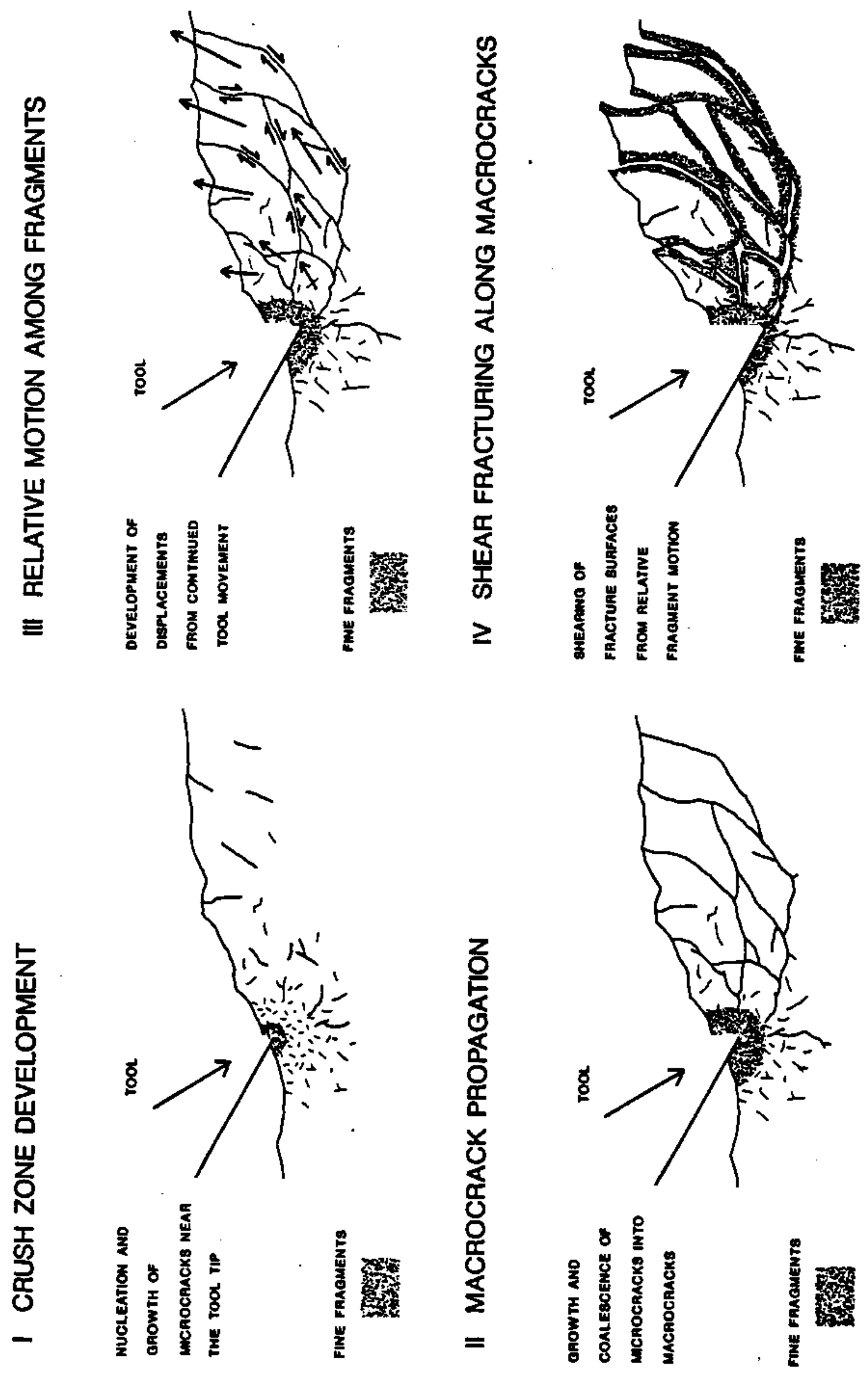


Figure 1. The fine fragment formation mechanism.

In the second step shown in figure 1, load on the tool increases to a maximum, and additional microcracks further from the tool nucleate and grow. Microcracks in the vicinity of the tool tip coalesce and totally fragment a certain volume of material into the 1 to 10 micron size range. This crush zone is the first location of fine fragment formation in the hypothesized mechanism. At maximum load, the crush zone reaches its maximum extent and several macrocracks propagate to form a variety of larger fragments. Load on the tool then drops to a lower value. The macrocracks form by the coalescence of presently active inherent flaws in the coal material and residual flaws from previous nearby passes of the cutting tool.

After macrocracks have grown to completion, the larger chips formed are not truly liberated because of interlocking along the newly created rough fracture surfaces. Continued motion of the tool at a load level less than the peak displaces the major fragments as shown in step 3 of figure 1. Displacement vectors for these fragments are not concordant; therefore, relative motion exists between major fragments which induces shear movement along the macrocracks as the fragments are liberated. Approximate displacement vectors and the induced shear displacement vectors are indicated.

The shear displacement during fragment liberation causes additional material disintegration along the macrocrack surfaces as shown in step 4. Shearing along macrocracks is the second location of fine fragment formation in the hypothesized mechanism, and it is not limited to the shearing of high points from the macrocrack surface. Since the nature of crack propagation involves the continuous nucleation, growth and coalescence of microcracks, considerable damage is expected at a substantial depth below the macrocrack surfaces. This sub-crack surface damage can be envisioned as a wake remaining from the passage of the crack tip and the surrounding fracture process zone. A portion of this damaged material is subject to further size reduction and removal by the shearing movement.

This mechanism contains two sources of fine fragments namely crushing under the tool tip and shearing along the macrocrack surfaces. The mechanism thus readily explains the major sources of fine fragments during a generic cutting tool/coal interaction and it also accounts for some secondary sources of fragments such as scraping and abrasion. Three key experimental requirements are identified with this mechanism: first, the character of the inherent flaw structure; second, the mixed mode fracture behavior of coal; and third, the physical character of the newly created fracture surfaces.

Mixed Mode Fracture Toughness Testing

An extensive mixed mode fracture toughness testing program was conducted on several different coals. A special mixed mode testing rig for geologic materials as shown in figure 2 was developed, and the strain energy density theory of mixed mode fracture was applied. The testing program systematically varied the specimen orientation, loading rate and fracture loading mode. K_{Ic} was found to be a reliable, repeatable material property characterizing the resistance to fracture of a coal material. Loading rate was found not to effect the fracture toughness over the quasi-static range tested. Orientation did have a significant effect on measured fracture toughness and observed crack extension angle. In the coals tested, the divider orientation was tougher than the arrester orientation which was tougher than the short transverse orientation. Data showed that one orientation could have almost twice the fracture toughness as another. In general, the strain energy density theory provided an adequate description of the mixed mode fracture behavior of coal such that it can be cautiously applied to fracture problems in coal.

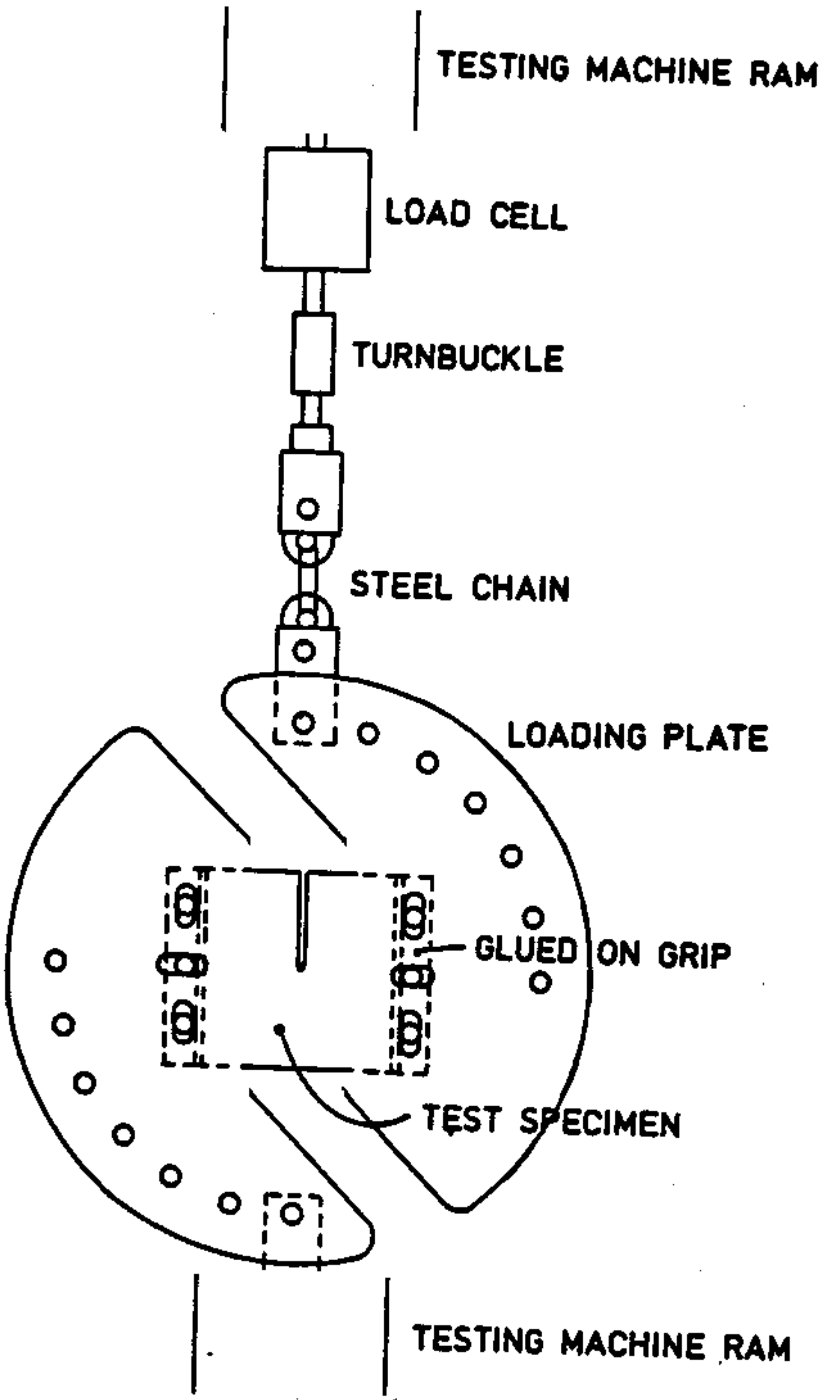


Figure 2. Schematic of the PSU Mixed Mode Test Fixture.

Orientation Effects

The critical fracture toughness and strain energy density factor from 138 tests is summarized by orientation effects in table 1 along with the associated standard deviations and coefficients of variation. As shown in table 1, the divider orientation has a greater fracture toughness than the arrester orientation which in turn is greater than the short transverse orientation. This trend is best exhibited in the Pittsburgh Coal where the most tests (54) were completed and the coefficients of variation are smallest. It seems to exist in the Lower Kittanning Coal as well where the least number of tests (26) are available. The fracture toughnesses of the high rank Anthracite Coal seem to show little orientation dependence. In this coal, the arrester orientation is the toughest; however, the reported value may be an anomaly since it only represents 6 tests. If more tests were done in this orientation, the same trend may exist among the three test orientations for the Anthracite Coal. The high coefficients of variation may suggest that this orientation dependence of fracture toughness is insignificant; however, when working with extremely heterogeneous materials such as coal, statistically good correlations are very difficult to measure. Nevertheless, we cautiously maintain that fracture toughness of coal does exhibit an orientation dependence such that the divider orientation is tougher than the arrester which is tougher than the short transverse.

Mixed Mode Fracture Behavior of Coal

Figures 3 and 4 which show the crack extension angle and fracture toughness data for Pittsburgh Coal in the divider orientation. Again, figure exist for the short transverse and arrester orientations for Pittsburgh Coal as well as for the Anthracite and Lower Kittanning Coals, and they are all included in a Ph.D. dissertation by Zipf. In figure 3, a range of theoretical crack extension angle curves is shown based on an average value for the Poisson's Ratio plus and minus approximately one standard deviation. Theoretical fracture toughness plus and minus one standard deviation and the average Poisson's Ratio.

The main conclusion from this major mixed mode testing effort is that the fracture toughness, K_{Ic} is a reliable, repeatable material property that characterizes a coals resistance to fracture. The average K_{Ic} values summarized in table 1 have coefficients of variation around 50% which is remarkably good for a material as heterogeneous as coal. In fact, because of this low variance, the fracture toughness may be better than the tensile or compressive strength as general indicator of a rock's competence.

The experimental program systematically changed certain variables to assess their impact on determination of the critical fracture toughness. Loading rate had no significant effect over the quasi-static range tested. Although it is known that the tensile or compressive strength can show a load rate dependence (especially at very high load rates), the fracture toughness as a fundamental material property should not exhibit such a dependence and apparently it does not. Test orientation can have a significant effect on measured fracture toughness and observed crack extension angle. In certain coals, the divider

Table 1. Critical Fracture Toughness and Strain energy density summary.

Critical Fracture Toughness and Strain Energy Density Summary
Orientation Effects

Specimen and Orientation	Number of Tests	Critical Fracture Toughness (MPa$\sqrt{m}$) Ave., Std. Dev. and Relative Error	Critical Strain Energy Density (N/m) Ave., Std. Dev. and Relative Error
Plaster of Paris	21	.2232 ±.0300 ±13%	2.049 ±.6590 ±32%
Pittsburgh Short Trans.	16	.0879 ±.0587 ±67%	.5422 ±.6743 ±124%
Pittsburgh Arrester	15	.1119 ±.0382 ±34%	.8193 ±.4482 ±55%
Pittsburgh Divider	23	.1431 ±.0523 ±37%	1.349 ±.9650 ±72%
Pittsburgh Total	54	.1181 ±.0553 ±47%	.9627 ±.8321 ±86%
Anthracite Short Trans.	18	.1761 ±.0861 ±49%	2.065 ±1.899 ±92%
Anthracite Arrester	6	.2327 ±.1162 ±50%	3.096 ±2.299 ±74%
Anthracite Divider	13	.1780 ±.0992 ±56%	1.494 ±1.256 ±84%
Anthracite Total	37	.1860 ±.0956 ±51%	2.032 ±1.805 ±89%
Lower Kitt. Short Trans.	9	.5113 ±.3013 ±59%	19.37 ±19.02 ±98%
Lower Kitt. Arrester	8	.8018 ±.4467 ±56%	32.75 ±35.70 ±109%
Lower Kitt. Divider	9	.8184 ±.5581 ±68%	20.29 ±20.98 ±103%
Lower Kitt. Total	26	.7070 ±.4536 ±64%	23.80 ±25.51 ±107%

orientation is tougher than the arrester orientation which is tougher than the short transverse. Data in table 1 shows that one orientation can have almost twice the fracture toughness as another. The potential significance of this difference is that fracture growth (hence cutting) in one direction may consume four times the energy as another orientation since fracture energy increases as the square of fracture toughness.

The strain energy density theory does provide an adequate description of the mixed mode fracture behavior of coal such that it can be cautiously applied to fracture problems in coal. Subsequent work will apply this theory and these fracture roughness measurements to estimates of the crush zone size under coal cutting tools. Certain significant discrepancies do exist and other mixed mode fracture theories do warrant full consideration; however, coal is certainly not the best material for testing the adequacy of one fracture theory against another. The strain energy density theory as applied in this work assumes an isotropic constitutive behavior. The experimental results indicate that incorporating a transverse isotropic constitutive model into the strain energy density theory might provide a better description of the observed crack extension angle behavior. It is not yet clear how the fracture toughness anisotropy observed in certain coals will effect the theoretical mixed mode stress intensities (i.e., the fracture locus) resulting in unstable crack growth.

Other Experimentation

Other related experimental research sought to understand the unstable crack growth velocity and the surface roughness of newly created fracture surfaces. Fracture velocity is important in the timing of the proposed four step fine fragment formation mechanism. Unfortunately, its measurement is fraught with uncertainty; nevertheless, a good tentative relationship exists between the critical stress intensity and the initial crack velocity such that the tougher the material, the higher the initial crack velocity.

Two different techniques were used in an attempt to quantitatively understand the fracture surface roughness and the factors controlling the generation of fine particles on those surfaces. Direct observations with the scanning electron microscope were generally disappointing since no positive mechanical controls on fracture surface roughness could be identified. Loading rate, orientation or fracture loading mode do not influence the fracture surface appearance in any readily discernible systematic fashion. A more promising approach to quantitatively describe fracture surface roughness was developed using the concept of a fractal dimension. Measurements of the fractal dimension for 23 fracture profiles generated during mixed mode testing of Pittsburgh Coal has produced the tentative though weak relationship between fractal dimension as a measure of fracture surface roughness and the fracture toughness. In general, the tougher the material, the rougher the fracture surface.

Estimating the Crush Zone Size Under a Cutting Tool

Model Description

The model used for these calculations consists of a boundary element program containing a failure criteria based on the strain energy density theory. In principle, the program is based on concepts advanced by Larchuk et al. (1985) for calculating the extent of crushing and material damage under a grinding tool acting on ceramics. The boundary element program provides linear elastic solutions for the stresses under a generic coal cutting tool. Stresses at numerous points in the coal material ahead of the bit are then input to a subroutine called CFLO which uses the strain energy density theory to determine the Critical Flaw Length and Orientation for a small crack at the boundary element stress computation point. Based on earlier postulates about the role of

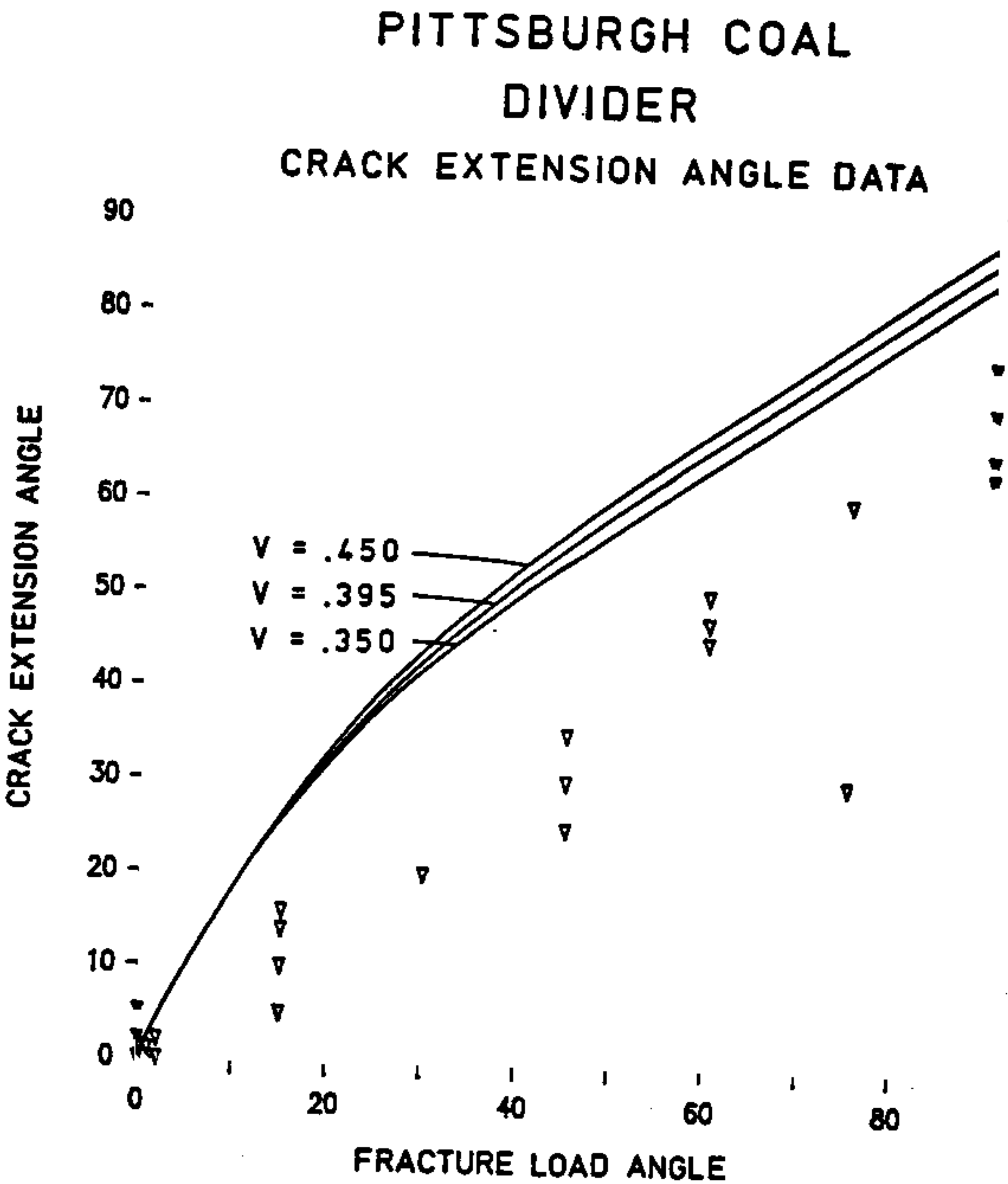


Figure 3. Pittsburgh Coal Divider Orientation Crack Extension Angle Data.

inherent flaws in a fragmentation process, the extent of material crushing in the 1 to 10 micron size range can be approximated. In order to form fragments in this size range, those postulates state first that the local stress field must activate flaws with a characteristic length less than 1 to 10 microns and second that the density of those 1 to 10 micron long inherent flaws is sufficient to provide an average spacing between flaws also on the order of 1 to 10 microns. Finally, the locus of active 10 micron flaws represents the maximum possible extent of fine fragmentation in the 10 micron or less size range again, assuming that a sufficient density of inherent flaws 10 microns or less in size exists.

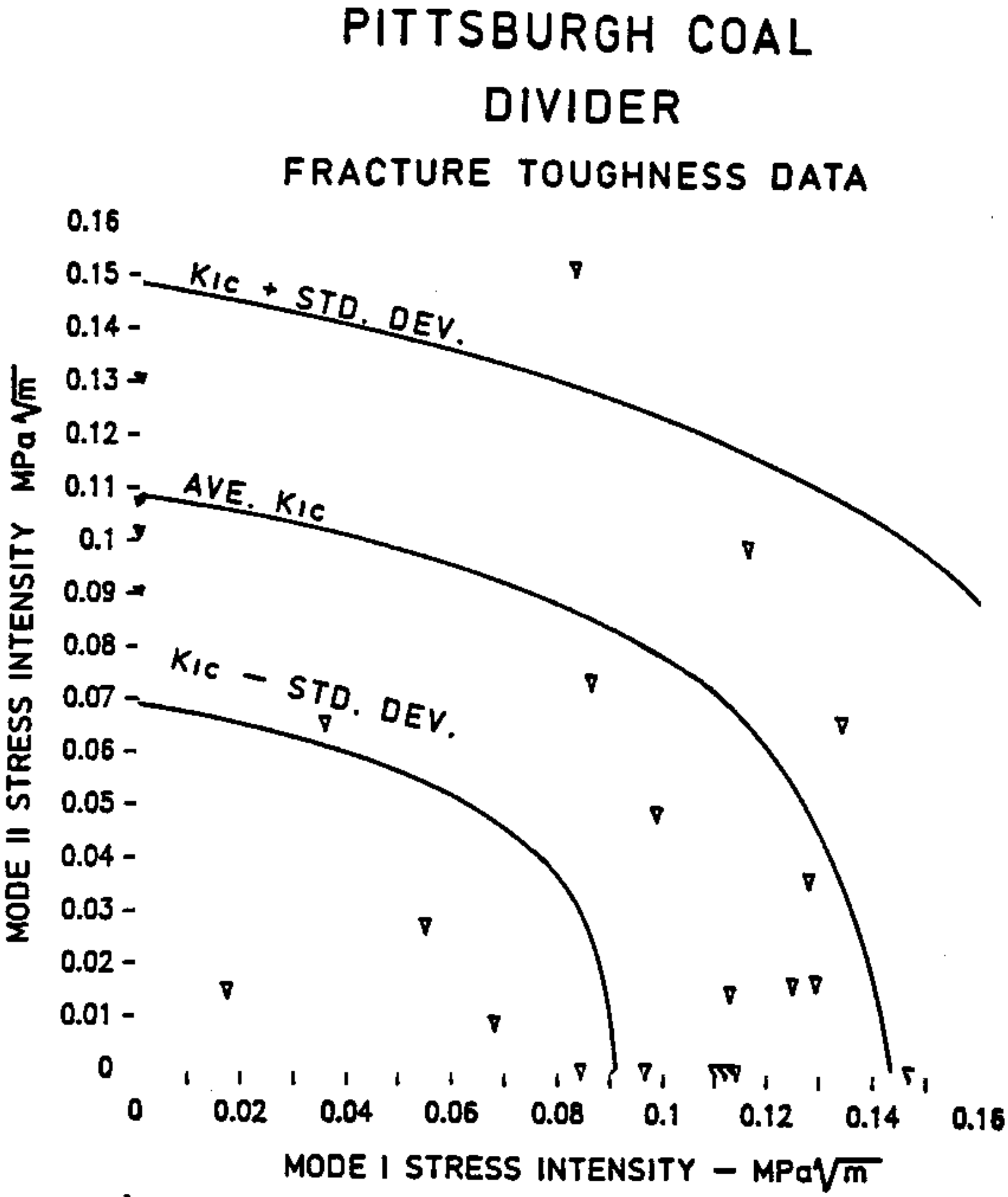


Figure 4. Pittsburgh Coal Divider Orientation Fracture Toughness Data.

Calculations with CFLO

CFLO has been used to make preliminary calculations of the extent of crushing under a generic coal cutting tool using typical modulus and fracture toughness values determined from laboratory experimentation. Results are generally encouraging for this simplistic computational procedure.

The computations systematically altered the tool geometry and the angle of attack. Tool geometries are a 60 degree, 90 degree and 120 degree wedge, and attack angles ranged from 0 to 60 degrees.

At each stress computation point, CFLO outputs each test flaw orientation and the computed crack extension angle and the critical flaw length in microns. From all the test flaw orientations, the smallest critical flaw length is selected and plotted at the appropriate stress computation point. Critical flaw lengths in the 1 to 5, 5 to 10, 10 to 100 and 100 to 1000 micron size range are displayed as zones in figures 5 through 7. The crush zone size under the tool tip is approximated as the locus where 10 micron or smaller flaws are active under the given loading conditions. This crush zone size is based on crucial assumptions concerning the role of inherent flaws in fragmentation processes. Again, to form 10 micron size fragments requires activation of flaws 10 microns or less in size with an average spacing also about 10 microns.

The crush zone size estimates shown in figures 5 through 7 must be considered tentative at best; nevertheless, they are extremely promising. First of all, the extent of crushing in the 1 to 10 micron size range certainly appears to be of the right magnitude. The calculations show that the depth of crushing is on the order of 1 to 2 millimeters below the tool/coal interface which generally agrees with the depth of crushing suggested in full scale tests with actual cutting tools.

The calculations clearly show how the crush zone size is influenced by the angle of attack. As seen in figure 5, normal forces produce the least amount of undesirable crushing. Increasing the angle of attack, i.e., increasing the tangential force component, increases the amount of crushing under the tool tip. This numerical observation is also in good general agreement with the empirical findings.

These calculations do not clearly indicate the effect of tool geometry on the extent of crushing. At present, they indicate that sharper tools produce more crushing than blunt tools which of course conflicts with all known observations. The performance of the tool geometries considered in these calculations are not directly comparable since the total bit forces are not the same for each tool. For this first modeling attempt with CFLO, the peak stress found from the earlier preliminary calculations is used at the bit interface. Tool width is also fixed; therefore, total bit forces for the 60 degree tool are greater than the 90 degree tool which is greater than the 120 degree tool. The more correct boundary condition is to keep the bit interface stresses and the total bit forces constant by adjusting the penetration depths somewhat; however, these calculations are reserved for further work.

Conclusions

This project applies fracture mechanics to explain how fine fragments of coal (respirable dust) are generated during a coal cutting process. Prior knowledge of the basic mechanics leading to generation of these particles was meager at best; therefore, that background was developed through this research program involving theory, experiment and application.

The first research objective sought to develop a hypothesis that sequentially describes the mechanics of fine fragment formation during a generic coal material/ coal cutting tool interaction. The four step hypothesis incorporates current understanding of mixed mode fracture

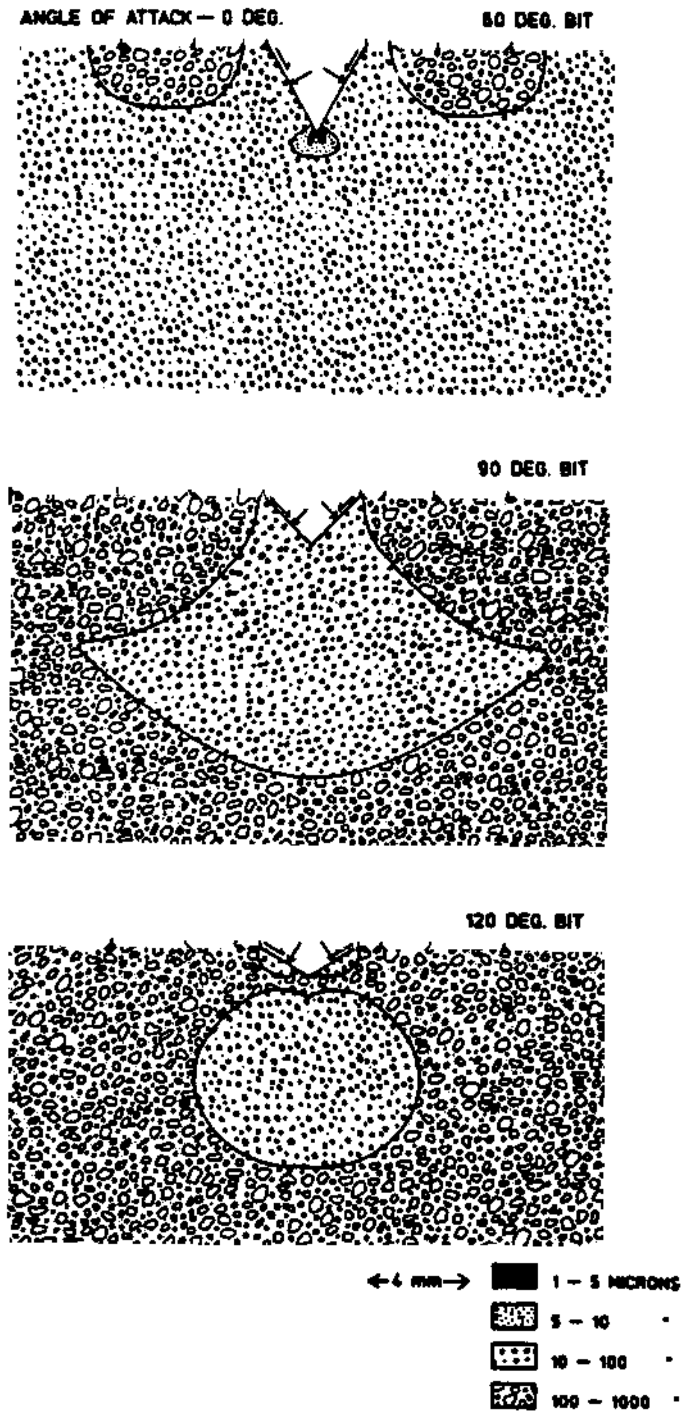


Figure 5. Potential fragmentation under a tool tip angle of attack - 0 degrees.

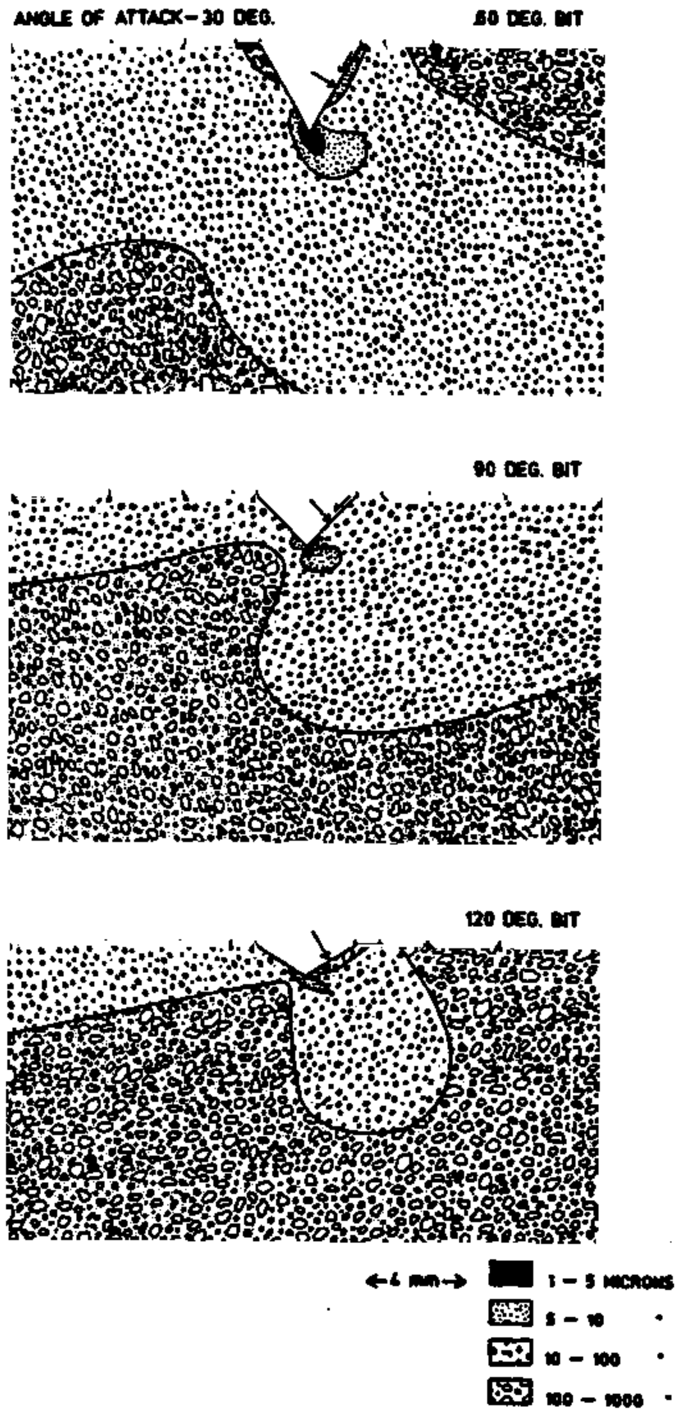


Figure 6. Potential fragmentation under a tool top angle attack - 30 degrees.

mechanics and the micromechanics of crack growth that leads to fragmentation at a microscopic scale. The second research objective sought to collect relevant fracture mechanics data that characterizes the tendency of various coals to fracture and produce fine fragments. The experimentation served to verify the applicability of the strain energy density theory of mixed mode fracture in coal and to observe the micromechanical details of fracture that lead to production of fine fragments. Finally, the last research objective sought to apply

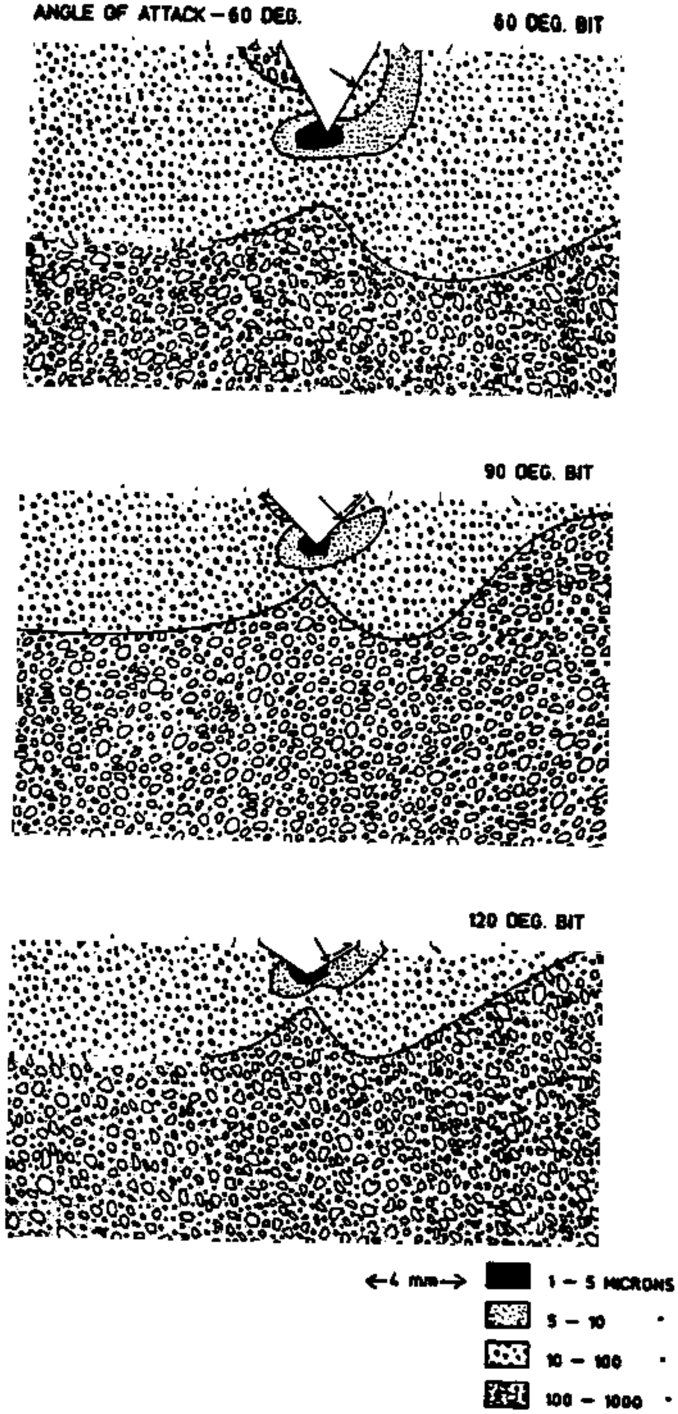


Figure 7. Potential fragementation under a tool tip angle of attack - 60 degrees.

fracture mechanics concepts in mathematical models that describe the production of fine fragments during certain key events in the hypothesis.

Regarding the first objective, a four step mechanism is proposed for fine fragment formation. Essentially, the steps in this model shown in figure 1 are:

1) development of a crush zone under the tool tip,
2) macrocrack propagation,
3) shear movement along macrocracks,
4) additional fragmentation from shear.

This mechanism implies two major sources of fine fragments: first, the crush zone and second, the fracture surfaces themselves.

The strength of the coal material and the creation of fine fragments of coal under a generic tool tip is in part controlled by a material property such as fracture toughness which governs the resistance of the material to crack growth and by geometric properties such as size and density of the inherent flaws that permeate all materials to one degree or another. Two relationships are suggested between the inherent flaw geometry and the production of fine fragments. First, in order to produce fine fragments with a nominal diameter of D_o requires the activation and growth of inherent flaws with a characteristic length L_o that is necessarily less than D_o. Second, to produce fragments of size D_o also requires a minimum density of inherent flaws such that their spacing S_o is also less than or approximately equal to D_o.

Regarding the second objective, an extensive mixed mode fracture toughness testing program was conducted in three different coals plus some work with Plaster of Paris. A total of 117 successful fracture toughness measurements were completed which represents a very significant addition to the 198 tests that had been previously reported in the open literature. These test results are summarized in Table 1.

The testing program required development of a mixed mode fracture toughness testing system for geologic materials such as coal. Use of the testing system has also contributed significantly to the very small amount of mixed mode fracture toughness testing that has been completed on rocks.

Regarding the third objective, a modeling approach was developed that uses the fracture toughness measurements and the strain energy density theory in calculations of the crush zone size. The model consists of a boundary element program containing a failure criteria based on the strain energy density theory. The program provides a linear elastic solution for the stress field about a tool tip and based on that stress field, a subroutine called CFLO calculates the critical flaw length and orientation from strain energy density theory. From earlier postulates concerning the role of inherent flaws in a fragmentation process, the extent of crushing is taken as the locus of active 10 micron flaws. This approach makes the critical assumption that a sufficient density of inherent flaws 10 microns or less in size exists in the coal material.

CFLO has been used to make preliminary calculations of the extent of crushing under a generic coal cutting tool using typical modulus and fracture toughness parameters determined from the laboratory experimentation. The calculated size of the crush zone appears reasonable and it is influenced by the angle of attack much like certain experimentation had shown. While there are many theoretical and numerical problems with the CFLO approach, it does supply some interesting tentative calculations of the crush zone size and does show considerable promise for future research.

Research Publications (1988)

Zipf, R. K. and Bieniawski, Z. T., (1988), "Microscopic Studies of Fractures Generated Under Mixed Mode Loading", Proc. 29th U S Rock Mechanics Symposium, A. A. Balkema, pp. 151-158.

Zipf, R. K., (1988), "The Mechanics of Fine Fragment Formation in Coal", Ph.D. Dissertation, The Pennsylvania State University, University Park, PA., 302 pp.

Zipf, R. K. and Bieniawski, Z. T., "A Fundamental Study of Respirable Dust Generation in Coal" submitted to Mining Science and Technology.

Zipf, R. K. and Bieniawski, Z. T., "Mixed Mode Fracture Toughness Testing of Coal", submitted to Int. J. Rock Mechanics, Mining Sciences and Geomechanics Abstracts.

Zipf, R. K. and Bieniawski, Z. T., "Estimating the Crush Zone Size Under a Cutting Tool in Coal", submitted to Int. J. Mining and Geological Engineering.

WV1/USBM 5401

An Experimental and Analytical Approach to Study the Mechanisms of Respirable Dust Generation and Entrainment

Khair, A.W.; Siriwardane, H.J.; Reddy, N.P.; Jung, S.S.; and Begley, R.D.

INTRODUCTION

The main objective of this project was to identify the mechanisms and sources of respirable dust generation in underground coal mines. This research involves both experimental and analytical approaches. The experimental study required the indentation and the rotary coal cutting experiments. In the indentation part quasi-static and dynamic indentation experiments were conducted. The quasi-static experiments were conducted to study the effect of load boundary conditions and material anisotropy on the failure mechanism and failure mode in rock and coal (Fig. 1). The facilities for dynamic indentation tests were designed and fabricabed indigenously. These tests were conducted to formulate a theory which will provide a better explanation of the input energy distribution during bit penetration. Bit penetration is accompanied by creating a damage zone in coal, which becomes a major source of respirable dust. The rotary cutting involved the design and fabrication of an automated rotary coal cutting simulator and conducting two sets of experiments. One set using multiple bits and the other set using single bits on the cutting drum. Multiple bit experiments were done to establish experimental procedures and study the bit-coal interaction in the bit path by examining the microscopic photographs while the single bit experiments provided the data for developing a statistical model to predict the required forces, specific energy and fine size distribution under a particular set of machine operating parameters and in-situ conditions.

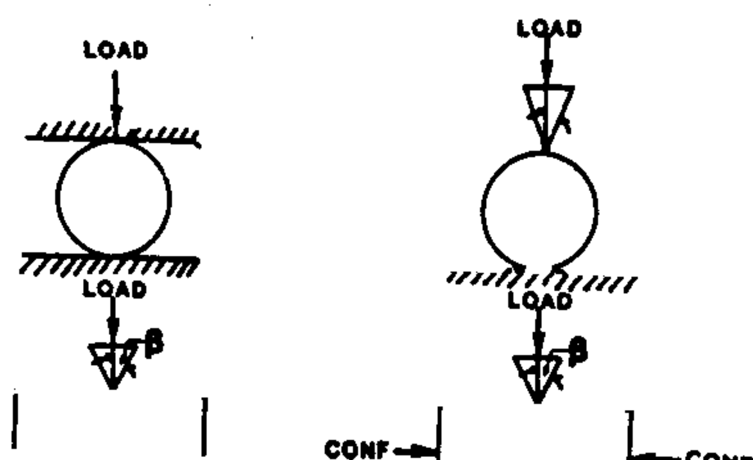


Figure 1. The test specimens and load boundary conditions for quasi-static experiments.

RATIONALE

The trend away from conventional mining to continuous mining-machine cutting of coal, using ever productive machines is inexorable. Over the years, face equipment has become larger and more powerful such that present-day machines have little difficulty in cutting coal, albeit inefficiently, at a much faster rate than can sometimes be handled by the coal clearance system. The fact that cutting problems still exist, however, is evident from the often intolerably high airborne dust levels generated during cutting. Continuous mining machines account for more than half the production of coal from underground mines. Unfortunately, these continuous miners which were designed for increased productivity have also increased the concentration of respirable dust in mines which causes Coal Workers Pneumoconiosis (CWP). Considerable improvements have been achieved in reducing the dust generation and controlling the generated dust in mine atmospheres through research and development by the U.S. Bureau of Mines, other agencies and industry. The regulations enacted in the 1969 Federal Coal Mine Health and Safety Act coupled with the assessment of the continuing burden on miners, the mining industry and tax payers provided an impetus for the mining community towards comprehending the different parameters that influence dust generation. As a result of this understanding USBM commissioned the South West Research Institute to summarize results into airborne respirable dust and recommend a course for future study. The report from this investigation "Basic Research on Coal Fragmentation and Dust Entrainment" listed cutting parameters and in-situ conditions influence as one of the six major areas that need further investigation. Therefore, any research towards reducing dust generation from the health, safety and productivity aspects of the nation's coal industry should be based on a parametric study of the cutting parameters which influence the source of dust generation.

Design, Fabrication and Instrumentation of laboratory Facilities:

Both the indentation facilities (Fig. 2) and the rotary cutting facilities (Fig. 3) were designed, fabricated and instrumented indigenously. This indentation facility enables the experimentor to vary the different indenting parameters such as the weight, height, equivalent in-situ conditions and the indenting bit. Blocks of coal 25.4 cm. x 25.4 cm x 15. 3 cm (10 in x 10 in x 6 in) were confined in the confining chamber to predetermined values of equivalent in-situ stresses and then subjected to indentation by dropping a coal cutting bit attached to a known weight from a known height. During and experiment a number of parameters were monitored and measured. The acoustic emission monitor was used to monitor the A.E. activity, sonic viewer was used to measure the wave travel time from one end of the block to the other end, microscope was used to map the fracture, LVDT was used to measure the penetration depth and the surface damage was measured by instrumenting the specimen with strain gages and recording the strains by the data acquisition and monitoring unit as well as using microscopic photography.

Similarly the design of the Automated Rotary Coal Cutting Simulator (ARCCS) incorporates the capability to study the different machine operating prarmeters and in-situ conditions that influence the fragmentation of coal and the resulting dust. It operates under the simulated mining conditions with equivalent in-situ stresses being applied to a coal block of 50.8 cm x 35.6 cm x 20.3 cm (20 in x 15 in x 8 in) located in a suitably designed confining

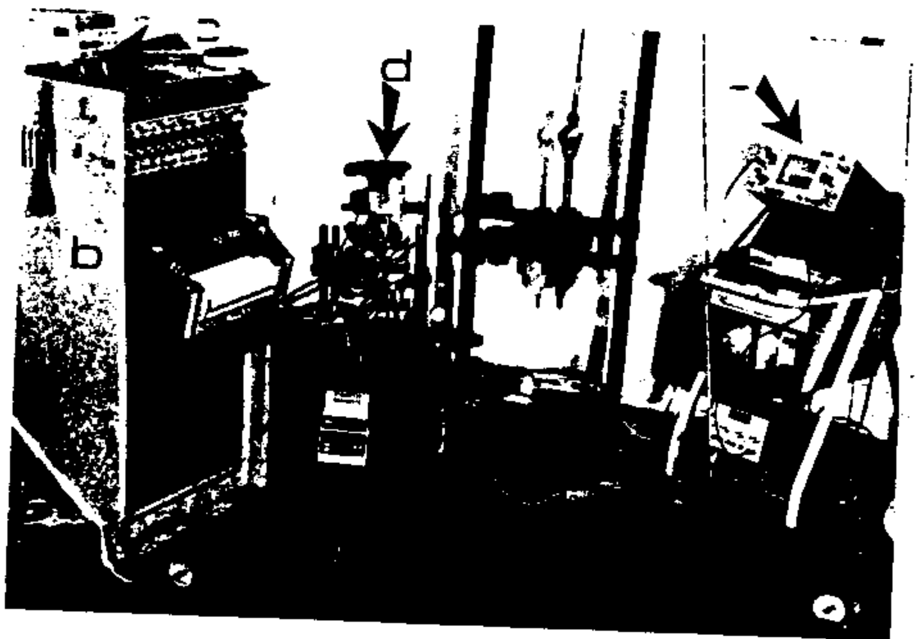


Figure 2. Test and monitoring facilities for dynamic indentatation. (a) sonic testing unit, (b) data acquisition and recording unit, (c) A.E. monitoring unit, (d) microscope with an attached camera.

chamber. The cutting drum with a maximum tip to tip diameter of 19 inches has the capability of rotating from 1 to 50 rpm. The drum can be stopped any time after a predetermined number of revolutions. Tests can be performed with four different bit attack angles; 15°, 30°, 45°, and 60°. A maximum of seven bits can be mounted on the drum in an echelon pattern. The ARCCS can be operated and controlled manually or automatically, and the operating parameters, which can be preset with a series of hydraulic valves can be recorded in analog/digital or in both forms. In addition to the test and monitoring facilities identified in figure 3, linear variable differential transformers (LVDTS), pressure transducers, flow meters, flow controls, and drum rpm were some of the other monitoring devices. LVDT's were used to monitor the displacment of the coal block as well as the depth of cut. Pressure transducers were used to monitor the pressure changes, both due to thrust and due to the intermittent rotary cutting. Flow controls were used to run the drum at a particular speed between 1 and 50 rpm and to provide a predetermined rate of advance. All the above mentioned devices were operated and monitored by a full automated control system. The fracture surface machine bit-coal interaction was characterized a) with the help of microscopic photographs taken at the end of each test using a camera attached to an optical microscope, (b) by monitoring the acoustic emission (A.E.), and (c) by monitoring the sonic signal in the coal block located in the confining chamber with the help of sonic transducers, signal generator, and an oscilloscope.

EXPERIMENTAL RESULTS

Quasi-static experiments were conducted on Berea sandstone and Coal Berg No. 2 coal seam. The specimen were prepared to proper dimensions and instrumented with strain gages. Figure 4a illustrates deformation characteristics (strains-load history) of diametrical specimen during tests where gage G1 located at the edge of the specimen close to the wedge

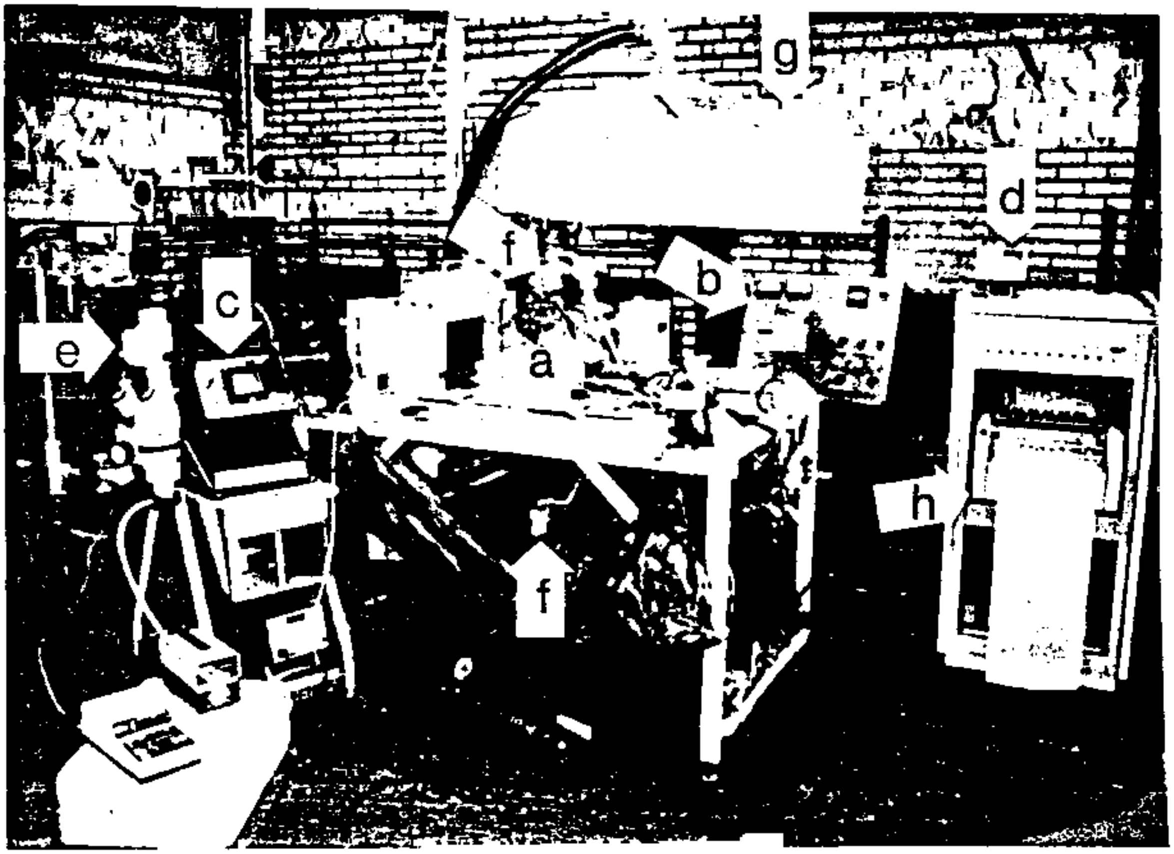


Figure 3. Test and monitoring facilities for rotary coal cutting experiments (a) automated roatary coal cutting simulator, (b) programmable control and monitoring unit, (c) sonic testing unit, (d) A.E. monitoring unit, (e) microscope with an attached camera, (f) cascade impactors, (g) hood and air current generating unit, (h) data acquisition and recording unit.

indentor and gage G3 indicates strain at the center of the specimen. Figure 4b indicated fracture formation in the specimen as illustrated by the high A.E. rate and drop in the load. The results indicated that under a flat wedge angle (β = 90°) in Brazilian test where failure of the specimen predicted by the elastic theory initiates from the center of the specimen due to the development of high tensile stress, the fracture propagates towards the edge. The magnitude of tensile stress is maximum at the center and decreases toward the edges. Decreasing the wedge angle (β = 60°, 45°, 20°) changes the load boundary condition, consequently changing the mode of failure in the specimen from pure tension to mixed mode tension-extension. Magnitude of tensile strain was highest at the center of the specimen, indicating tension and at the edge, under the indentor it was entension.

The results of the tests on rectangular specimen of Berea sandstone and coal indicated that the type of fracture formation (intensity and sizes) and mode of failure in the specimens is a function of wedge indentor angles (β) and lateral confining pressure. At zero lateral confining pressure, failure of the specimen under indentation loads (β = 20°, 45°, 60°) were in extension mode and characterized by a major fracture preceeding high A.E. activity. A crush zone developed under the indentor. This crush zone which is a major source of dust generation increased as the wedge angle increased and consequently the chipping reduced. Increasing lateral confining pressure altered mode of failure in the specimen. The chip formation was caused by the tension cracks while the failure of the specimen were in shear mode.

At zero confining pressure the fracture formation and the failure mode were same as in the case of rock. At high confining pressures failure mode remained to be in extension but failure was accompanied with less chipping and more crushing. Also as the wedge angle increased the chipping decreased and the crushing increased. The aim of these experiments was to find the conditions under which the chipping is maximum and the crushing is minimum.

From the parametric dynamic indentation experimental results, some general trends were observed. The geometry of the bit appears to have a significant effect in reducing dust generation. It was found that bit #1 with a narrow tip angle and smooth configuration produces less fine and more large fragments (Fig. 5). Cutting along the face cleat direction produces less fine fragments than cutting along the butt cleat direction (Fig. 6). Also, indentation of specimen under high confining pressures increased the fine fragments (Fig. 7), because confining pressures increase the resistance to indentation.

Identifying the possible sources of dust generation and analyzing the mechanisms by which it is created by the continuous miner are the vital aspects of any study that attempts to reduce dust generation. The mechanisms of respirable dust generation by a continuous miner is a function of the fragmentation process and machine bit-coal interaction. Fragmentation of coal under the action of a continuous miner cutting head, relatively is not a continuous process. Observations during the tests indicated that, the cutting cycle in rotary cutting involves two phases; crushing and chipping

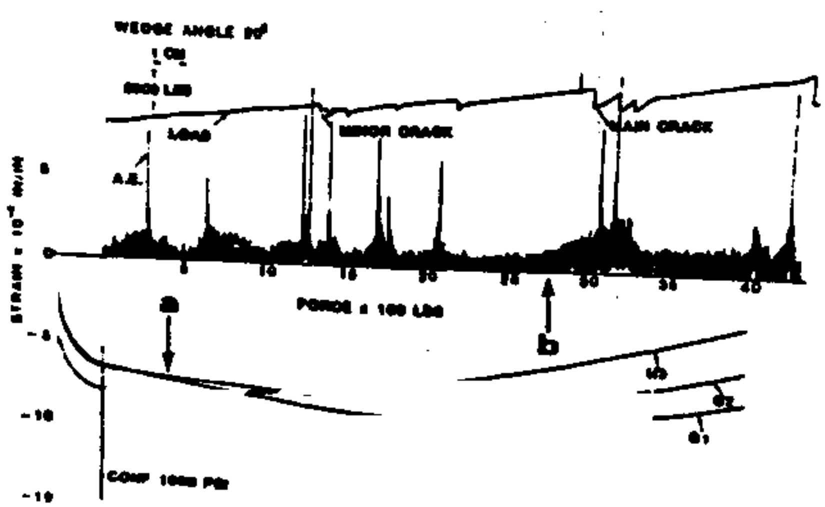


Figure 4. (a) Force-strain curve and (b) Load A.E. rate curve during quasi-static experiments.

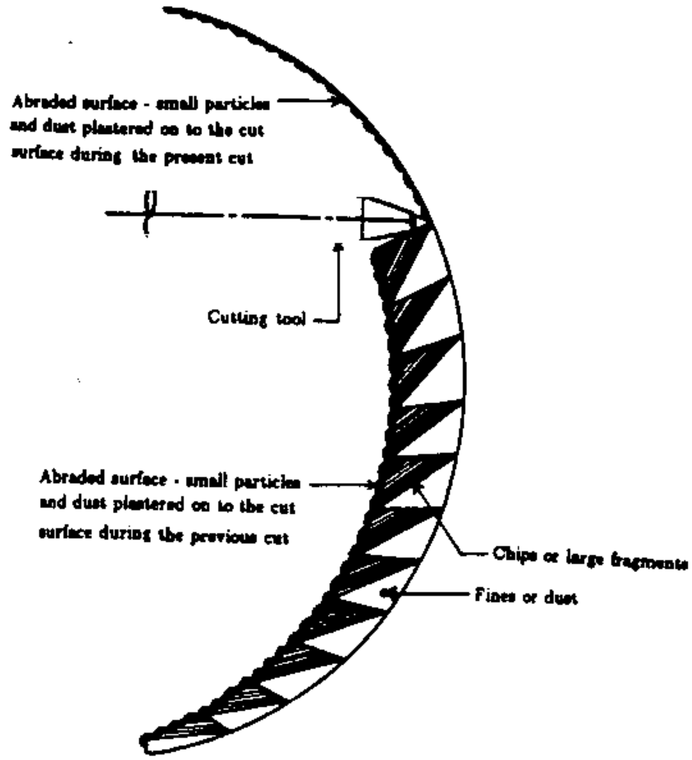


Figure 8. Simplified diagram of crushing and chip formation when cutting coal with a continuous miner.

electrostatic forces developed during cutting and abrasive action between the bit and coal. The frictional heat developed from the abrasive action fuses the particles and this fused material gets plastered on to the rough surface of the cutting path.

The characteristics of the plastered material were found to differ with the degree of machine bit-coal interaction. After the experiments, it was found that at the center of the cut grove the frictional heat generated by the abrasive action between the carbide tip of the bit and intact coal surface during the crushing face of the cutting cycle tends to liquify part of the crushed material causing it to fuse together. The material at the center of the cut grove is highly compacted. The degree of interaction between the body and coal on either side of the cut groove is much less than at the center. Therefore, the material on the sides is not compacted. When the plastered material at the center of the cut groove was disturbed, it exhibited brittle characteristics and broke into thin platy pieces and dust size particles, whereas the material on the sides of the cut groove broke into fine fragments and less dust size particles. Therefore the plastered material will become a major source of dust generation when disturbed during the subsequent cutting cycles. The thickness of the plastered material was found to range between 1/32 and 1/16 of an inch.

The mechanism of crushing and chipping was further extended to the rotary cutting wherein the cutting pattern was analyzed by the quasi-static and dynamic forces. As shown in figure 8 the arch-shaped area between the two arc lines is divided into the shaded and unshaded areas. The unshaded areas are hypothesized as the areas where curshing and grading take place due to quasi-static loading while the shaded areas were hypothesized as the

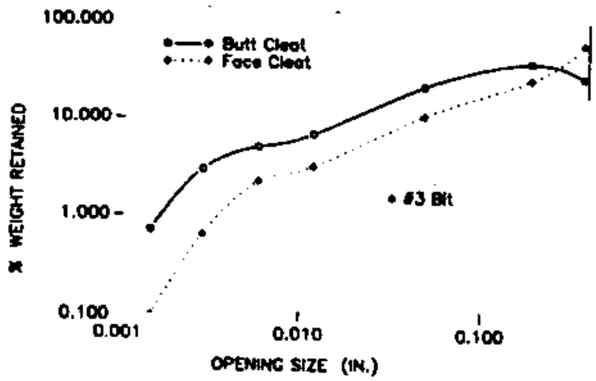


Figure 5.

Opening size vs. percentage weight retained as a function of bit type.

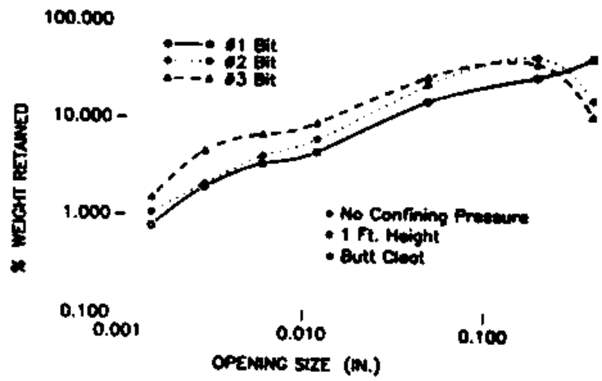


Figure 6.

Opening size vs. percentage weight retained as a function of coal orientation.

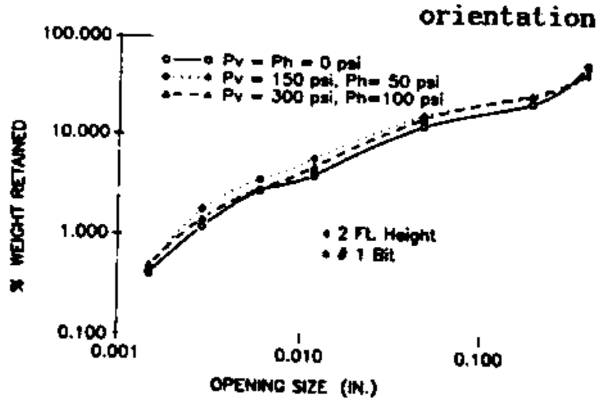


Figure 7. Opening size vs. percentage weight retained as a function of confining pressure.

(Fig. 8). When the bit first enters the coal it induces a zone of inelastic deformation about the contact point by crushing of all the surface irregularities. As depth of irregularities increases, crushing results in subsurface cracking which produces fine fragments and respirable dust particles. Coal has inherent weakness planes, in the form of face and butt cleats and bedding plane. The face cleats which are short and closely spaced will intersect with the subsurface cracks generated by the bit and aid in causing shorter subsurface cracks. As the bit advances, the subsurface cracking makes the uncrushed material face steeper and steeper inducing a high cutting resistance. When the cutting force (cutting resistance of coal) reaches high enough to overcome the strength of coal a major crack is generated under the bit tip. This crack propagates all the way to the free surface and a chip is formed thus making the coal face ahead of the bit shallow again which is ideal for grading and subsurface cracking to produce fine fragments and dust particles. As the cutting process of producing fine fragments and dust particles and large fragments or chips continues, some of the fine fragments and dust particles escape clearing off the coal face and get attracted by the cutting face due to the areas where chipping takes place due to dynamic loading. The coal in the unshaded area is subjected to subsurface cracking resulting in fine fragments and dust particles. At the end of the crushing cycle the cutting resistance reaches its peak and causes a major crack which propagates all the way to the free surface and chips the shaded area instantaneously.

From the above discussion it is logical to say that a major source of respirable dust is the intensely crushed material produced at the tip of the cutting tool during the quasi-static loading. Since this crushed material gets plastered and becomes a major soruce of respirable dust during subsequent cycles it was decided to analyze this area of bit-coal interaction by using microscopic photographs taken at three different locations of the bit paths; entrance, middle and exit. Such an analysis has enabled to relate the fragmentation process with the areas that contribute to the production of fine fragments and dust generation as a function of different machine operating parameters and in-situ conditions.

Microscopic photographs used to study the machine bit-coal interaction have identified three zones in a bit corresponding to three distinct zones of the bit path which influence respirable dust generation (Fig. 9). The three zones are: zone 1 which corresponds to the carbide tip, zone 2 which corresponds to the transition between the carbide tip and the bit body and zone 3 which corresponds to the bit body. The microscopic photograph in figure 9 was taken in the middle of the coal block. In the center of zone 1, there appears a shiny white line which corresponds to the area of contact with the center of carbide tip. The remaining portion of this zone corresponds to the area of contact with the sides of the carbide tip. Zone 2 appears as a line or ridge along the edge of zone 1 and corresponds to the

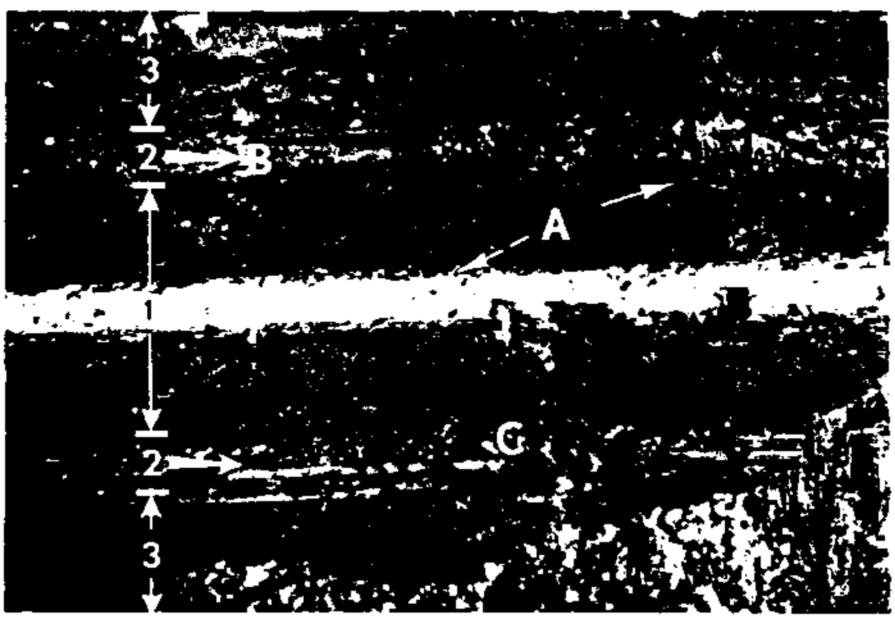


Figure 9. Microscopic photograph taken at the middle of the bit path indicating the three zones of bit-coal interaction and the three features, A, B, and C within these three zones.

gap between the carbide tip and bit body. Zone 3 corresponds to the area of contact with the bit body and has a varying appearance. Within these three zones there are three distinct features; A, B, and C which represent the shiny or black, brown and solid intact coal areas, respectively. Feature A is the plastered material formed as discussed above, feature B is the material formed due to a less degree of bit-coal interaction and hence is identified an area of lightly compacted materials.

Experimental results revealed that respirable dust generation is affected by the coal type itself and its cleat orientation. The operating parameters that affect respirable dust generation in the order of most to least important are: depth of cut, spacing of bits, geometry of the bit speed, and bit attack angle.

Single bit experiments were done based on a statistical design called the a x b factorial design. From these experiments it was found that the depth of cut and the confining pressure had high correlations with all the independent variables (Y_i); resultant force, specific energy and size distribution. Also proportional correlation within the independent variables for specific energy and fine size distribution was very high. In general the 35 drum rpm required th least force, consumed lowest energy and produced the least percent of fine fragments and dust particles.

A statistical model was developed to predict the resultant force, specific energy and fine size distribution. The model is

$$Y_i = A_o + \sum_{i=1}^{4} (A_i X_i + A_{ii} X_i^2) + \sum_{i=1}^{3} \sum_{j=i+1}^{4} A_{ij} X_i X_j$$

where A_o is the intercept, A_i are the coefficients and X_i are the dependent variables; depth of cut, attack angle, drum rpm, and confining pressure. Listing of the coefficents to predict all the three independent variables is beyond the scope of this report. Presently this laboratory developed model is being extended for field conditions using dimensional analysis.

CONCLUSIONS:

The failure mechanism in the quasi-static experiments was identified to change from extension mode at zero and low confining pressures to shear and extension modes at high confining pressures.

The two phases; crushing and chipping in the fragementation process were identified. It was concluded that the crushing phase should be minimized and the chipping phase should be maximized for dust reduction. It appears that the key to reducing respirable dust generation is to limit the degree of bit-coal interaction by chosing an optimum depth to spacing ratios that cause maximum bit to bit interaction and breaks of the coal boundary between the bits. A bit with a narrow tip angle and a smooth profile will limit bit-coal interaction and reduce dust generation. The statistical model developed predicted the independent values; resultant force, specific energy and size distribution which fell within the 95 percent confidence limits. Overall this research findings when applied in the field can reduce primary respirable dust, but more research is necessary to reduce secondary dust generation since the secondary dust is many times more than the primary dust.

CONTINUING WORK:

Presently research is being carried out on secondary dust generation which is defined as all the dust that is generated other than the primary dust generated during cutting. The objectives of this research are to quantify the magnitude of the dust produced due to regrinding per unit volume of coal cut and/or per unit length of arc cut, to establish a secondary communition index for respirable dust generation and to correlate the secondary fragmentation to some physical and mechanical properties such as hardgrove grindability index and compressive strength, respectively. The equipment modifications and fabrication for this project are being completed and the experiments are scheduled for June 1988.

TECH TRANSFER:

Several research papers were published from this project. A total of 10 research papers were published and a 11th paper is being considered by the publisher for publication. This project has also produced two M.S. theses and two Ph.D. dissertations.

WV15/USBM 5421

Correlation of Dust Due to Regrinding at the Face

Khair, A. W.; Reddy, N.P. and Xu, D.

INTRODUCTION

The objectives of the research are to quantify the magnitude of the dust produced due to regrinding per unit volume of coal cut and/or per unit length of arch cut, to establish a secondary communition index for respirable dust generation, and to correlate the secondary fragmentation to some physical and mechanical properties such as hardgrove grindability index and compressive strength, respectively.

Project objectives for the 1987-88 year were to design and fabricate a coal cutting chain saw, to design and fabricate the necessary modifications on the Automated Rotary Coal Cutting Simulator (ARCCS) to suit the testing procedures for secondary dust generation in the laboratory, to develop an analytical model and to conduct preliminary experiments on regrinding.

The objectives of 1987-88 year have been completed. Presently, work is being pursued on developing an analytical model and conducting preliminary experiments on regrinding.

RATIONALE

There are over 2000 continuous mining machines in use in the United States; they account for over half of the underground coal production. Studies have identified the continuous miner operator and helper as being at "high risk" for dust exposure in continuous mining section. Reducing their exposure to acceptable levels will substantially reduce dust and improve the mine environment for thousands of miners. Most of the dust generated at a continuous miner coal face is secondary dust.

The three major sources of secondary dust at the face are: grinding, falling, and gathering (Roepke, 1984). Falling and gathering are self explanatory while grinding is the process of communition of coal fragments cut during the previous cycle and not cleared before the subsequent cycles of cutting.

Laboratory investigations in the past have shown that less than one percent of the respirable dust generated during the cutting process becomes airborne while the remaining dust adheres to larger fragments of coal

(Roepke et al., 1976). If these larger fragments are not cleared efficiently from the bit paths they will be subjected to secondary grinding. This process will not only throw the dust adhering to the larger fragments into the air but will also create additional dust due to the communition of coal fragments.

A major cause for regrinding by a continuous miner is its crescent shape cutting action. However, regrinding and rubbing action can arise from several sources. When the top cutters start to remove coal, all the broken coal must be transported through the remaining area of the drum. The transport of already recovered coal through the cutting zone of the rotary head makes it a rotary grinder. It is hypothesized that the potential effect on dust generation by secondary grinding will be somewhere between 10 and 1000 times that produced by primary fragmentation depending on coal type (Roekpe, 1986).

An interesting void in the literature is that there are no measured estimates for dust produced by falling coal or from secondary fragmentation or grinding, while 10 percent of the total respirable dust fraction at the face was estimated to be due to gathering (Matta, 1976).

It has long been established that deep cutting reduces the dust generation. It is the secondary fragmentation of the product resulting from these deep cuts that needs to be understood in order to minimize secondary dust generation.

DESIGN, FABRICATION AND INSTRUMENTATION OF LABORATORY FACILITIES

The design and fabriction of a hydraulically powered chain saw has been completed. This chain saw is skid mounted for ease in maneuverability and transportation. This chain saw is being used to cut coal in the underground coal mines since it is very difficult to obtain large blocks of coal by any other means. The chain saw can be used within 100 ft. radius of a trolley line. Four specially designed coal block containers have been fabricated to retrieve coal from the face after cutting it with the chain saw. Once retrieved from the face, the coal can be constrained with the movable plates in the containers to avoid any damage to the coal block during transportation.

The design of modifications and their fabrication on the ARCCS has been completed. Before modification the minimum spacing possible on the cutting drum was 1.5 in. This has been modified to accommodate a minimum spacing of 0.5 in. This modification will allow the experimentor to vary the spacing from 0.5 in. to 3.0 in. depending upon the requirements of the experiments. Also the number of bits that can be mounted has increased from 7 to 22 (Figure 1a). The next modification was the design and fabrication of a cowl to hold a coal block at the bottom of the confining chamber. This cowl has built-in hydraulic cylinders which will advance the coal blocks upwards toward the cutting head bits, thus simulating the downward movement of the cutting head and aiding in providing a larger cutting contact with the cutting bits (Figure 2). The third modification was a hopper like feeder to be used in feeding a predetermined size of coal on to the entire width of the drum in order to simulate the coal/coal impact and the drum and/or face impact which are the two major mechanisms for dust generation due to regrinding (Figure 1b-1c). The final modification was an enclosure to completely cover up the cutting head. Such an enclosure enables the investigator to collect the total dust generated during cutting (Figure 3). The enclosure has an opening at the bottom covered with a door during an experiment. After every experiment the cut product is collected from this opening for size distribution analysis.

With the above mentioned modifications, the ARCCS incorporates the capability to study the different machine operating parameters that influence

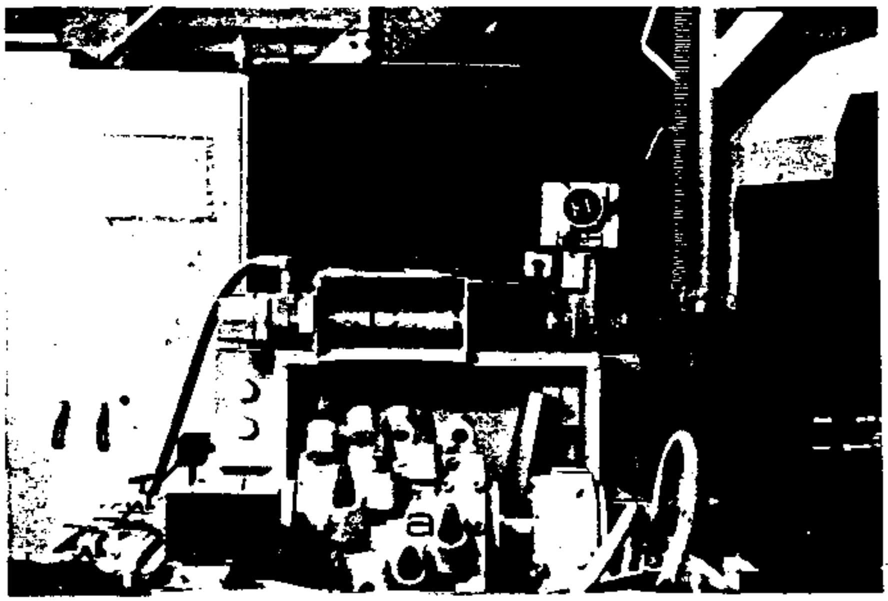


Figure 1. (a) The modified drum with bits mounted into the bit blocks, (b) the hopper in which coal can be filled and (c) the conveyor.

Figure 2. Cowl which has cylinders to push the coal block as the cutting progresses.

the secondary regrinding. It operates under simulated mining conditions with equivalent in-situ stresses being applied to a coal block of 50.8 cm x 35.6 cm x 20.3 cm (20 in. x 15 in. x 8 in.) located in a suitably designed confining chamber. The cutting drum with a maximum tip to tip diameter of about 50 cm (20 in.) has the capability of rotating a cutting bit from 1.6 m/min (5.2 ft/min) to 79.7 m/min (261.5 ft/min). The drum can be stopped anytime after a predetermined number of revolutions. The ARCCS can be operated and controlled manually or automatically, and the operating parameters, which can be preset with a series of hydraulic valves can be recorded in analog/digital or in both forms. In addition to the test and monitoring facilities identified in Figure 4, Linear Variable Differential Transformer (LVDT), pressure transducers, flow meters, flow controls, and drum rpm are some of the other monitoring devices. LVDT is used to monitor the depth of cut. Pressure transducers are used to monitor the pressure changes, both due to thrust and rotary cutting. Flow controls are used to run the drum at the desired bit speed, control the conveyor speed while feeding the coal fragments on to the drum and to lift the small coal block in the cowl as the cutting progresses. All the above mentioned devices are monitored by a fully automated control system.

ANALYTICAL MODELLING

Secondary regrinding or the resulting fragmentation at the face is caused due to the dynamic impact of coal/coal at the face between face and drum and between drum and/or face. Suppose two moving bodies of mass m_1 and m_2 impact each other. After impact the velocities are v_1 and v_2, respectively. From Newton's second law, the impact force will be

$$P = - m_1 \times dv_1/dt \text{ or } P = - m_2 \times dv_1/dt \qquad (1)$$

During impact the two bodies squeeze and approach cne another. The velocity of this approach is:

$$da/dt = v_1 + v_2$$

where a is the distance of this approach after both bodies come in contact and is called impact deformation. Hertz related the impact force to impact deformation as (Zukas (1982):

$$P = n \times a^{3/2} \qquad (2)$$

where $n = 4(R_1^{½}/3) \times 3.14(R_1 + k_2)$,
$k_1 = (1 - U_1^2)/3.14 \times E_1$, $k_2 = (1 - U_2^2)/3.14 \times E^3$, R_1 is the radius of body 1, E_1 and E_2 are Young's modulus and μ_1 and μ_2 are the Poisson's ratios.

From equations 1 and 2, we have,

$$d^2a/dt^2 = dv_1/dt + dv_2/dt = P/m_1 + P/m_2$$

$$= P(1/m_1 + 1/m_2) = PM = Mna^{3/2} \qquad (3)$$

Figure 3. The enclosure which encloses the cutting drum (a ... m opening at the bottom of the enclosure.

Integrating equation 3, we have,

$$(da/dt)^2 - v^2 = -(4/5)Mna^{3/2} \tag{4}$$

where, $v = da/dt(o)$, that is the initial approach velocity. When $da/dt = 0$, we get the maximum impact deformation, a_1

$$a_1 = (5\ v^2/4Mn)^{2/5} \tag{5}$$

Having the impact force and maximum impact deformation, another case wherein a moving ball impacts a semi-infinite body can be analyzed. From the conservation of energy law, we have

$$(1/2)\ m_1\ v_1^2 = \int_0^{a_1} P\ da = (2/5)\ n\ a_1^{5/2} \tag{6}$$

Because $v_2 = 0$, m_2 is infinite, greater in this case.

$$v = v_1,\ M = 1/m_1$$

$$P = n^{2/5}(5\ v^2/4M)^{3/5} \tag{7}$$

where P is the maximum impact force and it distributes on the contact area. Hertz has also found a relationship between the contact area and impact force (Zukas, 1982). Since contact area is a circle, its radius will be:

$$r = (3 \times 3.14\ P\ (k_1 + k_2)\ R_{1/4})^{1/3} \tag{8}$$

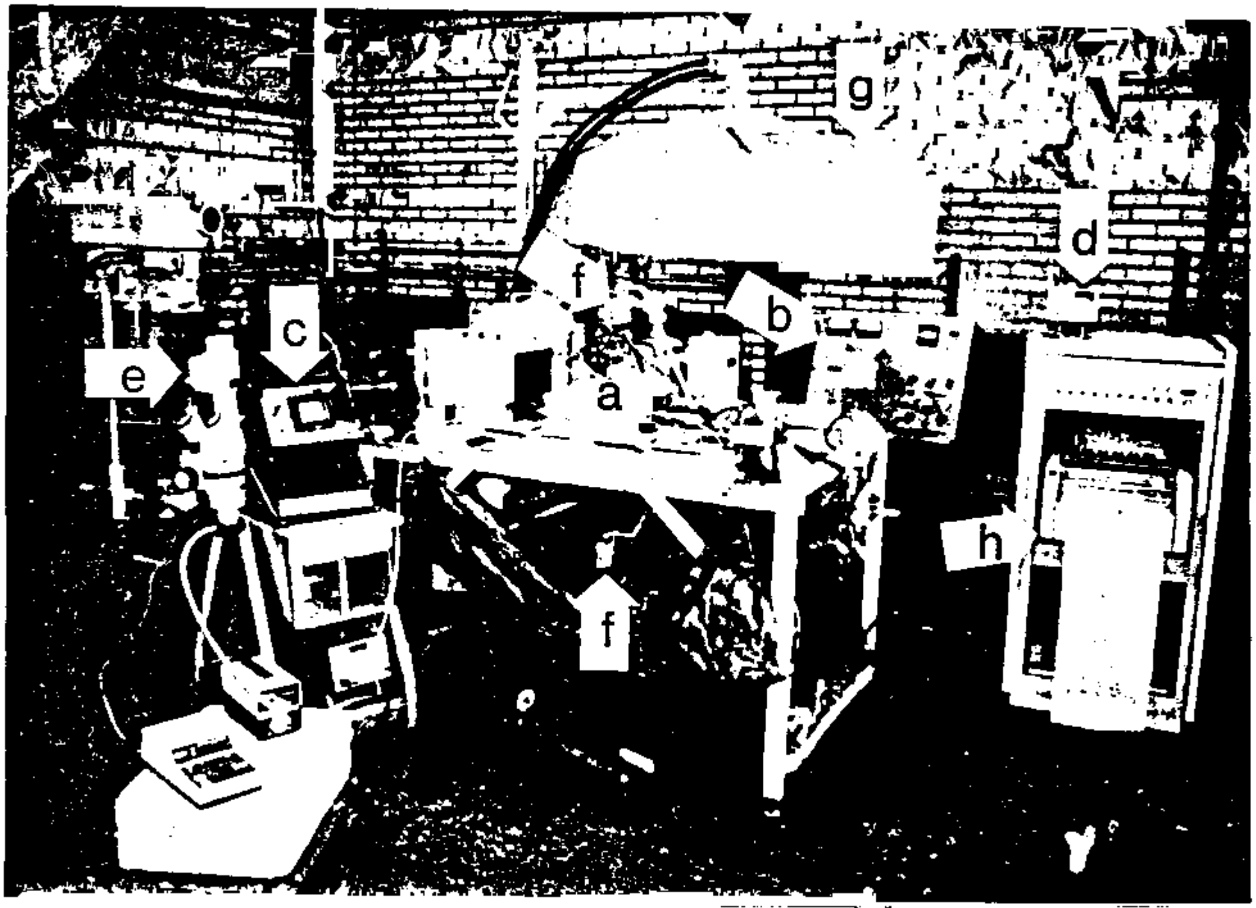


Figure 4. Test and monitoring equipment facilities (a) automated rotary coal cutting simulator, (b) programmable control and monitoring unit, (c) sonic testing unit, (d) acoustic emission, (e) microscope and the attached camera unit, (f) cascade impactors, (g) hood and air current generating unit and (h) data acquisition and recording unit.

effects of the factors and their interactions with other factors on the dependent variable can be found. With such a design the experimental error can be determined and the confidence limits can be placed on the results. But a complete factorial design contains too many parametric combinational experiments to be carried out. For example, if there are seven factors and three levels for each factor in an experimental design, the number of experiments will be $3^7 = 2187$. It is very difficult to carry out such a task considering the limitations in manpower, time and material resources. In fact, it is not necessary if higher order interaction effects are considered to be negligible. Practically only a part of the combinations are carried out. SUch replication is called fractional factorial design. What fraction should be carried out in a set of experiments? The answer depends on a particular case and its objectives. The design chosen for this study is called orthogonal fractional factorial design. The limitation in the number of pages precludes any further explanation of this design and the experimental arrangement it involves (Dey, 1985).

The distribution of impact force on the contact area is:

$$r = (x,y) = q_0(1 - x^2)/(r^2 - y^2 - r^2) \tag{9}$$

At center point $x = y = 0$

$$q_0 = 3P/(2 \times 3.14\ r^2) \tag{10}$$

Knowing the impact force and its distribution on the contact area, the internal stress can be analyzed with the help of finite element or elastic-plastic analysis. The high stress concentration at the contact or a results in a damage zone which depends on impact force and the properties of the material.

After analyzing the fragmentation mechanism a mathematical model to state the process of secondary fragementation quantitatively and to estimate the product should be developed. Since size reduction is propotional to energy consumption a relationship between these two will be established (Lunch, 1977). A combination of this relationship with the relationship of fragmentation mechanism will describe the process of secondary regrinding.

EXPERIMENTAL DESIGN

In the cutting system, the product is a combination of raw feed coal and the coal from primary cutting. The parameters that affect the product size distribution are, bit spacing (x_1), cutting velocity (x_2), cutting depth (x_3), type of coal (x_4) and size of feed material (x_5). In order to analyze the effects of these factors a multi factor design which can accommodate the multilevel testing of all these factors will be necessary. The experimental designs used in the past are classical designs. In a classical design, an experimentor keeps all the affecting factors unchanged except the factor to be investigated so that the effect of that single factor on the dependent variables can be found. For example, the depth of cut can be changed from 1/8 in. to 1/4 in. without changing any of the other factors. Similarly, the other factors can be changed one by one while keeping the rest constant. Classical experimental design is simple in arranging experiments and appears clear in the relationship between the dependent variable and all the other independent variables. But there are many problems in classical experimental designs. First, the effect of every independent variable on the dependent variable is correlated. In such correlation the effect of one independent variable on the dependent variable may depend on the magnitude of the other independent variables. Secondly, the interaction effects of two or more factors, if any cannot be determined. Finally, there are always many random conditions such as the skill of the operator, accuracy of the equipment, instruments used in measuring and recording data, etc. that influence experimental results. Such an influence results in experimental errors. These errors cannot be estimated in classical experimental designs. Therefore, there is no way of placing confidence limits on results obtained from such experiments (Finney, 1955).

In view of the above mentioned facts, a new experimental design called the orthogonal fractional factorial experimental design will be used. Factorial experimental design is a design that is used for arranging experiments which involve multiple factors and multiple levels. The experiments are designed according to the statistical theory. In a complete factorial design, all possible combinations are arranged. With the help of statistical analysis the

CONCLUSIONS

All the equipment requirements have been completed. A hydraulically powered and skid mounted chain saw was designed and fabricated and is being used to obtain coal from underground coal mines. All the necessary modifications on the automated rotary coal cutting simulator have been designed and fabricated to simulate the regrinding experiments. Coal has been obtained from two different seams, Waynesburg and Pittsburgh. The physical and mechanical properties of Waynesburg seam coal were determined in the laboratory. The orthogonal fractional factorial design has been chosen for the experimental study.

CONTINUING WORK

The physical and mechanical properties determination of Pittsburgh coal is in progress and the samples of this coal are being prepared for the regrinding experiments. It is planned to obtain coal from other seams after conducting the experiments on these two coals. The analytical model which links the secondary fragmentation mechanisms with the size distribution and the energy consumed, obtained from the experimental study is in progress. The experiments arranged according to the orthogonal ractional factorial design are being conducted on the Waynesburg coal. The outcome of the experiments on the different coals will enable the experimentor, 1) to quantify the magnitude of the dust produced due to regrinding per unit volume of coal cut and/or per unit length of arc cut, 2) to establish a secondary communition index for respirable dust generation and to correlate the secondary fragmentation to some physical and mechanical properties such as hardgrove grindability index and compressive strength, respectively.

TECH TRANSFER

Since the objectives of the first year for this project were to design and fabricate and/or to modify the existing equipment facilities no publications have resulted. However, a quarterly report, a half yearly report and an annual report is in the files of the Generic Technology Center for Respirable Dust. At the conclusion of this project, it is expected that there will be a Ph.D. dissertation and at least three papers.

REFERENCES

Dey, A., 1985, "Orthogonal Resolution III Designs for Symmetrical and Assymmetrical Factorials," Chapters 2 and 3, Orthogonal Fractional Factorial Design, Wiley and Sons, New York, pp. 24-73 and 109-115.

Finney, D. J., 1955, "Randomized Blocks, Latin Squares and Incomplete Block Designs," Chapters 4 and 5, Experimental Design and Its Statistical Basis, University of Chicago Press, Chicago, IL, pp. 45-112.

Lunch, A. J., 1977, "Fundamentals of Comminution and Mathematical Models of Size-Reduction Processes," Chapters 2 and 3, Mineral Crushing and Grinding Circuits, Elsevier, North-Holland, Inc., New York, pp. 1-44.

Matta, J. E., 1976, "Effect of Location and Type of Water Sprays for Respirable Dust Suppression on a Continuous Mining Machine," USBM, TPR 46, 11 pp.

Roepke, W. W., 1984, "General Methods of Primary Dust Control During Cutting," Mining Engineering, June, pp. 636-644.

Roepke, W. W., 1986, "Personal Communication," Twin Cities Research Center, USBM, Minnesota.

Roepke, W. W., Lindroth, D. P. and Myren, T. A., 1976, "Reduction of Dust and Energy During Coal Cutting Using Point Attack Bits," USBM, RI 8185, 53 pp.

Zukas, J. A., 1982, "Damage in Composite Material Due to Low Velocity Impact," Chapter 3, Impact Dynamics, Wiley and Sons, New York, pp. 55-94.

5
Appendix

APPENDIX 1

RESPIRABLE DUST CENTER PERSONNEL

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

BOLSAITIS, PETER
Massachusetts Institue of Technology
Department of Mineral Engineering
77 massachusetts Avenue
Cambridge, MA 02130
(614) 253-5069

ELLIOTT, JOHN F.
Massachusetts Institue of Technology
Department of Mineral Engineering
77 Massachusetts Avenue
Cambridge, MA 02130
(617) 253-3305

RING, TERRY
Department of Materials Science and Engineering
Massachusetts Institute of Technology
Cambridge, MA 02130
(6117) 253-4299

MICHIGAN TECHNOLOGY UNIVERSITY

CARLSON, DAVID
Senior Research Engineer
Department of Mining Engineering
Michigan Technological University
Houghton, MI 49931
(906) 487-2600

CORNILSEN, BAHNE
Department of Chemistry and Chemical Engineering
Michigan Technological University
Houghton, MI 49931
(906) 487-2295

JOHNSON, JOHN H.
Department of Mechanical Engineering
Engineering Mechanics
Michigan Technological University
Houghton, Michigan 49931
(906) 487-2551

THE PENNSYLVANIA STATE UNIVERSITY

APLAN, F. F.
Department of Mineral Engineering
Mineral Processing Section
The Pennsylvania State University
154 Mineral Sciences Building
University Park, PA 16802
(814) 863-1640

AUSTIN, L. G.
Department of Mineral Engineering
Mineral Processing Section
The Pennsylvania State University
103 Steidle Building
University Park, PA 16802
(814) 863-1825

BARTLETT, GERALD L.
Department of Pathology
Hershey Medical Center
The Pennsylvania State University
P.O. Box 850
Hershey, PA 17033
(814) 534-6184

BHAVANADAN, V. P.
Hershey Medical Center
The Pennsylvania State University
P.O. Box 850
Hershey, PA 17033
(814) 534-8154

BIENIAWSKI, Z. T.
Director, Mineral Research Institute
Department of Mineral Engineering
The Pennsylvania State University
110 Mineral Sciences Building
Univeristy Park, PA 16802
(814) 863-1645

BOWMAN, TERRI
Hershey Medical Center
The Pennsylvania State University
P.O. Box 850
Hershey, PA 17033
(814) 534-8474

CHANDER, S.
Department of Mineral Processing
The Pennsylvania State University
154 Mineral Sciences Building
University Park, PA 16802
(814) 863-1640

DEMERS, LAURENCE M.
Hershey Medical Center
The Pennsylvania State University
P.O. Box 850
Hershey, PA 17033
(814) 534-8316

DROZDOWIC, CARLA
Hershey Medical Center
The Pennsylvania State University
P.O. Box 850
Hershey, PA 17033
(814) 534-8474

FRANTZ, ROBERT L.
Co-Director, The Generic Mineral Technology
Center for Respirable Dust
Department of Mineal Engineering
The Pennsylvania State University
126 Mineral Sciences Building
University Park, PA 16802
(814) 865-7472

HOGG, R.
Department of Mineral Engineering
Mineral Processing Section
154 Mineral Sciences Building
University Park, PA 16802
(814) 863-1640

LUCKIE, PETER T.
Associate Dean of Research
Professor of Mineral Processing
415 Walker Building
The Pennsylvania State University
University Park, PA 16802
(814) 865-7659

MUTMANSKY, JAN
Department of Mineral Engineering
The Pennsylvania State University
120 Mineral Sciences Building
University Park, PA 16802
(814) 863-1642

RAMANI, R. V.
Co-Director, The Generic Mineral Technology
Center for Respirable Dust
Head, Department of Mineral Engineering
The Pennsylvania State University
103 Mineral Sciences Building
University Park, PA 16802
(814) 863-1617

SMITH, DEANE K.
Department of Geochemistry and Minerology
The Pennsylvania State University
239 Deike Building
University Park, PA 16802
(814) 865-5782

WEST VIRGINIA UNIVERSITY

ABRONS, H.
University Hospital
West Virginia University
Morgantown, WV 26505
(304) 293-4661

BAJURA, R. A.
West Virginia University
Director, Energy Research Center
Morgantown, WV 26505
(304) 293-2867

CHIANG, H. S.
Department of Mining Engineering
West Virginia University
P.O. Box 6070
Morgantown, WV 26505
(304) 293-5695 (X-21)

CILENTO, EUGENE
Chemical Engineering
West Virginia University
Morgantown, WV 26505
(304) 293-2619

DALAL, N.S.
Department of Chemistry
West Virginia University
P.O. Box 6045
Morgantown, WV 26505
(304) 293-3435

DIGREGORIO, K.
Chemical Engineering
West Virginia University
Morgantown, WV 26505
(304) 293-2619

GRAYSON, R. LARRY
Department of Mining Engineering
University of West Virginia
P.O. Box 6070
Morgantown, WV 26505
(304) 293-5695 (X-57)

KHAIR, A. W.
Department of Mining Engineering
University of West Virginia
P.O. Box 6070
Morgantown, Wv 26505
(304) 293-5695 (X-22)

MELOY, THOMAS P.
Particle Analysis Center
West Virginia University
Evansdale Campus
Morgantown, WV 26505
(304) 293-6016

PENG, S. S.
Department of Mining Engineering
West Virginia University
P.O. Box 6070
Morgantown, WV 26505
(304) 293-5695 (X-21)

SEEHRA, M. S.
Physics Department
West Virginia University
Morgantown, WV 26505
(304) 293-3421

SNECKENBERGER, J.
Mechanical & Aerospace Engineering
West Virginia University
Morgantown, WV 26505
(304) 293-3111

STANLEY, C.
Mechanical & Aerospace Engineering
West Virginia University
Morgantown, WV 26505
(304) 293-3111

STOBBE, T.
Department of Industrial Engineering
West Virginia University
P.O. Box 6070
Morgantown, WV 26505
(304) 293-4607

VALLYATHAN, V.
944 Chestnut Ridge Road NIOSH
Morgantown, WV 26505-2888
(3040 291-4126

VANDYKE, K.
Professor, Pharmacology
Health Sciences
Department of Pharmacology
West Virginia University
Morgantown, WV 26506
(304) 293-5449

WALLACE, WILLIAM
Engineering Sciences
West Virginia University
Evansdale Campus
Morgantown, Wv 26505

UNIVERSITY OF MINNESOTA

MARPLE, V.
Department of Mechanical Engineering
University of Minnesota
111 Church Street, S.E.
Minneapolis, MN 55455
(612) 625-3441

RUBOW, K.
Department of Mechanical Engineering
University of Minnesota
111 Church Street, S.E.
Minneapolis, MN 55455
(612) 625-8354

APPENDIX 2

CHARACTERISTICS OF COAL USED TO PREPARE STANDARD DUSTS

Coal Designation	Seam	Seam Location, County	ASTM Rank
MP3	U. Freeport	Armstrong	High Vol. A Bit.
PSOC 1192	L. Kittanning	Clearfield	Medium Vol. A. Bit.
PSOC 1361P	U. Freeport	Lawrence	High Vol. A Bit.
PSOC 867	Primrose	Schuylkill	Anthracite

Coal Identification: MP3

Coal Seam: Upper Freeport

Location: Plumcreek Township
Armstrong County, PA
Mine: Margaret No. 11

Collection: Hand-mined channel sample from freshly prepared face. Sealed in plastic-lined burlap bags. Returned to the laboratory at University Park.

Collection Date: September 27, 1979.

** PENN STATE COAL DATA BASE **

```
******************
*                *
* SAMPLE HISTORY *
*                *
******************
```

PENN STATE NUMBER	PSOC-1192
COLLECTED BY	PENNSYLVANIA STATE UNIVERSITY
COLLECTION DATE	10/16/79
COLLECTOR'S NUMBER	1192
REPORTED RANK	
SAMPLE TYPE	CHANNEL WHOLE SEAM
OTHER SAMPLE INFORMATION	
SAMPLE RESERVE	150
SEAM NAME	LOWER KITTANNING
ALTERNATE SEAM NAME	B SEAM
TOTAL SEAM THICKNESS	1 FT. 10 IN.
THICKNESS OF SEAM SAMPLED	1 FT. 10 IN.
PORTION RECOVERED IN CORE	
DIAMETER OF CORE	

SEAM NAME LOWER KITTANNING
APPARENT RANK MEDIUM VOLATILE BITUMINOUS (MVB)

```
***********************
*                     *
* GEOLOGIC INFORMATION *
*                     *
***********************
```

SYSTEM (AGE)	PENNSYLVANIAN
SERIES	
GROUP	
FORMATION	ALLEGHENY
OVERBURDEN LITHOLOGY	SHALE
FLOOR LITHOLOGY	SHALE

Characteristics of Coals Used to Prepare Standard Dusts

CHEMICAL DATA 1

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF (PARR)	DMMF (PARR-G)	DMMF (DIR MM)
% MOISTURE	0.67					
% ASH	11.40	11.48				
% VOLATILE MATTER	24.09	24.24	27.38	25.46	25.53	
% FIXED CARBON	63.85	64.28	72.62	74.54	74.47	

CHEMICAL DATA 2

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF(PARR)
				(14.55 %MM)
% ASH	11.40	11.48		
% CARBON	76.08	76.59	86.52	89.64
% HYDROGEN	4.50*	4.53	5.12	5.30
% NITROGEN	1.42	1.43	1.62	1.67
% SULFUR	3.89	3.92	4.43	
% CHLORINE	0.08	0.09	0.10	0.10
% OXYGEN(DIFF)	1.95*	1.97	2.23	3.30

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	3.14	0.02	0.76	3.92
DAF	3.55	0.02	0.86	4.43
OPTICAL				

ELEMENTAL ANALYSIS	DRY	DMMF(MOD.P)	DMMF(DIR.)
		(14.49%MM)	(%MM)
% CARBON	76.41	89.36	
% HYDROGEN	4.32	5.05	
% NITROGEN	1.43	1.67	
% ORGANIC SULFUR	0.76	0.89	
% OXYGEN(DIFF)	2.59	2.94	
% CHLORINE	0.09	0.10	
% MINERAL MATTER	14.49		

(INCLUDES 5.87 % FES2)

****
* CHEMICAL DATA 3 *
****

% MOISTURE IN COAL = 0.40
% HIGH TEMPERATURE ASH = 11.70 AT 750 DEGREES C

TRACE ELEMENT ANALYSIS	PPM HTA	PPM TOTAL COAL	MAJOR ELEMENT ANALYSIS	OXIDE % OF HTA	ELEMENT % OF TOTAL DRY COAL
AG			SIO2	34.20	1.87
B			AL2O3	23.10	1.43
BA	780	91	TIO2	0.90	0.06
BE	35	4	FE2O3	38.50	3.15
BI			MGO	0.45	0.03
CE			CAO	1.12	0.09
CO			NA2O	0.21	0.02
CR	170	20	K2O	1.06	0.10
CU	95	11	P2O5	0.12	0.01
GA			SO3	1.20	0.06
GE					
LA					
LI					
MN					
MO			VOLATILES		PPM TOTAL COAL
NI	140	16			
NB			AS		
PB			BR		
RB	50	6	CD		
SC			CL		
SN			F		
SR	370	43	HG		
TH			SB		
U			SE		
V	250	29			
Y					
YB					
ZN	220	26			
ZR	220	26			

PETROGRAPHIC DATA

MACERAL COMPOSITION WHITE ANALYSIS ONLY

	DRY VOLUME %	DMMF VOLUME %	DRY WEIGHT %
VITRINITE (CALC.)	80.5	87.1	74.4
INERTINITE (CALC.)	11.8	12.8	10.9
LIPTINITE (CALC.)	0.1	0.1	0.1
MINERAL MATTER (CALC.)	7.6		14.6
VITRINOIDS			
VITRINITE	79.4	85.9	73.4
PSEUDOVITRINITE	1.1	1.2	1.0
FUSINITE	2.5	2.7	2.3
SEMI-FUSINITE	7.0	7.6	6.5
MACRINITE	0.6	0.6	0.5
MICRINITE	1.8	1.9	1.6
SCLEROTINITE	0.0	0.0	0.0
SPORINITE			
CUTINITE			
EXINITE (ANAL.)	0.1	0.1	0.1
RESINITE	0.0	0.0	0.0
SUBERINITE			
EXUDATINITE			
FLUORINITE			
BITUMINITE			
ALGINITE	0.0	0.0	0.0
LIPTODETRINITE			
MINERAL MATTER(ANAL.)			
INERTINITE(ANAL.)			
LIPTINITE(ANAL.)			

REFLECTANCE DATA (%.IN OIL)	HIGH	LOW	RANGE	MEAN MAX	STAND.DEV.
VITRINITE	1.49	1.20	0.29	1.32	0.05
PSEUDOVITRINITE					
VITRINOIDS					

% VITRINOID REFLECTANCE	HALF-TYPE	VOLUME PERCENT
1.20-1.24	VHT 1.225	7.00
1.25-1.29	VHT 1.275	20.00
1.30-1.34	VHT 1.325	41.00
1.35-1.39	VHT 1.375	17.00
1.40-1.44	VHT 1.425	4.00
1.45-1.49	VHT 1.475	3.00

% VITRINOID REFLECTANCE	V-TYPE	VOLUME PERCENT
1.20-1.29	V12	27.00
1.30-1.39	V13	58.00
1.40-1.49	V14	7.00

** PENN STATE COAL DATA BASE **

```
*****************
*               *
* SAMPLE HISTORY *
*               *
*****************
```

PENN STATE NUMBER	PSOC-1361P
COLLECTED BY	PENNSYLVANIA STATE UNIVERSITY
COLLECTION DATE	2/24/82
COLLECTOR'S NUMBER	
REPORTED RANK	
SAMPLE TYPE	CHANNEL WHOLE SEAM
OTHER SAMPLE INFORMATION	PREMIUM SAMPLE
SAMPLE RESERVE	80
SEAM NAME	UPPER FREEPORT
ALTERNATE SEAM NAME	E SEAM
TOTAL SEAM THICKNESS	0 FT. 26 IN.
THICKNESS OF SEAM SAMPLED	0 FT. 26 IN.
PORTION RECOVERED IN CORE	
DIAMETER OF CORE	

SEAM NAME UPPER FREEPORT
APPARENT RANK HIGH VOLATILE A BITUMINOUS (HVAB)

```
***********************
*                     *
* GEOLOGIC INFORMATION *
*                     *
***********************
```

SYSTEM (AGE)	PENNSYLVANIAN
SERIES	
GROUP	ALLEGHENY
FORMATION	
OVERBURDEN LITHOLOGY	BLACK SHALE
FLOOR LITHOLOGY	CLAY

CHEMICAL DATA 1

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF (PARR)	DMMF (PARR-G)	DMMF (DIR MM)
% MOISTURE	1.90					
% ASH	8.31	8.47				
% VOLATILE MATTER	37.43	38.16	41.69	40.88	40.85	
% FIXED CARBON	52.36	53.37	58.31	59.12	59.15	

CHEMICAL DATA 2

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF(PARR)
				(10.21 %MM)
% ASH	8.31	8.47		
% CARBON	73.57	75.00	81.94	83.53
% HYDROGEN	5.12*	5.22	5.70	5.81
% NITROGEN	1.38	1.41	1.54	1.57
% SULFUR	1.90	1.94	2.12	
% CHLORINE				
% OXYGEN(DIFF)	7.81*	7.96	8.70	9.08

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	1.17	0.05	0.72	1.94
DAF	1.28	0.05	0.79	2.12
OPTICAL				

ELEMENTAL ANALYSIS	DRY	DMMF(MOD.P)	DMMF(DIR.)
		(10.12%MM)	(%MM)
% CARBON	74.87	83.31	
% HYDROGEN	5.09	5.66	
% NITROGEN	1.41	1.57	
% ORGANIC SULFUR	0.72	0.80	
% OXYGEN(DIFF)	7.79	8.66	
% CHLORINE	-		
% MINERAL MATTER (INCLUDES 2.19 % FES2)	10.12		

CHEMICAL DATA 3

% MOISTURE IN COAL = 1.90
% HIGH TEMPERATURE ASH = 8.27 AT 750 DEGREES C

TRACE ELEMENT ANALYSIS	PPM HTA	PPM TOTAL COAL
AG		
B		
BA	1000	83
BE	20	2
BI		
CE		
CO		
CR	150	12
CU	190	16
GA		
GE		
LA		
LI		
MN		
MO		
NI	150	12
NB		
PB		
RB	90	7
SC		
SN		
SR	1050	87
TH		
U		
V	160	13
Y		
YB		
ZN	290	23
ZR	230	19

MAJOR ELEMENT ANALYSIS	OXIDE % OF HTA	ELEMENT % OF TOTAL DRY COAL
SIO2	42.40	1.64
AL2O3	23.20	1.02
TIO2	1.02	0.05
FE2O3	26.40	1.53
MGO	0.74	0.04
CAO	1.15	0.07
NA2O	0.38	0.02
K2O	2.36	0.16
P2O5	0.48	0.02
SO3	0.80	0.03

VOLATILES	PPM TOTAL COAL
AS	
BR	
CD	
CL	
F	
HG	
SB	
SE	

*** PETROGRAPHIC DATA ***

MACERAL COMPOSITION WHITE ANALYSIS ONLY

	DRY VOLUME %	DMMF VOLUME %	DRY WEIGHT %
VITRINITE (CALC.)	74.4	78.5	70.5
INERTINITE (CALC.)	15.1	15.9	14.3
LIPTINITE (CALC.)	5.3	5.6	5.0
MINERAL MATTER (CALC.)	5.2		10.2
VITRINOIDS			
VITRINITE	71.1	75.0	67.3
PSEUDOVITRINITE	3.3	3.5	3.1
FUSINITE	4.2	4.4	3.9
SEMI-FUSINITE	4.3	4.5	4.0
MACRINITE	0.9	0.9	0.8
MICRINITE	5.8	6.1	5.5
SCLEROTINITE	0.0	0.0	0.0
SPORINITE			
CUTINITE			
EXINITE (ANAL.)	4.7	5.0	4.5
RESINITE	0.6	0.6	0.5
SUBERINITE			
EXUDATINITE			
FLUORINITE			
BITUMINITE			
ALGINITE	0.0	0.0	0.0
LIPTODETRINITE			
MINERAL MATTER(ANAL.)			
INERTINITE(ANAL.)			
LIPTINITE(ANAL.)			

REFLECTANCE DATA (%,IN OIL)	HIGH	LOW	RANGE	MEAN MAX	STAND.DEV.
VITRINITE	0.93	0.73	0.20	0.83	0.04
PSEUDOVITRINITE					
VITRINOIDS					

% VITRINOID REFLECTANCE	HALF-TYPE	VOLUME PERCENT	% VITRINOID REFLECTANCE	V-TYPE	VOLUME PERCENT
0.70-0.74	VHT 0.725	2.00			
0.75-0.79	VHT 0.775	12.00	0.70-0.79	V7	14.00
0.80-0.84	VHT 0.825	55.00			
0.85-0.89	VHT 0.875	25.00	0.80-0.89	V8	80.00
0.90-0.94	VHT 0.925	6.00			
0.95-0.99	VHT 0.975		0.90-0.99	V9	5.00

** PENN STATE COAL DATA BASE **

```
******************
*                *
* SAMPLE HISTORY *
*                *
******************
```

PENN STATE NUMBER	PSOC-867
COLLECTED BY	PENNSYLVANIA STATE UNIVERSITY
COLLECTION DATE	8/29/76
COLLECTOR'S NUMBER	867
REPORTED RANK	ANTHRACITE (AN)
SAMPLE TYPE	CHANNEL WHOLE SEAM
OTHER SAMPLE INFORMATION	
SAMPLE RESERVE	329
SEAM NAME	PRIMROSE
ALTERNATE SEAM NAME	
TOTAL SEAM THICKNESS	16 FT. 0 IN.
THICKNESS OF SEAM SAMPLED	16 FT. 0 IN.
PORTION RECOVERED IN CORE	
DIAMETER OF CORE	

SEAM NAME PRIMROSE
APPARENT RANK ANTHRACITE (AN)

```
***********************
*                     *
* GEOLOGIC INFORMATION *
*                     *
***********************
```

SYSTEM (AGE)	PENNSYLVANIAN
SERIES	
GROUP	
FORMATION	LLEWELLYN
OVERBURDEN LITHOLOGY	SHALE
FLOOR LITHOLOGY	SHALE

```
******************
*                *
* CHEMICAL DATA 1 *
*                *
******************
```

PROXIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF (PARR)	DMMF (PARR-G)	DMMF (DIR MM)
% MOISTURE	3.77					
% ASH	13.39	13.91				
% VOLATILE MATTER	3.57	3.71	4.31	2.82	1.08	
% FIXED CARBON	79.27	82.38	95.69	97.18	98.12	

```
******************
*                *
* CHEMICAL DATA 2 *
*                *
******************
```

ULTIMATE ANALYSIS	AS REC'D	DRY	DAF	DMMF(PARR) (15.31 %MM)
% ASH	13.39	13.91		
% CARBON	78.76	81.85	95.07	96.65
% HYDROGEN	1.02*	1.06	1.23	1.25
% NITROGEN	0.64	0.66	0.77	0.78
% SULFUR	0.50	0.52	0.60	
% CHLORINE	0.02	0.03	0.03	0.03
% OXYGEN(DIFF)	1.90*	1.97	2.30	1.30

SULFUR FORMS	% PYRITIC	% SULFATIC	% ORGANIC	% TOTAL
DRY	0.05	0.01	0.46	0.52
DAF	0.06	0.01	0.53	0.60
OPTICAL				

ELEMENTAL ANALYSIS	DRY	DMMF(MOD.P) (15.75%MM)	DMMF(DIR.) (%MM)
% CARBON	81.65	96.92	
% HYDROGEN	0.88	1.04	
% NITROGEN	0.66	0.78	
% ORGANIC SULFUR	0.46	0.55	
% OXYGEN(DIFF)	0.59	0.68	
% CHLORINE	0.03	0.03	
% MINERAL MATTER (INCLUDES 0.09 % FES2)	15.75		

```
******************
*                *
* CHEMICAL DATA 3 *
*                *
******************
```

% MOISTURE IN COAL = 1.23
% HIGH TEMPERATURE ASH = 13.67 AT 750 DEGREES C

TRACE ELEMENT ANALYSIS	PPM HTA	PPM TOTAL COAL
AG		
B		
BA	1440	197
BE	6	1
BI		
CE		
CO		
CR	260	36
CU	180	25
GA		
GE		
LA		
LI		
MN		
MO		
NI	160	22
NB		
PB		
RB	180	25
SC		
SN		
SR	670	92
TH		
U		
V	220	30
Y		
YB		
ZN	110	15
ZR	340	46

MAJOR ELEMENT ANALYSIS	OXIDE % OF HTA	ELEMENT % OF TOTAL DRY COAL
SIO2	55.00	3.51
AL2O3	31.60	2.29
TIO2	1.93	0.16
FE2O3	3.30	0.32
MGO	0.86	0.07
CAO	0.65	0.06
NA2O	1.01	0.10
K2O	3.38	0.38
P2O5	0.26	0.02
SO3	0.60	0.03

VOLATILES	PPM TOTAL COAL
AS	
BR	
CD	
CL	
F	
HG	
SB	
SE	

****
*   *
* PETROGRAPHIC DATA *
*   *
****

MACERAL COMPOSITION WHITE ANALYSIS ONLY

	DRY VOLUME %	DMMF VOLUME %	DRY WEIGHT %
VITRINITE (CALC.)	71.7	77.9	66.0
INERTINITE (CALC.)	20.3	22.1	18.7
LIPTINITE (CALC.)		0.0	0.0
MINERAL MATTER (CALC.)	8.0		15.3
VITRINOIDS			
VITRINITE	71.7	77.9	66.0
PSEUDOVITRINITE	0.0	0.0	0.0
FUSINITE	0.7	0.8	0.7
SEMI-FUSINITE	19.5	21.2	17.9
MACRINITE	0.1	0.1	0.1
MICRINITE	0.0	0.0	0.0
SCLEROTINITE	0.0	0.0	0.0
SPORINITE	0.0	0.0	0.0
CUTINITE	0.0	0.0	0.0
EXINITE (ANAL.)	0.0	0.0	0.0
RESINITE	0.0	0.0	0.0
SUBERINITE			
EXUDATINITE			
FLUORINITE			
BITUMINITE			
ALGINITE	0.0	0.0	0.0
LIPTODETRINITE			
MINERAL MATTER(ANAL.)			
INERTINITE(ANAL.)			
LIPTINITE(ANAL.)			

REFLECTANCE DATA (%, IN OIL)	HIGH	LOW	RANGE	MEAN MAX	STAND.DEV.
VITRINITE	5.80	4.86	0.94	5.77	0.38
PSEUDOVITRINITE					
VITRINOIDS					

Size Distribution of Standard Respirable Dusts as Determined by Ladal Pipet Centrifuge.

MP3-1		MP3-2		MP3-3		PSOC 1192		PSOC 1192M		PSOC 867		PSOC 1361P		Kaolinite		Quartz	
X[≠]	F[+]	X	F	X	F	X	F	X	F	X	F	X	F	X	F	X	F
4.63	100.0	9.80	100.0	6.55	82.1	6.55	100.0	4.63	86.2	4.33	81.3	4.63	71.6	17.5[+]	95.7	3.14	46.8
3.08	89.1	6.56	91.3	4.63	48.2	4.34	88.3	2.97	43.8	2.88	39.0	3.08	34.7	12.5[+]	91.9	2.09	25.8
1.99	73.4	4.21	75.2	3.07	26.8	2.79	45.6	1.88	23.9	2.03	24.4	1.99	12.8	8.4[+]	90.8	1.35	14.4
1.27	52.4	2.65	28.4	1.98	15.4	1.77	19.2	1.18	12.2	1.32	9.0	1.27	4.7	6.9[+]	88.5	0.86	6.6
0.79	28.3	1.69	9.6	1.25	8.3	1.10	7.1	0.74	6.0	0.84	3.9	0.79	1.9	5.0[+]	82.7	0.54	2.3
0.49	9.0	1.05	2.8	0.77	3.4	0.66	1.1	0.46	3.0	0.52	2.4	0.49	1.1	3.35[+]	73.1	0.33	0.94
0.28	3.7	0.66	1.0	0.47	2.2	0.39	0.68	0.26	1.3	0.32	1.9	0.29	0.59	2.22	67.4		
				0.27	1.0					0.19	1.4			1.48	58.8		
														0.96	45.2		
														0.61	32.5		
														0.38	26.5		
														0.23	13.7		
														0.14	8.2		

≠ size of particle in μm
* Cumulative weight percent finer than size
+ Analysis extended with Andreasen Pipet

Size Distribution of Standard Respirable Dusts as Determined by Microtrac Small Particle Ánalyser.

Particle	Weight percent finer than size								
Size, µm	MP3-1	MP3-2	MP3-3	PSOC 1192	PSOC 1192M	PCOS 1361P	PSOC 867	Kaolinite	Quartz
42.21	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
29.85	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
21.10	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.7	100.0
14.92	100.0	100.0	93.2	100.0	99.1	100.0	100.0	91.4	97.5
10.55	100.0	100.0	84.7	99.3	97.5	100.0	100.0	85.4	90.9
7.46	98.7	87.9	67.2	94.6	88.8	89.2	88.6	65.4	75.2
5.27	97.1	60.0	44.7	69.7	67.6	61.6	60.3	62.8	52.7
3.73	92.2	34.0	28.6	39.6	45.4	35.7	36.5	50.1	35.6
2.63	77.6	18.5	19.1	20.9	29.7	20.2	21.7	37.4	23.0
1.69	59.6	9.8	12.6	10.4	19.3	11.1	10.8	27.2	13.5
1.01	37.8	4.7	7.3	5.1	11.7	5.7	4.1	17.7	6.7
0.66	17.2	1.9	3.3	1.8	5.4	2.3	1.3	11.2	2.4
0.43	7.0	0.7	1.3	0.7	2.2	0.8	0.1	8.5	0.8
0.34	2.2	0.2	0.4	0.2	0.7	0.2	0.0	7.2	0.3
0.24	0.8	0.0	0.1	0.0	0.2	0.0	0.0	6.8	0.1
0.17	0.2	0.0	0.0	0.0	0.1	0.0	0.0	6.4	0.0

Mineralogical Composition of Standard Respirable Dusts as Determined by the Mineral Constitution Laboratory of The Pennsylvania State University.

Sample	PSOC 867	PSOC 1192M	PSOC 1361P	MP3-2
LTA	25.7%	9.58%	9.03%	10.1%
Quartz	14	4	8	12
Pyrite	n.d.	22	32	16
Kaolinite	35-45	30-40	30-40	25-35
Illite*	-	10-20	10-20	20-30
Illite plus mixed-layer clays*	20-30	-	-	-
Chlorite*	5-15	n.d.	n.d.	n.d.
Feldspars*	5-10	n.d.	n.d.	n.d.

n.d. = not detected
* = estimated value based on normative analyses.

Spectrochemical Analysis of Standard Respirable Dusts Expressed as Oxides.

Oxide	Percent of high temperature ash						
	PSOC 867	PSOC 1192	PSOC 1192M	PSOC 1361P	MP3-2	Kaolinite	Quartz
SiO_2	53.4	33.5	36.9	43.1	47.3	45.2	95
Al_2O_3	33.1	25.2	27.6	27.7	27.6	38.1	2.06
TiO_2	1.46	1.02	1.27	1.12	1.35	1.36	<0.1
Fe_2O_3	5.30	34.4	27.7	22.5	14.7	0.34	0.50
MgO	1.23	0.49	0.58	0.84	1.00	<0.1	<0.1
CaO	0.60	1.56	1.74	1.25	2.07	<0.1	<0.1
MnO	0.02	0.02	0.02	0.088	0.012	<0.01	<0.01
Na_2O	0.93	0.17	0.21	0.27	0.26	0.05	0.10
K_2O	2.84	1.24	1.38	1.77	2.60	0.12	0.39
P_2O_5	0.17	0.18	0.21	0.44	0.75	-	-
SO_3	0.2	0.5	0.3	0.1	0.6	-	-
TOTAL	99.3%	98.3%	97.9%	99.1%	98.3%	85.2%*	98.0%

* Loss of H_2O on ignition (750°C) < 15.2%.

Size-Specific Gravity Distribution of PSOC 1192M as a Percentage of the Total Coal.

Size, µm	42.21	29.85	21.10	14.92	10.55	7.42	6.27	3.73	2.63	1.69	1.01	0.66	0.43	0.34	0.24	0.17
(% Total)	0.0	0.0	2.1	0.8	8.3	22.7	23.9	15.8	9.6	7.3	5.4	2.5	1.1	0.4	0.1	0.3
SINK/FLOAT 1.3	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.3 x 1.4	0.0	0.0	0.1	0.0	4.9	13.4	13.8	8.0	3.8	2.7	1.8	0.7	0.0	0.0	0.0	0.0
1.4 x 1.5	0.0	0.0	0.4	0.5	2.3	3.5	3.3	2.3	2.1	1.6	1.1	0.5	0.0	0.0	0.0	0.0
1.5 x 1.6	0.0	0.0	0.0	0.0	0.9	2.7	1.5	0.9	1.4	1.1	0.8	0.3	0.0	0.0	0.0	0.0
1.6 x 1.7	0.0	0.0	0.0	0.0	0.0	0.0	3.6	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.7 x 1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.1	1.1	0.9	0.5	0.0	0.0	0.0	0.0
1.8 x 1.9	0.0	0.0	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.9	0.4	0.1	0.0
1.9 x 2.0	0.0	0.0	1.0	0.1	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.0	0.0	0.0	0.1	0.0	0.2	0.9	1.5	1.3	1.1	0.8	0.8	0.4	0.2	0.0	0.0	0.0

Size-Specific Gravity Distribution of PSOC 1361P as a Percentage of the Total Coal.

Size, µm	42.21	29.85	21.10	14.92	10.55	7.42	6.27	3.73	2.63	1.69	1.01	0.66	0.43	0.34	0.24	0.17
(% Total)	0.0	0.1	0.8	4.5	10.3	26.1	27.4	14.7	7.0	4.6	2.8	0.9	0.4	0.3	0.0	0.0
SINK/FLOAT 1.3	0.0	0.0	0.2	0.3	1.9	5.1	4.7	2.0	0.6	0.4	0.2	0.1	0.0	0.0	0.0	0.0
1.3 x 1.4	0.0	0.0	0.1	0.2	2.4	6.1	6.4	3.2	1.1	0.7	0.4	0.2	0.1	0.0	0.0	0.0
1.4 x 1.5	0.0	0.0	0.0	0.7	2.8	7.8	8.6	5.7	3.3	1.8	1.3	0.4	0.2	0.1	0.0	0.0
1.5 x 1.6	0.0	0.0	0.0	0.6	2.5	4.5	3.6	1.7	0.4	0.5	0.3	0.1	0.0	0.0	0.0	0.0
1.6 x 1.7	0.0	0.0	0.0	0.6	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.7 x 1.8	0.0	0.1	0.3	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.8 x 1.9	0.0	0.0	0.0	0.0	0.0	1.5	2.8	0.9	0.5	0.6	0.0	0.0	0.0	0.1	0.0	0.0
1.9 x 2.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
2.0	0.0	0.0	0.2	0.1	0.4	1.0	1.0	1.4	1.2	0.8	0.5	0.2	0.1	0.0	0.0	0.0

Size-Specific Gravity Distribution of PSOC 867 as a Percentage of the Total Coal.

Size, μm	42.21	29.85	21.10	14.92	10.55	7.42	6.27	3.73	2.63	1.69	1.01	0.66	0.43	0.34	0.24	0.17
(% Total)	0.0	0.0	0.6	2.0	11.2	25.7	24.0	17.3	9.9	5.0	3.3	0.9	0.1	0.0	0.0	0.0
SINK/FLOAT 1.3	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
1.3 x 1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.4 x 1.5	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5 x 1.6	0.0	0.0	0.3	0.5	1.6	3.4	2.6	0.8	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
1.6 x 1.7	0.0	0.0	0.0	0.6	5.7	11.6	8.6	4.3	1.1	0.4	0.4	0.0	0.0	0.0	0.0	0.0
1.7 x 1.8	0.0	0.0	0.0	0.1	1.3	5.4	6.4	4.3	2.6	1.1	0.6	0.1	0.0	0.0	0.0	0.0
1.8 x 1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.4	1.0	0.2	0.2	0.1	0.0	0.0	0.0	0.0
1.9 x 2.0	0.0	0.0	0.0	0.1	0.4	0.0	0.6	1.8	1.4	0.8	0.6	0.2	0.0	0.0	0.0	0.0
2.0	0.0	0.0	0.3	0.6	2.0	5.0	5.4	4.7	3.4	2.3	1.5	0.5	0.1	0.0	0.0	0.0