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Human Factors in Mining

By Mark S. Sanders and James M. Peay

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	kg-m	kilogram-meter
c	candle	kHz	kilohertz
c/in^2	candle per square inch	kJ	kilojoule
c/m^2	candle per square meter	km	kilometer
cal	calorie	L	liter
cal/min	calorie per minute	L/min	liter per minute
cm	centimeter	lb	pound
dB	decibel	lb-in	pound-inch
dBA	decibel, A-weighted	lm	lumen
deg	degree	lm/ft^2	lumen per square foot
°F	degree Fahrenheit	lx	lux
fc	footcandle	m	meter
fL	footlambert	m/s^2	meter per square second
ft	foot	m^2	square meter
ft-lb	foot-pound	mg	milligram
ft/s^2	foot per square second	min	minute
h	hour	mL	milliliter
Hz	hertz	mL/(kg/min)	milliliter per kilogram per minute
in	in	mm	millimeter
in/oz	inch per ounce	$\mu N/m^2$	micronewton per square meter
in/s^2	inch per square second	oz	ounce
in^2	square inch	psi	pound (force) per square inch
J	joule	s	second
kcal	kilocalorie	sr	steradian
kcal/h	kilocalorie per hour	st	short ton
kcal/kg-m	kilocalorie per kilogram-meter	W	watt
$kcal/(m^2/h)$	kilocalorie per square meter per hour	yd	yard
kcal/min	kilocalorie per minute	yr	year
kg	kilogram		

HUMAN FACTORS IN MINING

By Mark S. Sanders[1] and James M. Peay[2]

ABSTRACT

There is a growing awareness among mining professionals that the human factor plays a significant role in safety and productivity. Since the 1960's, the science of human factors, or ergonomics, has been making inroads into the mining industry, and a considerable amount of research has documented human-factor-related mining problems and solutions. This Bureau of Mines report is directed toward summarizing the application of human factors to improving safety, productivity, and the general physical and psychological working conditions of miners.

The aim of this report is to familiarize the readers with the role of human factors in the mining industry and the benefits that can accrue by systematically applying available human factors principles and data. The text contains 10 chapters dealing with human, equipment, and environmental factors. Each chapter builds on the previous chapter; therefore, it is recommended that the chapters be read sequentially. However, if the report is used as a supplemental text, say in a mining safety course, chapters can be assigned in any order to supplement other readings.

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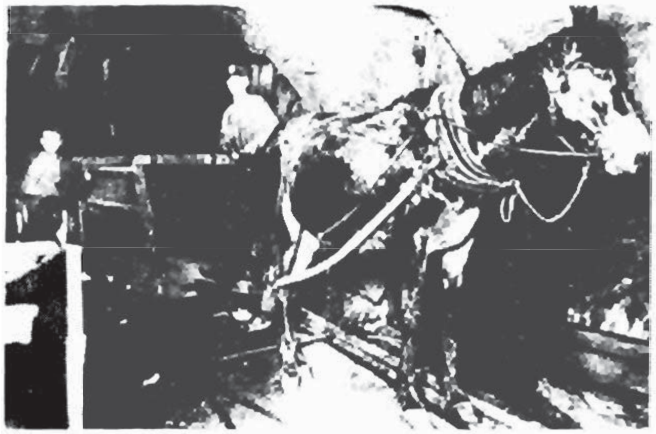
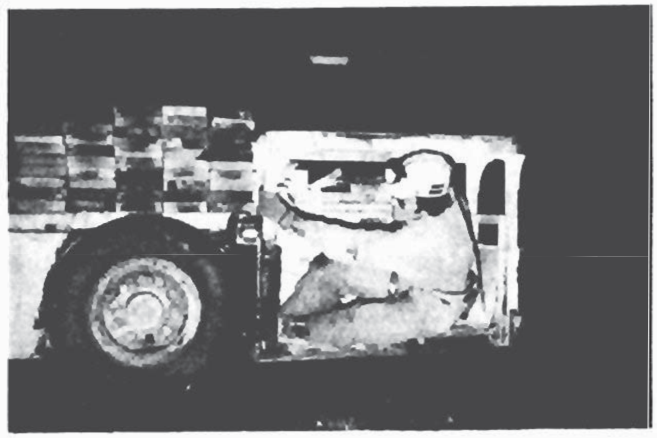
CHAPTER 1.—INTRODUCTION





The mining industry has undergone and continues to undergo technological innovation at an increasingly rapid pace.

It was not too long ago that horses were still in the mines, and people loaded ore and coal by hand. In 1950, for example, almost one-third of the coal produced underground in the United States was loaded by hand (*24*).[1] Although many jobs still require high levels of physical labor, mechanization has greatly reduced the physical demands placed on the mine worker. Today, mines are safer than at any period in the past and safety is now an important part of mine management. Coupled with the concern for safety is management's ever present concern for productivity and the resultant economic viability of the mining operation.

Over the last quarter century or so, there has been a growing recognition within industrialized countries that people are the key to both safety and productivity. Technology has done much to increase productivity and safety in the mining industry. It has become obvious, however, that as technology advanced, new demands were being placed on the worker. More attention, not less, had to be paid to how people and technology would work together. How could equipment and tasks be designed to match the capabilities and limitations of the people who had to operate and maintain them? This is one of the questions addressed by human factors. The Bureau of Mines launched its human factors research program over a decade ago (*19*), and a considerable body of knowledge now exists concerning human factors in mining.

The purpose of this report is to introduce the reader to human factors and its application in mining, to summarize much of the current knowledge, and to illustrate the utility of considering human factors in the design of equipment, tasks, procedures, and environments within the mining industry.

DEFINITION OF HUMAN FACTORS

Before attempting to define human factors, a word about terminology is in order. Unfortunately, several terms are used interchangeably to refer to the same scientific discipline. The two leading terms are *human factors* and *ergonomics*. A third term, *human engineering*, is somewhat dated and seems to be declining in use. The term "human factors" is used most often in the United States and Canada. Both countries have professional associations that use the term in their name (i.e., The Human Factors Society in the United States and The Human Factors Association of Canada in Canada). In the United States, however, the more scientific sounding term "ergonomics" is often used in product advertisements for such things as automobiles, computer hardware, and chairs.

In the rest of the world, the term "ergonomics" is preferred; and in many countries, including the United Kingdom, France, Federal Republic of Germany, Poland, Israel, and Mexico, there are ergonomic professional organizations.

Although most authors do not attempt to distinguish the two terms, one book does try to make the distinction (*7*). Reference 7 indicates that ergonomics traditionally focuses on how work affects people, emphasizing physiological responses to physically demanding work; environmental stressors, such as heat, noise, and illumination; complex psychomotor assembly tasks; and visual monitoring tasks. The goal is chiefly to reduce fatigue by designing tasks within people's work capacity. In contrast, reference 7 argues that human factors traditionally is more interested in the human-hardware interaction, focusing on behavior of people as they interact with equipment, workplaces, and their environment, as well as on human size and strength capabilities relevant to equipment and workspace design. The goal is chiefly to reduce the potential for human error.

Although this distinction may be correct in theory, in practice there is so much overlap in focus, emphasis, and goals that it is safer to consider the two terms synonymous. In fact, it should be pointed out that it was the Human Factors section at Eastman Kodak that published the book entitled "Ergonomic Design for People at Work" (*7*). The term "human factors" will be used in this report, but human factors and ergonomics will be considered synonymous.

What then is the definition of human factors? The simplest definition is that human factors is designing for

[1] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

human use. The following is a more elaborate definition that most people would find acceptable. Human factors is the systematic application of relevant information about human characteristics, abilities, expectations, and behaviors to the design of machines, tools, facilities, procedures, and environments that people use. The goal of human factors is to enhance the operational efficiency, and the health and safety of the people using the system.

BASIC MODEL

Human factors focuses on the human-hardware-environment system. The basic system, one person and one machine operating inside an environment, is shown in figure 1-1. This, of course, is an oversimplification. Most systems involve more than one person and more than one piece of hardware, and they operate within a changing environment. Systems are more fully discussed in chapter 2, but this rudimentary model illustrates the basic elements of concern to human factors. The person receives information from the machine by way of displays. These displays can be visual, auditory, tactual, and olfactory in nature. The human processes the information and makes inputs to the machine by way of control devices: push buttons, knobs, joysticks, steering wheels, etc. The person and machine are affected by, and receive information from, the environment. The machine affects the environment, often at the direction of the person. Although people can directly influence the environment, this is usually accomplished through some hardware device.

As an example of this model, consider a worker operating a jackleg drill in a hard-rock mine. The person receives information from the drill: hydraulic pressure from a gauge, vibrations and feel of the drill, visual confirmation of the bit penetrating the rock, and the sound of the drill. Based on this information and previous experience and knowledge, the worker manipulates the controls to successfully drill the hole. Drilling the hole alters the environment. It puts a hole where none existed before; noise, dust, and mist are generated; and perhaps rocks on the floor are moved by the support leg of the drill. These aspects of the environment affect the worker by reducing visibility, creating new tripping hazards, or perhaps causing a temporary, partial loss of hearing.

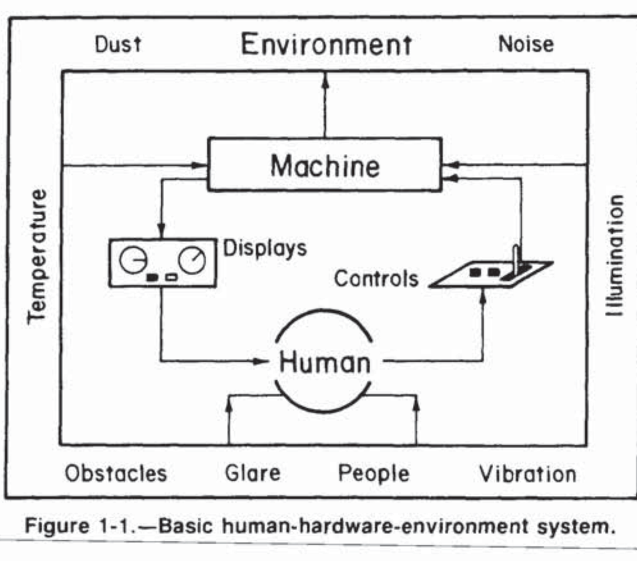


Figure 1-1.—Basic human-hardware-environment system.

WHAT HUMAN FACTORS IS NOT

Human factors specialists are concerned with the human and the human's interactions with equipment and environment. They are concerned with how best to present information, configure controls, and design the hardware so humans can operate it efficiently, comfortably, and safely. They are concerned with how the environment affects human performance, and how humans sense and respond to the environment. They are interested in the human as an information processor, decisionmaker, and energy source for physical work.

These are just some of the concerns human factors specialists have regarding the human-hardware-environment system. Equally important to the understanding of human factors is understanding what human factors is not. Unfortunately, when asked what human factors is, many engineers, designers, and supervisors often tell what it is not.

Human factors is not just the application of checklists and guidelines. Although checklists can be helpful, they do not constitute a human factors evaluation. The problem with checklists is that they do not deal with interactions between items and the tradeoffs that must be made between competing criteria. Guidelines are just that, guidelines. Two people using the same guidelines can produce vastly different designs (*26*).

Human factors is not using yourself as the model for designing things. Just because it makes sense to you, or fits your capabilities, is absolutely no guarantee that it will make sense to, or fit, the people who will ultimately use it. There is considerable information available to assist in designing tools, procedures, equipment, etc., but one thing readily apparent is that nobody is typical. Constructing an ore chute so that you can safely walk under it does not mean it is at a safe height for other people. Instructions written to make sense to an engineer may totally confuse someone else.

Finally, human factors is not just common sense. Of course, human factors involves common sense, but it is more than that. Probably one reason why human factors seems like common sense is that human factors recommendations often make intuitive sense after they are explained. It is much like a mathematician's proof. Once it has been developed, it is obvious; but arriving at the proof was a highly creative endeavor. Sometimes human factors information even runs counter to what some would call common sense. For example, it is common sense that increasing the intensity of an alarm will make the person respond faster. This appears true for simple responses, but it is not necessarily true for complex responses. In fact, increasing intensity may even cause the person to respond more slowly (*29*). Would common sense have predicted that surface irregularities could be detected more accurately when a person wears a thin cloth glove than when the bare fingers are used alone? It does not seem like common sense, but it is true (*21*).

ROADBLOCKS TO THE APPLICATION OF HUMAN FACTORS

Although it may be intuitively obvious that human factors considerations in a system are central to maintaining production and efficiency, people have been somewhat slow in applying the principles to the design of workplaces and equipment. There are at least five common misconceptions that serve as roadblocks, and are often encountered when attempts are made to introduce human factors into an organization.

1. *All people are created equal.* In fact, no two people are exactly alike. Systems must be designed to accommodate the diversity in the population. When one size fits all, you can bet that the one size will fit all—poorly.

2. *People can be trained to overcome design deficiencies.* This is true to some extent, but training can be somewhat unreliable. Under stress, people will respond the way they think systems should work, which may not be how the systems actually work.

3. *Engineers and designers know how people think and act.* Engineers and designers may know how engineers and designers think and act, but engineers and designers do not necessarily think or act like everyone else.

4. *Minor human factors deficiencies are not important.* Minor deficiencies often compound into major deficiencies. Minor deficiencies also have a way of insiduously eating into productivity and efficiency. Minor human factors deficiencies are much like minor hydraulic leaks; neither one can be ignored for long.

5. *No serious incidents indicate no human factors problems.* The Three Mile Island Nuclear Powerplant had numerous human factors deficiencies in the control room, and until the day the plant came within 60 min of meltdown, it had no serious incidents.

HISTORY OF HUMAN FACTORS

To appreciate the current state of human factors, it is instructive to know a little history about the discipline. Some would say that human factors started when the first cavedweller fashioned a rock to skin an animal, and formed the rock to fit the hand comfortably. For all practical purposes, the discipline of human factors started during World War II.

1940-50—War Years

It became apparent during World War II that the new, sophisticated equipment was exceeding operators' capabilities. At one time during the war, more pilots were lost in training than were lost in combat. Experimental psychologists were asked to collaborate with engineers in designing various military hardware, including aircraft cockpits, radar consoles, combat information centers, and binoculars (*10*).

1950-60—Birth of a Profession

After the war, human engineering or engineering psychology laboratories (as they were called then) were established by the Navy and Air Force. Activity was maintained almost exclusively within the military-industrial complex. During this period, the Soviet Union launched Sputnik, and the race for space began. The industry that built planes and guns now turned to space, and with that came human factors. The Ergonomic Research Society of Great Britain was formed in 1950, and The Human Factors Society in the United States was established in 1957. In 1960, the membership of The Human Factors Society was 500.

1960-80—Recognition and Expansion

As an indication of expansion during this period, the membership of The Human Factors Society grew to over 3,000. Human factors expanded beyond the military-aerospace industry and entered civilian government and industrial organizations. It was during this period that the Bureau launched its human factors research efforts to improve safety in the mines. Human factors people were also employed by civilian industries to design and evaluate workplaces and consumer products.

1980—A Household Word

Advertisers have begun to use the terms "ergonomics" and "human-engineered" in advertisements for cars, lawnmowers, truck seats, computer terminals, and even dental chairs. The following is a partial list of companies employing human factors professionals (*20*):

Aluminum Company of America	Hughes Aircraft
AT&T	IBM Corp.
Boeing Corp.	International Harvester Co.
Clark Equipment Co.	Liberty Mutual Insurance Co.
Control Data Corp.	Lockheed Corp.
Deere & Co. Corp.	NCR Corp.
Eastman Kodak Corp.	Northrop Corp.
Federal Express Corp.	Pitney Bowes
FMC Corp.	RCA
Ford Motor Co.	Rockwell International
General Electric	3M Co.
General Motors Corp.	Westinghouse Corp.
Harris Corp.	Xerox Corp.
Hewlett Packard Corp.	
Honeywell, Inc.	

Other professional organizations, including The American Society of Mechanical Engineers, Institute of Electrical and Electronics Engineers, American Industrial Hygiene Association, and Society of Automotive Engineers have human factors or ergonomics subcommittees or technical groups. There are now about 60 graduate programs in human factors at universities in the United States (*27*).

This brief history points out the early thrusts and current expansion of the human factors profession. The following section provides a brief historical look at human factors in mining, with an emphasis on the research activities of the Bureau.

HISTORY OF HUMAN FACTORS IN MINING

Human factors concerns are often stimulated by the introduction of new technology into the workplace. In the mining industry, new technologies have had their greatest impact in the underground environment. On the other hand, surface mining innovations have typically been in terms of increased size and efficiency of earth- and ore-moving equipment, and for the most part, have not involved the introduction of revolutionary new technologies.

Underground mining, before mechanization, was backbreaking, dangerous work; picks and shovels were state-of-the-art. Miners could spend 3 to 6 h undercutting a coal face. As shown in figure 1-2, this was done lying on their sides and using picks to make a horizontal slit 3 to 4 ft deep at the bottom of the seam.

1870-1950—Early Mechnization

Mechanization of underground mining really began in the 1870's. At the beginning of the decade, steam locomotives were introduced underground. Early attempts were made to mechanize loading, but they did not attract much attention. In the latter part of the decade, cutting machines were introduced to undercut the coal face. Figure 1-3 depicts two miners operating an early Harrison Pick cutting machine. A little over a decade after cutting machines were introduced, the first electrically driven drill was used. These early machines were extremely noisy, vibrated so violently that they caused internal injuries, and liberated more dust and methane than could be handled by the ventilation systems. Technology moved slowly in the mining industry and by 1915, almost 40 yr after the introduction of cutting

Figure 1-2.—Undercutting a coal face before mechanization. (Courtesy of National Archives, Washington, DC)

Figure 1-3.—Early Harrison Pick cutting macnine. (Courtesy of National Archives, Washington, DC)

machines, only about one half of the Nation's coal output was mined by such machines (*6*). It was not until 1930 that the industry fully mechanized the undercutting operation. Mechanical loading of coal increased during the 1920's and 1930's (*28*), but it was not until 1943-44 that more coal was mechanically loaded than was loaded by hand (*24*). Although electric locomotives were generally accepted in the early 1900's, West Virginia still reported 1,600 animals used for haulage in 1938. A common sight was the horse-drawn mine car shown in figure 1-4.

During this early mechanization period, the Bureau was established (1910) as part of the Department of the Interior. It was initially set up as strictly an information-gathering agency. Not until 1941 was the Bureau given authority to enter and inspect underground coal mines.

1950-70—Modern Mechanization and the Coal Act

The next "revolution" in underground mining was the introduction of continuous mining machines. Actually, experimental models were being tested in several mines during the late 1940's. Initially, the industry was skeptical, but as larger and more powerful machines were developed, the skepticism slowly abated. The machines were widely adopted in the late 1950's and early 1960's. Early continuous mining machines were not much different in appearance from machines in use today.

During this period, there was virtually no human factors research being conducted in the United States, despite the growing recognition of human factors in the military and aerospace industries. In Europe, however, some human factors work was being done, but on a limited and fragmented scale. In 1969 the National Coal Board in England established the Institute of Occupational Medicine, which was chartered to conduct ergonomic research for underground coal mining.

In 1968, a mining disaster in Farmington, WV, killed 78 workers. One year later, the U.S. Congress passed the Federal Coal Mine Health and Safety Act of 1969. This act gave enforcement powers to the Bureau and significantly broadened its mandate regarding health and safety research in coal mining.

1970—Birth and Growth of Human Factors in Mining

After the passage of the 1969 coal act, the Bureau began sponsoring human factors research programs. The first formal human factors project was a problem identification study in underground coal completed in 1971 (*19*). That study proposed research dealing with equipment design, personal protective equipment, communications, illumination, noise, roof testing, and training. That was followed a year later by a review of the human performance literature (*11*) in which only 49 documents (mostly European) could be found that addressed mining-related tasks and contained quantitative results or factual support for conclusions.

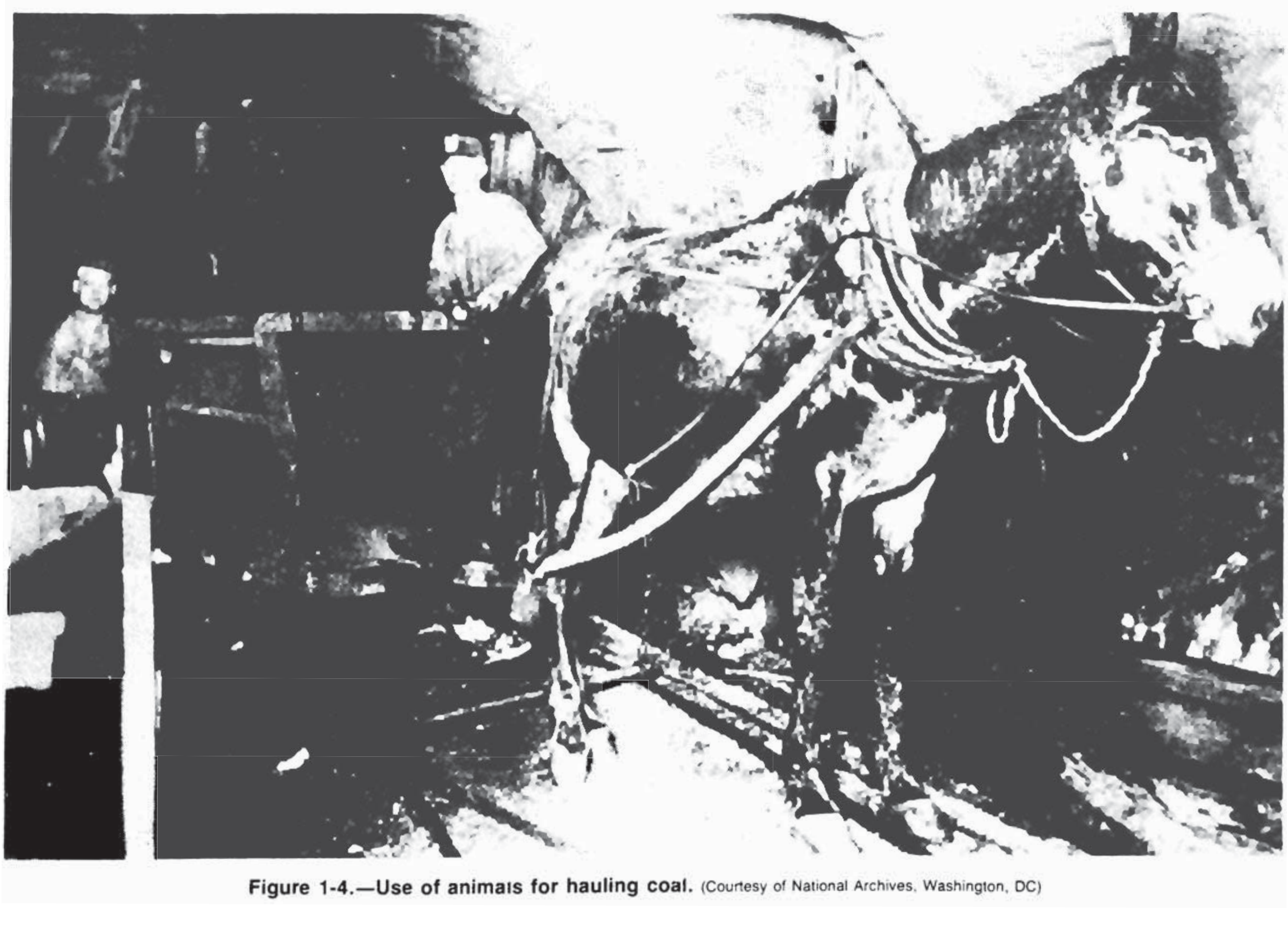


Figure 1-4.—Use of animals for hauling coal. (Courtesy of National Archives, Washington, DC)

In the next few years, the Bureau sponsored projects to address identified problems (*19*). One project investigated the standardization of controls for underground electric face equipment and focused on the development of design guidelines that would provide some degree of consistency in control configurations for this equipment (*15*). Another project involved machine canopies, in particular the fabrication and evaluation of overhead protective structures for underground equipment operators (*1-2, 8-9, 17-18*). A project that dealt with optimized operator compartments integrated and extended the results of earlier work by developing and validating design guidelines for underground mining-equipment operator compartments (*3, 12, 22*). The Inherently Safe Mining Systems project developed and demonstrated equipment modifications for improved safety in conventional and continuous coal mining systems (*13*).

During the early and mid-1970's, a series of disasters rocked the industry. In 1977 Congress passed another mine safety and health act that extended the 1969 act to metal and nonmetal mining, shifted enforcement to the Department of Labor (Mine Safety and Health Administration), and made provisions for mandatory training regulations. Much of the early human factors work in underground coal was applicable to underground metal and nonmetal mines because the same equipment was used. Nevertheless, differences did exist, and in the 1980's two human factors problem identification studies were launched for the underground metal-nonmetal industry (*16, 25*).

The majority of human factors research has been conducted for the underground environment, but surface mining has also attracted some of the attention of human factors researchers. One area that received early attention in surface mining was the problem of limited visibility (field of view) from large haulage trucks (*14, 23*). In 1982, two human factors problem-identification studies directed at surface mining were published. One dealt with the mining process itself (*4*), and the other with processing plants (*5*).

It is apparent from this brief historical review that human factors research in the mining industry has been a relatively recent development, spurred on by advances in technology and the recognized need to improve safety and productivity. As will be seen in subsequent chapters, there is a large body of human factors data, principles, and methods, developed outside the mining industry, that can be brought to bear on problems encountered within the industry today.

COVERAGE

The remaining chapters will review in more depth human factors concepts applicable to the mining industry and review much of the quickly expanding human factors in mining literature. Chapters 2, 3, and 4 present basic foundational information: the role of human factors in system design, including analytical tools used by human factors specialists; a review of human capabilities and limitations that form the basis for many design decisions; and the role of human error in accidents.

Chapters 5, 6, and 7 deal with design of equipment and tasks. Special emphasis is given to the design of work that involves physical labor because, despite the advances in mechanization, there still remain numerous tasks involving lifting, carrying, etc. Chapter 8 focuses on the environment and its impact on human performance. The four environmental stressors discussed are illumination, thermal conditions, noise, and vibration. The last two chapters deal with topics traditionally subsumed under industrial and organizational psychology, including training, motivation, and organizational development.

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CHAPTER 2.—HUMAN FACTORS IN THE DESIGN OF SYSTEMS

Effective system design should include system definition, task analysis, efficient interface design, and field testing.

As indicated in chapter 1, a central concept in human factors is the system. Although various authors use different definitions for the term, a very simple one is used here. A system is an entity that exists to carry out some purpose (*2*).[1] A system is composed of humans, machines, and other things that work together (i.e., interact) to accomplish some goal that these same components could not produce independently. Using systems concepts serves to structure the approach to the development, analysis, and evaluation of complex collections of humans and machines. According to Bailey (*2*)

> The concept of a system implies that we recognize a purpose; we carefully analyze the purpose; we understand what is required to achieve the purpose; we design the system's parts to accomplish the requirements; and we fashion a well-coordinated system that effectively meets our purpose.

This chapter first discusses the major characteristics of a system, using a haulage vehicle in an underground mine as the focus. The chapter then traces the development of a system and indicates the various human factors activities that could be applied to insure the resulting system meets its stated objectives.

CHARACTERISTICS OF SYSTEMS

In discussing the various characteristics of systems it will be helpful to have an example that illustrates the various concepts. In underground mining, both coal and noncoal, haulage vehicles are used to move the coal, or ore, from the working face to a more permanent continuous haulage system, usually a conveyor belt system or train. Examples of such haulage vehicles are front-end loaders, scoops, shuttle cars, and load-haul-dump (LHD) vehicles. These vehicles are run by batteries, diesel motors, or electricity supplied by cable. They are operated by a single operator, although the operator may have a helper to assist. In some cases the vehicle picks up the coal or ore itself, as in the case of a scoop or LHD; in other cases the vehicle is loaded by another machine, as in the case of shuttle cars. Given this basic concept of an underground haulage vehicle, the following is a discussion of the characteristics of systems.

Systems Have a Purpose

In Bailey's definition of a system (*2*), it was stressed that a system has a purpose. Every system must have a purpose, or it is nothing more than a collection of odds and ends that coexist. The purpose of a system is the system goal or objective, but systems can have more than one purpose. The goals of a system should be stated in general terms so that they need not be changed every time something in the system changes. Appropriate system goals for a haulage vehicle would include

- Haul ore (or coal) from the working face to the continuous haulage system.
- Load ore (or coal) from the floor.
- Protect the operator from roof falls.

[1] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

It is important that the goals or objectives of the system be clearly understood and agreed upon before designing, developing, or evaluating a system. For example, the common typewriter keyboard (QWERTY, so named for the first six keys of the first letter row) has been criticized as inefficient and slow. The most common letters are positioned for the left hand, and common letter combinations require awkward finger movements. Actually, when the goal of the system is understood, the keyboard organization has a purpose. When typewriters were first invented, fast typists could easily jam the keys. The keyboard, therefore, was actually designed to slow the typist down and to separate common letter combinations (e.g., QU) so that the key bars would not come from the same side of the machine and jam. As this example illustrates, failure to understand the goals of a system can lead to irrelevant evaluations. It must be pointed out, however, that one can challenge the adequacy and relevance of system goals. With the advent of element balls, daisy wheels, and word processor printers, there is no need to slow down typists because there are no keys to jam.

Systems Are Hierarchical

A system can be considered to be a part of a larger system and, when analyzed, the system itself can be composed of more molecular systems (also called subsystems). This is illustrated in figure 2-1, where a haulage vehicle system is shown as one subsystem in the larger mine haulage system, which in turn is one subsystem in the even larger mine system. A closer look at the haulage vehicle

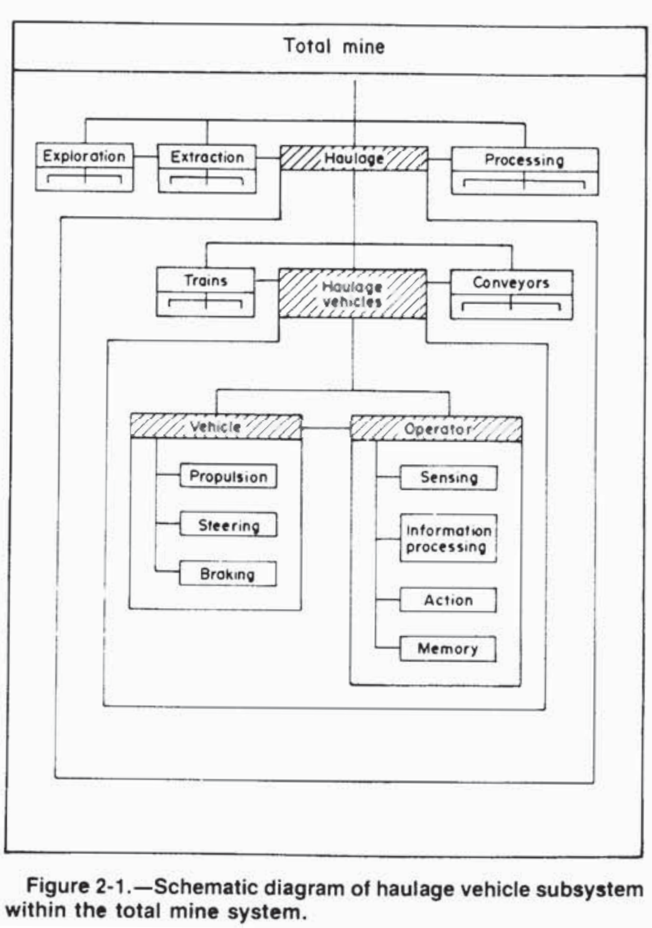

Figure 2-1.—Schematic diagram of haulage vehicle subsystem within the total mine system.

subsystem shows that it is composed of a vehicle subsystem and an operator subsystem. Each of these in turn is composed of more molecular systems, such as the propulsion system or the steering system. When faced with the task of describing or analyzing a system, one often asks: "Where do you start?" and "Where do you stop?" The answer to both these questions is: "It depends."

In describing and analyzing a system two decisions must be made. First, one has to decide on the *boundary of the system*; that is, what is to be considered part of the system under study, and what is to be considered outside the system? There is no right or wrong answer, but the choice must be logical and result in a system that performs an identifiable function. Thus, one could focus on the haulage vehicle as the system and consider conveyors and trains as outside the system. Alternatively, one could focus on the mine haulage system, with haulage vehicles as one subsystem or component of the larger system.

In some systems it appears that the designers drew the boundary of the system in such a way that the operator and maintainer of the equipment were considered outside the system. When this sort of design philosophy prevails, one finds systems that are difficult to operate, require excessive training, are prone to operator errors, and are difficult to maintain. As a general rule, one should always include operators and maintainers inside the system boundary to help insure that the system is designed to accommodate and facilitate human performance and safety.

The second decision that must be made is to set the *limit of resolution* for the system. That is, how far down into the system do you want to go? At the lowest level of analysis are components. A component in one analysis may be a *subsystem* in another analysis that uses a more detailed limit of resolution. Focusing on the haulage vehicle as a system, the analysis can be limited and the vehicle and operator can be considered the components. Alternatively, the analysis could be extended to consider the vehicle and operator as subsystems and things such as propulsion and steering as the components. As with setting system boundaries, there is no right or wrong limit of resolution. The proper limit depends on why one is describing or analyzing the situation in the first place.

Systems Operate in an Environment

The environment of a system, whether a closed- or open-loop system, is everything outside its boundary; therefore, the environment of a haulage vehicle system includes the roadways of the mine; other vehicles, objects, and people in the area; the conveyor system; the loading machine; etc. An open-loop system cannot sense its own actions and cannot alter its course of action. On the other hand, a closed-loop system can sense its own action and alter its course based on that information.

Humans are inherently closed-loop systems. To illustrate the difference, a haulage vehicle, without a driver, would be considered an open-loop system when the vehicle rolls down a slope. There is no mechanism to feed back information to the system regarding its position relative to obstacles in the environment or to take corrective action to avoid them. The same haulage vehicle, with a driver maneuvering down a roadway, is a closed-loop system. The operator functions in the feedback loop, sensing the position of the vehicle and the position of obstacles in the environment, and changing the course of the vehicle to avoid the obstacles.

Components Serve Functions

Every component (the lowest level of analysis) must serve at least one function in the system. Further, these functions must be related to the fulfillment of one or more of the system's goals or objectives. One of the tasks of human factors specialists is to aid in making decisions as to whether humans or machines (including computer software) should carry out a particular system function. For example, who or what should limit the speed of a haulage vehicle system? Should a speed governor be installed to automatically limit speed, or should that function be given to the driver? Who should be responsible for sensing the speed of the vehicle? Can a human estimate speed accurately enough, or should a speedometer be provided as a component in the system? By understanding the capabilities and limitations of humans, human factors specialists can provide valuable information to the decisions regarding allocation of function.

Humans serve various functions in systems (7). These functions involve

1. Sensing (seeing, hearing, feeling),
2. Storage (memory),
3. Information processing (thinking),
4. Decisionmaking, and
5. Action (movement, speaking).

Components Interact

To say that components interact simply means the components work together to achieve system goals. Each component has an effect, however small, on other components. One of the outcomes of a systems analysis is the description and understanding of these component and subsystem interactions.

Systems, Subsystems, and Components Have Inputs and Outputs

At all levels of a system there are inputs and outputs. The outputs of one subsystem or component are the inputs to another. It is through inputs and outputs that components and subsystems interact. Inputs can be physical entities (such as materials and products), electrical impulses, mechanical forces, or information. As illustrated in figure 2-2, a haulage vehicle outputs information on speed from its speedometer. That information becomes an input to the operator subsystem. The operator subsystem processes the information and outputs an action; e.g., stepping on the brake. That mechanical force then becomes an input to the braking subsystem of the vehicle.

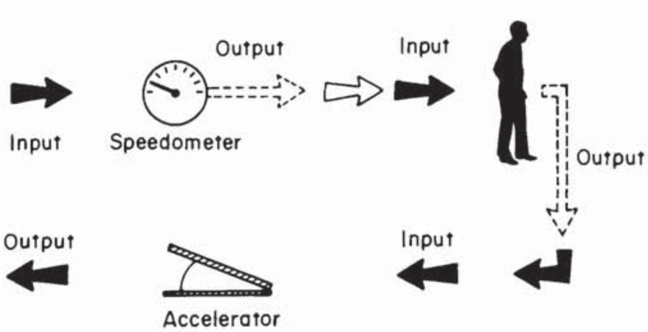

Figure 2-2.—Schematic diagram of inputs and outputs between subsystems of a system.

An analysis of a system must specify all the inputs and outputs required for each component and subsystem to perform its functions. Human factors specialists are especially qualified to determine the inputs and outputs that are necessary for the human component to successfully carry out its functions. Failure to supply adequate and proper inputs or the facilities necessary to produce outputs will result in degraded system performance. For example, how appropriate is an auditory warning of excessive speed in an underground mine? Which is more appropriate for inputting steering commands to the vehicle, a wheel or a joystick?

From this short overview, it can be seen that systems have a purpose and are made up of subsystems and components interacting through inputs and outputs to perform functions in support of system objectives. Systems operate within an environment, but the definition of what is part of the system and what is part of the environment is a somewhat arbitrary decision made to facilitate analysis and evaluation. With this in mind, a discussion of the system design process and the types of activities that human factors specialists conduct is presented.

HOW ENGINEERS REALLY DESIGN

Several earlier studies that addressed the question of how engineers design and how they make use of human factors information in the design process were analyzed (*8*). Forty-four mechanical and electrical engineers, each with approximately 15 yr of experience, served as subjects in the studies. Basically, a design problem was presented to the engineers, and information was provided them during the design process. The tasks, or design problems, included designing a command-control console, a circuitboard tester, an air traffic control radar-monitoring console, and test equipment to check an electronic subsystem. Each problem took several days to complete.

What this analysis (*8*) found was that "almost immediately after examining the problem, they (the engineers) started to design hardware without performing much deliberate, systematic analysis." Little or no consideration was given to how the equipment was to be used by the operator, the sequence of use, or which functions were most important or most frequently used. No attempts were made to allocate functions between people and hardware. In essence, the engineers appeared to skip over the first two stages of system development. The engineers relied overwhelmingly on design solutions that they had used before. This prevented them from considering novel approaches to the designs. Further, there was a reluctance to modify their initial designs, except in minor respects when new information was made available to them. For example, halfway through the process the engineers were told that instead of four people to operate the console, only two could be used. This resulted in only minor changes in the placement of displays and controls, but no overall revision of the basic design concept.

As far as the attitudes of the engineers toward human factors was concerned, the analysis (*8*) concluded that: "One of the most consistent findings of our research, confirmed in each study with all subjects regardless of sophistication, years of experience, or type of design problem, is that the typical design engineer does *not* consider human factors in his design." In questioning the engineers during the analysis, however, it was found that they had a strong, profound interest in human factors and a dedication to consider human factors in their designs. These verbal statements, however, were totally inconsistent with their actual behavior on the design problems.

Although this analysis was carried out over 15 yr ago, the situation, while improved, is still not much different today. Recently, one of the authors of this Information Circular was called upon to evaluate the human factors aspects of a large demineralizer panel. The engineers who laid out the displays on the console did not know what information the operator needed to run the panel, the operating sequence, how often various displays would be used, or the importance of various displays in operating the system. Despite this, they had no misgivings about placing the displays on the panel.

STAGES IN THE DESIGN OF SYSTEMS

Systems do not just spring into life; they go through a process of development. Sometimes the process is structured and the stages are easy to identify. More often, systems are developed in a more fluid, unstructured manner, where it is almost impossible to separate the various stages of their development. When a manufacturer develops a new bucketwheel excavator for a surface mine, it is likely that the stages of development are carefully planned and executed. When the superintendent of a surface mine puts together an all-purpose maintenance vehicle, the stages of development are passed through more informally. Although the same sorts of decisions and considerations may be involved, the process is not as systematic or exhaustive as it is portrayed in this chapter.

Six stages in the design of a system are listed by Bailey (2). These stages are depicted in figure 2-3. Dividing the design process into stages gives the impression of a simple linear process. In actual practice, however, the process is iterative; that is, it cycles over and over, becoming more detailed in each pass through the stages. Information developed in a later stage may influence decisions made in earlier stages, thus requiring a reappraisal. The concept of a surface mining all-purpose maintenance vehicle will be used to illustrate the various stages in the design of a system.

Stage 1: Determine Objectives and System Specifications

As already discussed, one cannot design a system without a clearly stated set of objectives. The objective of the maintenance vehicle is to carry the required tools, equipment, parts, and personnel to perform maintenance tasks on equipment in the field. Performance specifications state what the system must do to meet its objectives. These requirements are derived from a careful study of user needs. Typically, according to Bailey (2), the information is collected using interviews, questionnaires, site visits, and work studies. Usually, constraints are part of the system requirements. For example, a maintenance vehicle has to operate in mud, in high winds, and in temperatures below freezing. System designers must also deal with constraints related to the human component of the system. These relate to the skills, knowledges, and capabilities of the operators, and the number of people required to operate the system. For example, one constraint for the maintenance vehicle might be that it can carry at least two people.

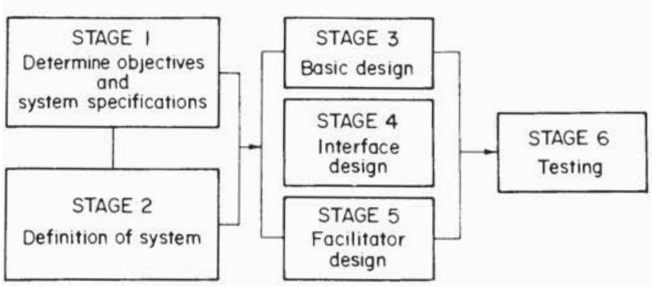

Figure 2-3.—Stages in the development of a system (based on stages suggested by Bailey (*2*)).

Stage 2: Define the System

The second stage involves listing the functions that the system must perform to achieve the objectives and system specifications defined in stage 1. Some functions of the maintenance vehicle system would include

Transporting people and equipment to the worksite,
Fixing hydraulic leaks,
Welding broken parts,
Lifting objects weighing up to 1 st, and
Communicating with the base maintenance shop.

During this stage, people-related information would also be collected. This would include information regarding the availability of people and the basic characteristics of the potential user population (operators and maintainers), such as size, education, skills, and abilities. In some cases the constraints of the system will be modified as information concerning the available labor pool is obtained. For example, it may not be feasible to use a highly technical system if the operators lack the required skills to understand it.

Stage 3: Basic Design

In this stage the functions identified in stage 2 are allocated to human or machine, and the resulting tasks of the human are analyzed. Central to this activity is the process of task analysis. Task analysis is the process by which the human's functions are broken down into required activities, and each activity is analyzed to determine human and system requirements needed to successfully carry out the particular activity.

Task analysis is probably the most important and fundamental process performed by human factors specialists. Its use transcends system design and becomes the basic tool for understanding the human component in any system. Task analysis is as much an art as it is a science. It involves a series of methodologies for collecting task data and various formats for presenting the information. It will not be possible to cover all the facts of task analysis in this report. The reader interested in more information can refer to reference 9.

Table 2-1 lists the various methods that can be used to collect task analysis information. Generally, more than one method is used to insure that complete and accurate information is obtained. One of the most comprehensive examples of task analysis for the mining industry was carried out by Crooks (3) in which virtually all underground metal-nonmetal unit operations were analyzed. Examples of unit operations included feedleg drilling, rock bolting, sand filling, slusher operation, track maintenance, timber construction, and ore skip operation. The task analysis team, with an "expert" (supervisor, safety engineer, etc.)

present, conducted onsite observations of workers performing the various unit operations. The team followed up the observations by conducting two-person, group interviews with experienced workers away from their jobs. A minimum of four workers were interviewed for each unit operation. After completion of the interviews, technical conferences with one or two supervisors were held to verify the completeness of the information collected. A total of 188 interviews were conducted to analyze 43 unit operations. Each of the unit operations (e.g., feedleg drilling) was broken down into tasks (e.g., prepares drill, drills, maintains drill), and each task was further analyzed into activities (e.g., collars hole, drills hole, removes bound steel).

Table 2-1.—Methods of collecting task analysis information

Observation	Observe worker performing job.
Interview:	
Observational	Observe and interview worker while performing job.
Individual	Interview worker away from jobsite.
Group	Interview more than one worker at same time, away from jobsite.
Technical conference	Interview subject matter experts or supervisors regarding job of worker.
Checklist	Worker checks tasks that are performed on the job from a master list.
Questionnaire	Open-ended questions that worker answers regarding work tasks.
Diary	Worker keeps a record of job activities throughout day.
Motion picture	Motion pictures are made of worker performing specific tasks.

The type of information collected in a task analysis depends on the purpose of the analysis. For example, task analysis information can be used for determining training requirements for a task, for assessing hazards and unsafe conditions or procedures involved in a task, for designing or modifying equipment or procedures, or for determining the type and level of people needed to operate and maintain a system. As another example, a task analysis approach to determine visibility requirements for operation of continuous miners, shuttle cars, and scoops in underground coal mines was used by Sanders and Kelley (*10*). It is also worthwhile by way of illustration to point out that the following task analysis data were collected by Crooks (*3*) for underground metal-nonmetal tasks:

Minimum and maximum times to complete.
Amount of training required.
Percentage of time standing.
Physical energy level required.
Degree to which 12 classes of physical activities (such as climbing, stooping, handling, talking) were present.
Degree to which six classes of visual requirements (such as near acuity, depth perception, color vision) were present.
Generic classes of hazards involved (such as electrical, hot-cold surfaces, sharp objects, explosives).
Common errors or accidents.
Principal visual features involved in performing the task.
Type of illumination usually present.
Worksites where the unit operation was performed.

This is a rather extensive list of information for a single task analysis. Several of the items in this tabulation were included because a primary purpose of the analysis was to establish illumination requirements for the unit operations.

The various formats used for presenting task analysis information depend, of course, on what information is collected and on the purpose of the analysis. Common formats include column format, operational sequence diagrams, and timelines.

With a column format, the steps or activities composing a task are listed down the page, and the information categories are listed across the top of the page. For each step or activity, the required information is filled in across the page. Figure 2-4 is an example of a column format.

Operational sequence diagrams depict the sequence of steps and the interrelationships among the components of a system in carrying out a particular task. Standard symbols are used to present the information. Figure 2-5 presents an example of an operational sequence diagram for handling an emergency in a steam generation plant (*6*).

Timelines depict the activities performed along a time scale. Where several persons, or persons and machines are interacting, a timeline presentation can graphically illustrate periods of overload and underload during the execution of a task. Figure 2-6 shows an example of a timeline generated by a computer program developed by the National Coal Board in England (*11*).

Direction	Operator Task	Helper Task	Comments	Controls	Displays or feedback
3 Position miner in entry	Maneuver machine to line up overhead paint markings with a known point on either side of the cutting head that will yield the planned entry width while keeping machine clear of ribs and roof	Lift and pull cable into place along the right rib so that it is out of the way of the crawler tracks as the miner is trammed forward and back.	Foreman painted centerline on ceiling. Bolt crew hung a reflector on the last row of bolts to show boundary of safe roof.	Tram levers. Conveyor boom elevation lever. Conveyor boom swing lever.	View of roof and painted centerline. View of reflector on last row of bolts.
	Tram to face while raising or lowering cutting head to starting elevation and while lowering the gathering head		Different operators take different approaches to starting point for cutting operation (top, middle, or bottom). Some would bump into the middle of the face and then tram back a few inches and start head rotation	Tram levers. Cutting head elevation lever. Gathering head elevation lever.	View of cutting head position. View of gathering head position. View of face relative to machine. Sound of cutting head bumping into face. View of ceiling paint marks relative to cutting head. View of machine relative to ribs. View of helper and cable.

Figure 2-4.—Example of a column format used in task analysis.

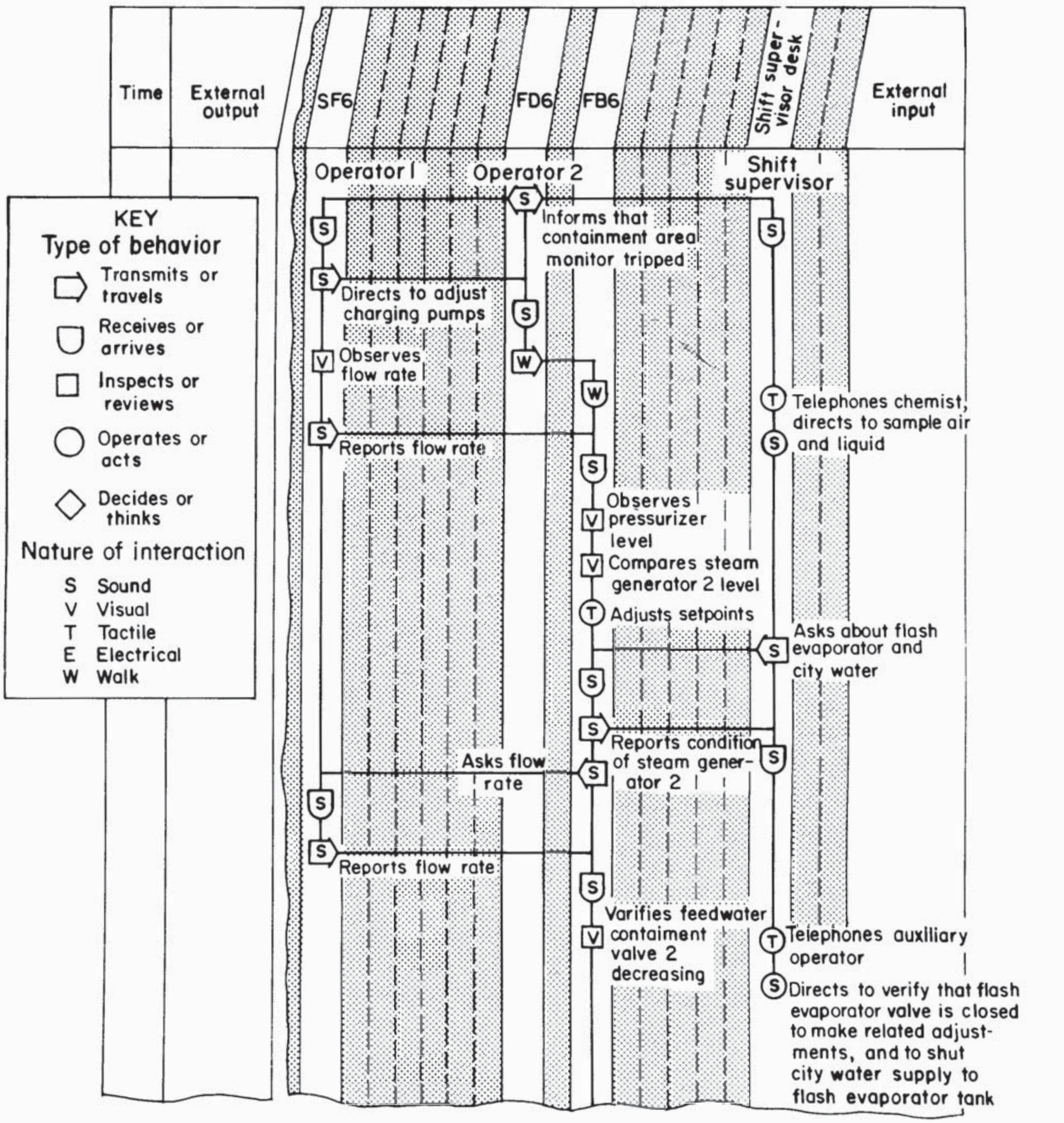

Figure 2-5.—Example of an operational sequence diagram (OSD) used in task analysis (*6*). (Copyright 1984, Electric Power Research Institute, Report NP-3659, "Human Factors Guide For Nuclear Power Plant Control Room Development." Reprinted with permission.)

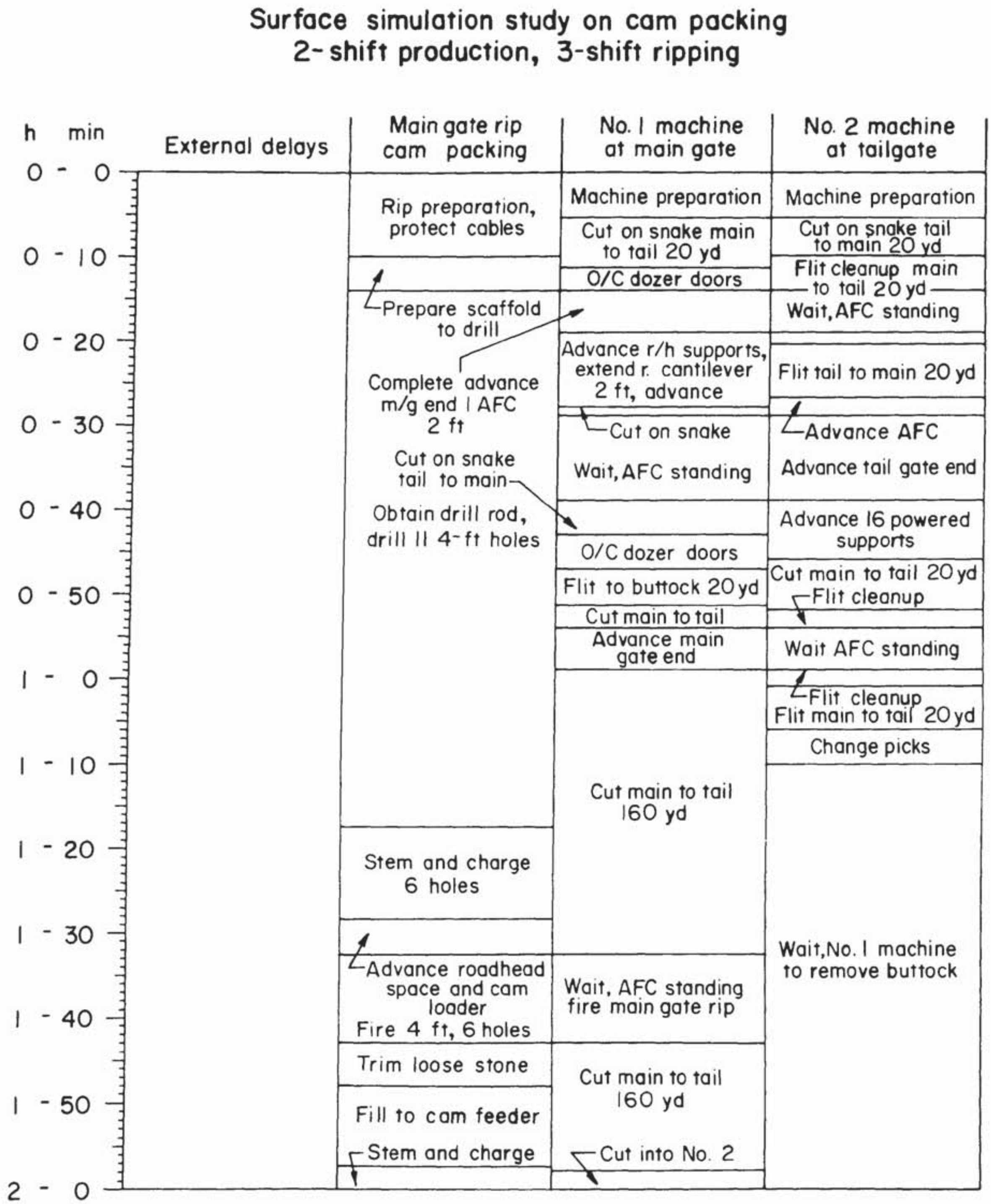

Figure 2-6.—Example of a timeline used in task analysis (*11*). (Courtesy of Butterworth Scientific Ltd.)

The information obtained from the task analysis phase of system design represents the primary source of data for the remaining stages of the design process. Again, it should be pointed out that the design process and task analysis are iterative in nature. As more and more details are defined in the system, more and more details can be added to the task analysis. This serves to verify system design decisions and to point the way toward further refinements in the system.

Stage 4: Interface Design

Based on the information collected and decisions made in stage 3, the designer moves to a more molecular level and begins designing the human-equipment and human-environment interfaces. These include the layout of workspaces, controls, displays, human-computer dialogues, forms, etc. This is the phase of design where decisions such as the following are made: What type of display should be used? How many scale markers need there be? What type of control should be used? How much resistance should be included in the control? How close together should the switches be placed?

One human factors technique often used to develop optimized panels, workstations, and work areas is link analysis. The purpose of link analysis is to graphically depict the frequency and/or criticality associated with each of the various interactions occurring between the operator and equipment and/or between one operator and another (*5*). The links that are analyzed could be eye movements between displays on a console, or between objects in the environment. Hand movements between controls are often analyzed as well. The objective is to modify the arrangement of the components to shorten the distance between components connected by frequently employed links.

Figure 2-7 shows the controls on an underground roof bolting machine and the results of a link analysis carried out on the bolting operation (*4*). The thickness of the lines connecting the controls indicates the relative frequency of hand movements between the respective controls. One aspect that stands out is the long, relatively frequent link between the boom swing and the head sump controls.

Another tool used by human factors specialists to aid in interface design is the mockup. Mockups are usually, but need not always be, full-scale models of the equipment or facility. They are usually made of inexpensive materials, such as foam-core cardboard or plywood. The components are represented by actual items of hardware or by drawings and photographs of the items. Typically, various sized operators pretend to operate the equipment under the watchful eye of the human factors specialist. The specialist observes behavior, questions the operators, and makes measurements to determine things such as whether there is enough room for the operator to work, whether the operator can reach all the controls and see all the displays, how much of the enviroment around the equipment the operator can see, whether there are safety hazards or bumping and snagging hazards, whether there will be problems getting into or out of the equipment, and whether the equipment is laid out in an optimum manner to facilitate human performance.

Short of constructing full-scale mockups, evaluations can be made of the engineering drawings of the equipment and workstations by laying two-dimensional, articulated plastic manikins over the drawings. These manikins can be manipulated through typical operator movement patterns. The manikins come in various sizes that represent various scale models (e.g., one-tenth or one-quarter) of large and small people. Figure 2-8, for example, shows an inexpensive front-, side-, and top-view manikin (*12*). A study was

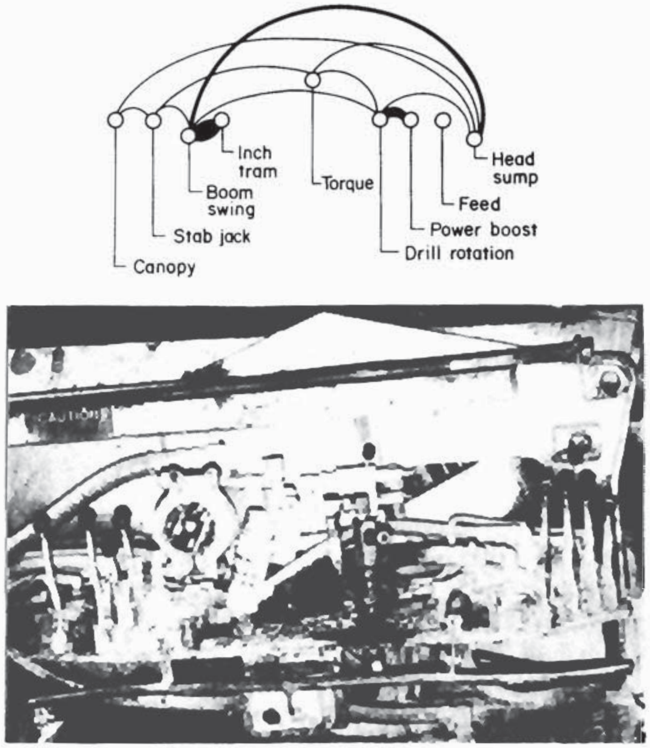

Figure 2-7.—Graphic illustration of the results of a link analysis of a roof bolting operation (*4*).

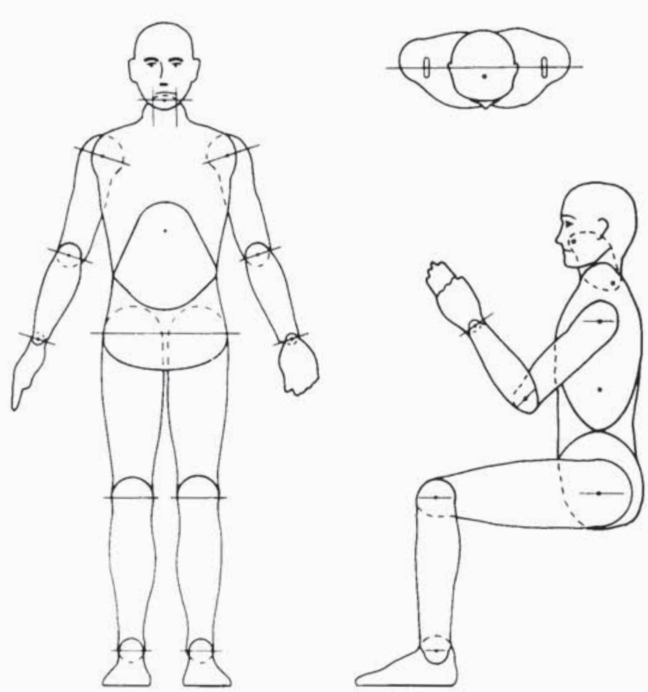

Figure 2-8.—Example of an articulated plastic manikin for evaluation of engineering drawings (*12*). (Courtesy of S.P. Rogers Corp.)

made of the body dimensions of low-seam underground coal miners, from which plans were presented for constructing two-dimensional manikins representing small (5th percentile), average (50th percentile), and large (95th percentile) male and female miners (*1*). Such manikins can be used to uncover design deficiencies early in the interface design stage. They should not, however, be considered a substitute for a full-scale mockup evaluation.

With the growing use of computers to aid the design process, it is not surprising that several systems would be developed to assist in the design of workstation layouts. Most of these were developed within a military context. However, one system, the crewstation assessment of reach program developed for the Naval Air Development Center, is being modified by the Bureau for use in evaluating the design of underground mining equipment. The Bureau's crewstation analysis program (CAP) is intended for use by original equipment manufacturers and mining companies for the initial design work on new machines, and to evaluate existing machines.

By using CAP, a designer can define the workstation (controls, seat, eye position, line of sight, and head clearance point) in three-dimensional space, and provide dimensions of a sample population or an individual. CAP then proceeds to evaluate the workstation with respect to the accommodation of the computer-generated test subjects.

Most of the analysis sections of CAP require a sample population for testing. CAP allows the user to input either the actual external anthropometric measurements for one or more individuals directly, or to generate a sample population from the means, standard deviations, and correlations of a set of anthropometric measurements using statistical methods. The external measurements (fig. 2-9) for the sample are transformed into internal link lengths and link circumferences, and are used to create either a link-person or a three-dimensional manikin as shown in figure 2-9.

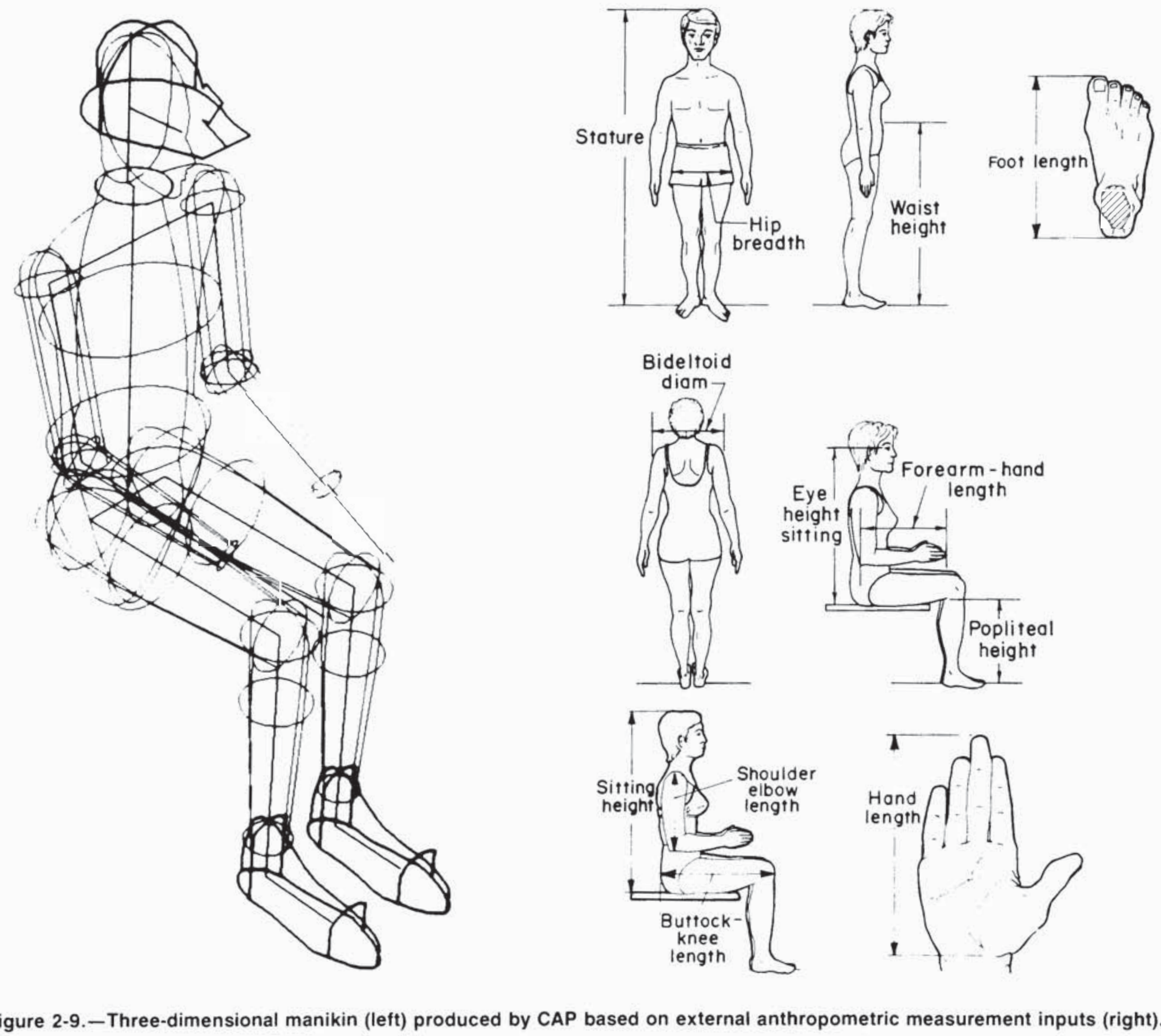

Figure 2-9.—Three-dimensional manikin (left) produced by CAP based on external anthropometric measurement inputs (right).

It is hoped that CAP and similar systems will expedite the incorporation of human factors considerations in the design of mining equipment. The use of such systems allows designers to quickly and inexpensively experiment with alternative design concepts, refining them and testing their adequacy for accommodating the user population.

Stage 5: Facilitator Design

During this stage, the designer plans for a set of materials that will encourage acceptable human performance (*2*). For example, preliminary selection requirements are developed to help insure that people with the proper skills and abilities are chosen to operate and maintain the system. The designer also identifies where instructions, performance aids, and training will be needed and best used. (Chapter 9 deals with the development and evaluation of training in the mining environment.)

Stage 6: Testing

The last stage of the design process is testing. The development of a system cannot be considered complete unless the system is tested and evaluated to insure that it meets the objectives set forth in stage 1 and does not produce any unintended negative effects. Actually, testing should be conducted throughout the development of the interface and facilitator design stages. To wait until a system is complete, before testing it, could result in an enormous waste of resources. The earlier in the process problems are discovered, the less costly it is to correct them.

Initially, testing is usually carried out in a laboratory setting. These tests are primarily concerned with assessing whether the system performs as the engineers expected. Human factors specialists would assess the human performance aspects of the tests and look for potential problems in interface design. Ultimately, the system would be field tested in real-world environments using actual operators and maintainers. Human factors specialists would observe the operation and maintenance of the system, develop objective data collection forms and surveys, and interview the users to assess human factors problems with the design of the system.

Design and preparation for a field evaluation takes time and thought. Simply putting a new system or piece of equipment in a mine and returning in 6 months for opinions is a sure way to kill the best of systems. The test participants must be trained and briefed on the operation of the equipment and the purpose of the evaluation. Their cooperation must be solicited, and they must be made to feel a part of the team. Not only should their opinions of the system be collected, but also they must be given the opportunity to suggest ways of improving the system. Further, the system development team must be receptive to the suggestions made. If the system is so far along that no real changes can be made, regardless of the outcome of the field test, then one should seriously question the utility of the test and perhaps even the system itself. The testing stage of system development is of prime importance to the design process and not an afterthought performed merely to confirm the obvious.

DISCUSSION

As pointed out at the beginning of the discussion of the system design process, most things designed and developed by mining companies do not go through the various stages of design in a rigorous way; and for simple things, it is probably not necessary. Nevertheless, the processes of defining what a system is to do, analyzing the tasks humans will do, designing the interfaces to facilitate human performance and safety, and field testing the system should be part of any design effort, no matter how small or simple it appears to be. The difference between designing a simple system and a complex system should be in the degree of formality and documentation required. The basic steps and considerations outlined in this chapter should be incorporated to the degree commensurate with the criticality and complexity of the system being designed.

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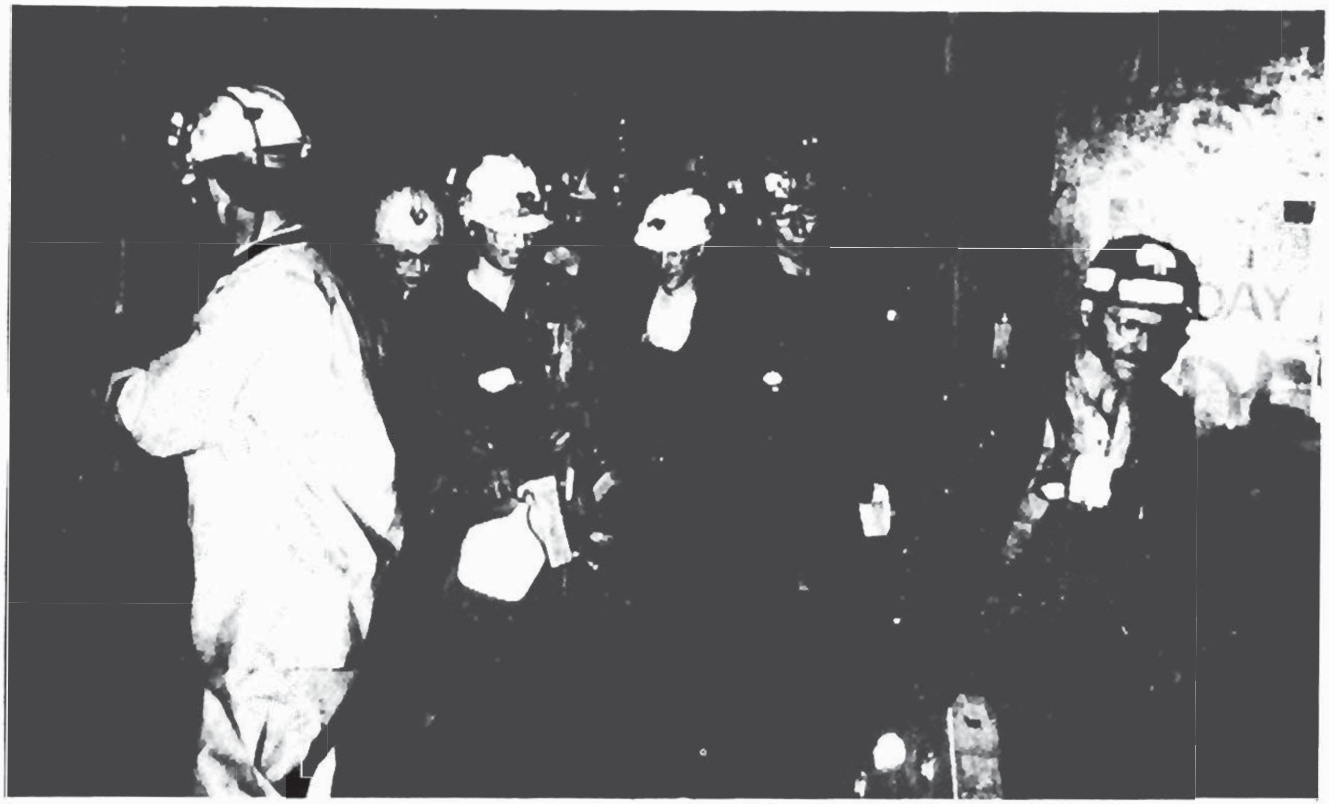
CHAPTER 3.—HUMAN CAPABILITIES AND LIMITATIONS



People are not infinitely adaptable; they have limitations. Recognition of these limitations is a step toward designing for increased safety and productivity.

In chapter 2 the human-hardware environmental system was presented. The human as a system component was described as receiving information, processing it, and taking actions based on it. These three functions will serve as the basis for organizing the diverse information in this chapter. In addition to the information reception-processing-action aspects of humans, their anatomical and biological characteristics also impose limitations and provide capabilities that affect system effectiveness. The last section of this chapter will address these topics.

WHO ARE MINERS

There has not been much literature describing the characteristics of today's miners. What data exist, however, point toward several consistent trends that are changing, and will continue to change, the composition of the mining workforce. The first trend is that miners are getting younger. For example, the National Research Council of the National Academy of Sciences (*23*)[1] reports that among underground coal miners, those under 30 yr of age increased from 20% of the workforce in 1971 to 41% by 1979. This trend is seen also in the superintendent and supervisor ranks where average ages are dropping.

The second trend, associated with the first, is that newly hired miners have less mining experience than miners in the past. Companies do not have the substantial pools of experienced miners from which to select, as they did in prior years.

Today's young miners are also better educated than miners in the past. The President's Commission on Coal (*24*) estimated that three-fourths of entering miners have at least a high school education, with many (one-third or more) having some education beyond high school.

The proportion of female miners is also increasing. Reflecting the changing social climate, women are being hired to perform what in the past had been traditionally male-dominated jobs. It is estimated that women will compose 10% or more of the mining work force in the near future.

These trends toward younger, more educated workers, and increasing numbers of women in the workforce have implications for training and equipment design that cannot be ignored.

[1] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

HUMAN AS AN INFORMATION RECEIVER

People receive information about their environment through their senses of sight, sound, smell, touch, and taste. People, however, have certain built-in limitations and characteristics that affect the range and amount of information they can receive. Only the first three senses are discussed in this section.

Sight

A simple diagram of the eye is shown in figure 3-1. Light enters the eye through the transparent cornea and passes through a clear fluid called aqueous humor. The light then passes through the pupil, a circular aperture whose size is changed by muscles attached to the iris. The iris is the part of the eye that gives it its characteristic color (blue, brown, etc.). The pupil is the black spot (actually a hole) in the center of the eye. The iris regulates the amount of light entering the pupil by enlarging (dilating) the pupil or by constricting it. Light rays passing through the pupil are refracted (bent) by the lens. The light is bent so that the light rays are brought to focus on the back inside surface of the eyeball called the retina.

Accommodation

The lens is adjustable in thickness to permit objects located at different distances to be focused on the retina. This focusing is done automatically by small ciliary muscles attached to the lens. When focusing on objects close to the eye, the muscles contract and cause the lens to increase in thickness. When viewing objects far away, the muscles relax and the lens becomes thinner. This process of changing focus is called accommodation.

Everyone has an accommodation range; that is, the eye can focus objects within a given range of distances. Objects too close to, or too far away from, the eyes cannot be brought into sharp focus. The shortest distance at which an object can be brought into sharp focus is called the near point, and the longest distance is called the far point. Age has a profound effect on the power of accommodation because the lens gradually loses its elasticity; therefore, the near point gradually recedes, while the far point remains more or less the same. (This is why older people who become farsighted hold newspapers at arms' length to read them.) The average near point, in inches, for various ages, as given by Grandjean (*9*), is as follows:

16 yr..3.2, 32 yr..4.9, 44 yr..9.8, 50 yr..19.7, 60 yr..39.4.

The level of illumination is a critical factor in accommodation. When lighting is poor, the far point moves nearer and the near point recedes, giving a smaller range of accommodation. Both speed and precision of accommodation are reduced. Contrast is also important: the more an object stands out against its background, the quicker and more precise the accommodation. This is why signs, to be readable at long distances, should be well lit, clean, and have high-contrast lettering.

The retina is the heart of the visual process. It is composed of two types of light-sensitive receptors called cones and rods. There are 6 to 7 million cones concentrated in an area called the fovea, which is located around the optical axis. This is the area of maximum visual resolution. Cones require relatively high levels of illumination to become effective, and therefore are used primarily for daylight vision.

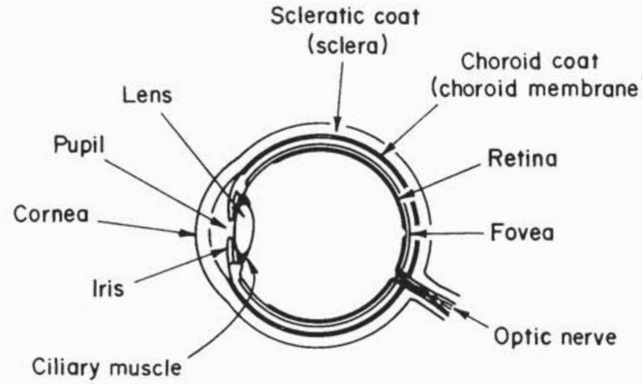


Figure 3-1.—Diagram of the eye. (Adapted from reference 9, courtesy of Taylor and Francis Ltd.)

In addition, cones are sensitive to differences in color and give rise to color vision.

Outside of the foveal area, the concentration of cones drops off markedly, while the concentration of rods increases dramatically. Although rods are more sensitive to light than are cones, they do not detect fine differences in shape or color. They become the dominant sense receptor in poor illumination.

Adaptation

As illumination levels change, the rods and cones must adapt to these changing light levels. This process is called adaptation. With decreasing levels of illumination, sensitivity to light increases. Adaptation to darkness (dark adaptation) takes a comparatively long time. Going from bright daylight into a dark room results in partial adaptation within 5 to 10 min, with full adaptation taking 30 to 60 min. Hence, sufficient time must be given to acquire good night vision.

Light adaptation is much faster than dark adaptation. Initial reductions of 80% in retinal sensitivity occur in 0.05 s, with full adaptation occurring in 1 or 2 min. The implication of this is that, if there is a bright light in an otherwise dark environment, the eye will tend to adapt to that bright light and hence lose sensitivity for viewing the darker surroundings.

There is another phenomenon (Purkinje shift) related to color perception that occurs as levels of illumination change. At high levels of illumination, the eye is most sensitive to green and yellow-green colors. As illumination levels decrease, however, the eye becomes most sensitive to blue-green colors. This is the reason that fire trucks in many communities are painted a greenish shade rather than red.

Field of Vision

The field of vision is that part of one's surroundings that can be seen when both the eyes and the head are held still. Figure 3-2 shows the field of vision and also indicates the effect of moving only the eyes, only the head, or both (*12*). This figure uses the concept of visual angle, which is illustrated in figure 3-3. Figure 3-3 also presents a formula for computing visual angles of objects at various distances. The further away an object is located, the larger it must be to maintain a constant visual angle. Consideration of the field of vision is important in designing equipment to help insure that needed information and displays can be seen without excessive head movements.

With the eyes and head stationary, the area of distinct vision is only about 1′ of visual angle, corresponding to the foveal region on the retina. Outside this area (middle and outer fields of vision), objects become progressively blurred and indistinct. In the middle field, movement and changing contrasts or levels of illumination are noticed. Objects in the outer field must flicker or move to be noticed.

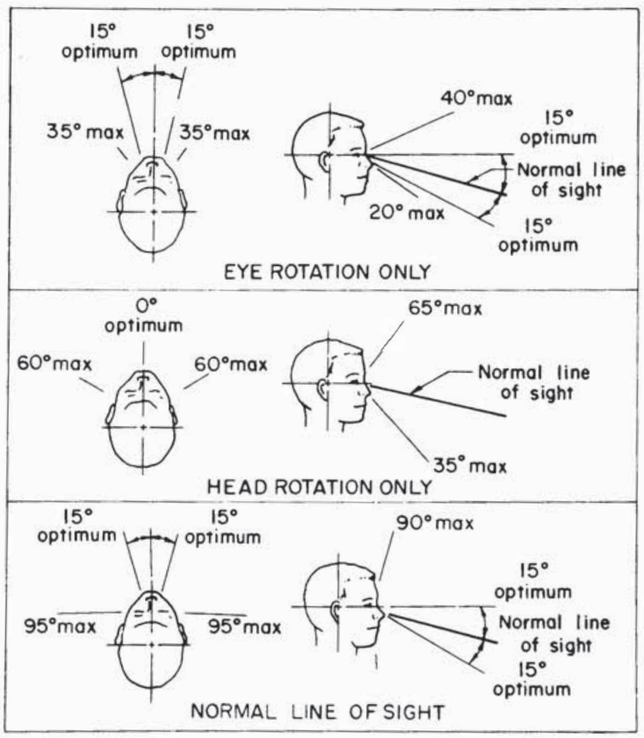
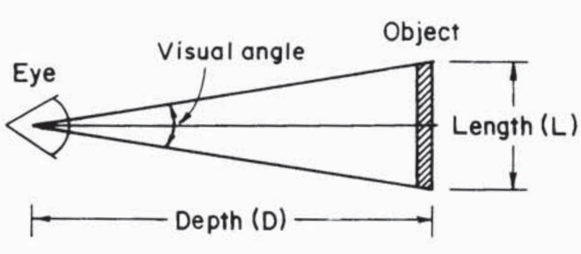


Figure 3-2.—Field of vision and effect of eye and head rotation. (Adapted from reference 9, courtesy of Taylor and Francis Ltd.)



To compute angles up to 10° (600′):

$$\text{Visual angle} = \frac{(3{,}438)\cdot(L)}{D}$$

(L and D must be measured in the same units, i.e., inches, centimeters, etc.)

Figure 3-3.—Illustration of the concept of visual angle.

Visual Acuity

Visual acuity is the ability to see fine detail clearly. Actually, there are several types of visual acuity. Minimum separable acuity refers to the smallest space between parts of a target that the eye can detect. This acuity is measured using the standard eye charts consisting of different letters, or "E's" facing different directions. Vernier acuity refers to the ability to distinguish the lateral displacement (or offset) of one line from another such that if the displacement did not exist, the two lines would form one continuous line. Minimum perceptible acuity is the ability to detect a spot or dot. Stereoscopic acuity refers to the ability to differentiate two objects as being different distances from the eyes.

In all types of visual acuity, the more peripheral a target is in the visual field, the poorer the acuity. The greater the illumination and contrast of a target, the greater will be the acuity. As a point of reference, under good illumination and contrast, the normal minimum separable acuity is about 1′ of visual angle (this corresponds to 20/20 vision).

Detection of Movement

Movement is perceived in two ways. First, a moving object is kept in view by moving the eyes, and the person receives information regarding the object's motion from the eye movements. In the second case the eyes are stationary, and the object's image moves across the retina. Under this condition, the minimum velocity (movement threshold) that can normally be detected is about 1′ to 2′ of arc per second. The movement threshold can be reduced by an order of 10 if another stationary object is also present in the visual field. This has implications in underground and surface mines where stationary objects may not be visible at night.

The effect of adding general background illumination, in addition to caplamp illumination, on the detection of moving objects in the peripheral visual field was reported by Martin and Graveling (*17*). For each condition, the mean peripheral detection angle was computed. The results indicated an improvement in detection angle by adding only 5 lx of background luminance. Figure 3-4 summarizes the

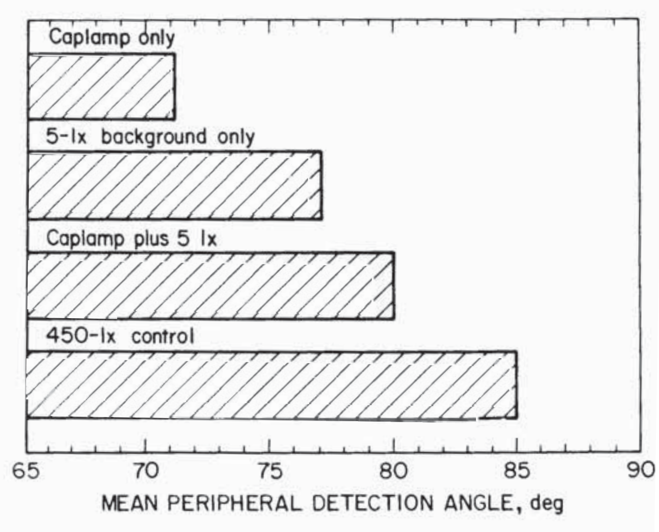


Figure 3-4.—Effect of caplamp and background illumination on detection of moving objects in the periphery of the visual field. (Adapted from reference 17, courtesy of Butterworth Scientific Ltd.)

results. The 9° increase in detection angle, achieved by adding background illumination to caplamp illumination, translates into an increase in the visual field of approximately 5 ft at a distance of 50 ft.

Hearing

Sound originates from vibrations of some source. The vibration causes air molecules to move back and forth, creating corresponding increases and decreases in air pressure. The sound "waves," much like the ripples caused by dropping a rock in a still pond, are sensed by the hearing mechanism of the ear.

Figure 3-5 shows a diagram of the ear divided into three anatomical divisions: outer ear, middle ear, and inner ear. The outer ear consists of the pinna, which collects sound energy and passes it through the auditory canal to the tympanic membrane (eardrum). The sound waves cause the eardrum to vibrate. This vibration is transmitted through the middle ear by three, very small, interconnected bones or ossicles (malleus, incus, and stapes). The stapes is attached to the oval window of the cochlea. The cochlea, located in the inner ear, is the organ that transforms the sound vibration into electrical impulses that are transmitted to the brain for interpretation.

One point worth mentioning is that the air pressure acting on the outer ear and middle ear sides of the eardrum should be equal. To achieve this, there is a tube (the eustachian tube) that connects the middle ear to the back of the throat. When a person changes elevation rapidly, as would be the case when descending or ascending a mine shaft, the eustachian tube may close, and pressure may build up on one side of the eardrum. This differential pressure causes the eardrum to stretch and can be quite painful. In addition, the stretched eardrum cannot vibrate freely, and the affected person loses some of his or her sensitivity to sound. This loss of hearing can be dangerous if the person depends on sounds to alert him or her of danger. The eustachian tube can usually be opened by chewing, swallowing, or yawning.

Figure 3-6 illustrates the cochlea as it would appear if one looked into it from the middle ear. The cochlea is filled with fluid, and when the stapes of the middle ear vibrate the oval window, a wave pattern is set up in the fluid. The movements of the fluid force the basilar membrane to vibrate, which in turn forces the small hair cells on the organ of Corti to brush against the tectorial membrane. This stimulates the hair cells, and electrical impulses are sent to the brain. If a person is repeatedly exposed to loud noises, the hair cells can be permanently damaged by hitting against the tectorial membrane. The actual process of how complex sounds are encoded in the cochlea and later interpreted by the brain is still largely a mystery. Several theories are postulated, but none fully explains the complex processes involved.

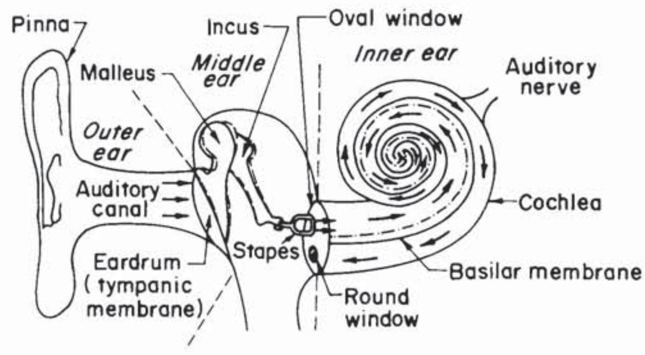


Figure 3-5.—Illustration of principal structures of the ear.
(Adapted from reference 18, courtesy of McGraw-Hill)

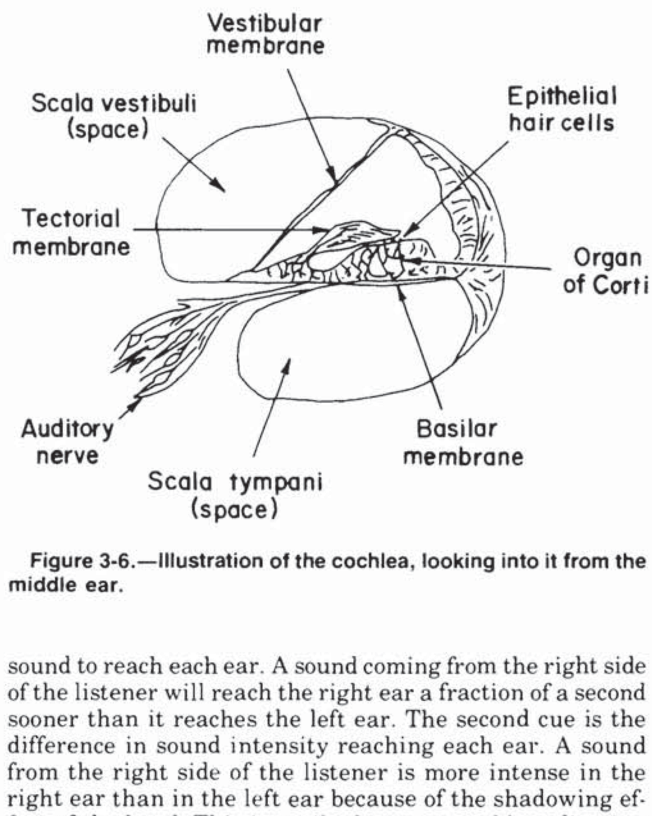


Figure 3-6.—Illustration of the cochlea, looking into it from the middle ear.

Sound Localization

The position of our ears enables us to tell what direction a sound is coming from. This sort of information is extremely beneficial in the work environment. Knowing what direction a moving vehicle is coming from, or where the creaks and groans of the "working" roof are emanating from, can mean the difference between life and death.

The ear uses two cues to determine the location of a sound. The first cue is the difference in time it takes the sound to reach each ear. A sound coming from the right side of the listener will reach the right ear a fraction of a second sooner than it reaches the left ear. The second cue is the difference in sound intensity reaching each ear. A sound from the right side of the listener is more intense in the right ear than in the left ear because of the shadowing effect of the head. This is easily demonstrated by adjusting the relative loudness of two speakers in a stereophonic system. For example, increasing the loudness of the right speaker makes the sound appear to move across the room to the right.

Accurate localization, however, occurs only when the sound source is situated to the right or to the left of the listener. If the head is fixed, front-back and up-down discrimination is poor. It is very important, therefore, that the head be free to move, allowing the person to place the sound source along a left-right line relative to the ears.

There are several design features that can alter the ability to accurately locate sounds. If the sound is blocked to one ear, localization is poor. For example, if a driver keeps the left window of a vehicle cab down and the right window up, sounds will appear louder in the left ear even if they are coming from the right side of the vehicle. (This same phenomenon occurs with operator cabs that are open on only one side.) Sound bounces off surfaces, making it extremely difficult to localize the actual source. This kind of problem is especially acute in underground mines. Finally, if a person has a differential hearing loss in one ear relative to the other, his or her ability to localize sounds will be impaired.

Tone and Loudness Discrimination

In the work environment, it is necessary to discriminate between sounds in terms of tone (actually frequency) and/or loudness (intensity). The loudness and tone of roof "talk" can serve as an alert to an impending roof fall. Motor noises, if correctly identified, can indicate mechanical problems. Two types of discrimination can be defined. The first type is a relative judgment in which there is an opportunity to compare two or more stimuli to determine which is louder, higher pitched, or simply whether they differ. The second type is an absolute judgment in which no opportunity exists for comparison. In essence, one must compare the sound to a sound one remembers hearing. In most work situations, discriminations are absolute judgments. Unfortunately, the ability of people to make absolute discriminations between individual stimuli is not very great. In this connection, reference 21 referred to "the magical number seven, plus or minus two" (i.e., five to nine) as the number of absolute discriminations people can make along a single dimension. Thus, one would expect that people can discriminate five or six sounds of different loudness or different tone. If different dimensions are combined (e.g., loud and soft intensity with high and low frequency), the number of absolute judgments can be increased tenfold or more.

Masking

The major limitation of the ear is its relative inability to detect a signal in a noisy environment. When this occurs, the signal is said to be masked by the noise. Masking will be further discussed in chapter 8.

Effect of Age on Hearing

As one advances in age, hearing sensitivity declines. The effect is greater for higher frequencies than for lower frequencies. Figure 3-7 shows the deterioration in hearing threshold with age for 1,320 underground coal miners (*11*). As can be seen, the major loss of sensitivity occurs with frequencies above 3 kHz (3,000 Hz). It is at frequencies above 3,000 Hz that important speech sounds are contained. Thus, with advancing age, speech comprehension declines. The presence of masking noise makes the situation even worse for older individuals. It should be pointed out that the hearing loss pattern observed in the miner population shows little difference from that of nonminer populations (*11*).

Smell

The sense of smell is relied on to provide information about hazardous things in the work environment such as spilled or leaking chemicals, dangerous fumes, or the presence of fire. The sense organ for smell is a small 2- to 3-in² patch of cells located in the upper part of each nostril. A sense of smell is not very good when it comes to making absolute identifications of specific odors. Untrained observers can identify approximately 15 to 32 common odors (e.g., coffee, paint, banana, etc.). With respect to identifying odors in terms of intensity only, about four different levels can be identified. Another limitation of the sense of smell is that a person adapts to an odor rather rapidly and soon becomes unaware of its presence.

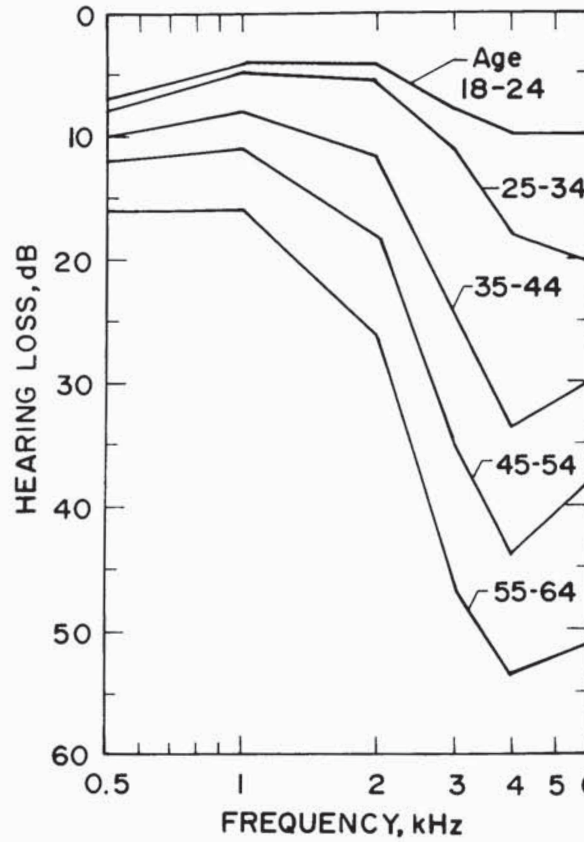


Figure 3-7.—Changes in hearing sensitivity with age for 1,320 underground coal miners. (Adapted from reference 11, courtesy of National Institute for Occupational Safety and Health)

Many U.S. metal mines use a stench system to alert miners of an emergency; a foul-smelling substance is released into the ventilation system. As will be discussed in chapter 5, the selection and design of such systems are influenced by the limitations of the olfactory sense.

HUMAN AS INFORMATION PROCESSOR

In order to process information, three functions must be present: (1) memory, the ability to store information; (2) decisionmaking, the ability to evaluate alternatives and select a course of action; and (3) attention, the ability to attend to environmental features and numerous sources of information.

Memory

Human memory can be conceptualized as consisting of two components, a working memory and a long-term memory.

Working memory receives inputs from sensory channels (eyes, ears, etc.) and stores a coded representation of that information. A characteristic of working memory is that in the absence of attention, information will degrade, and any operations performed with this information will deteriorate.

The fragile nature of working memory can be easily demonstrated. Ask someone to remember three random letters (e.g., ZBL) while counting backwards by threes from a given number (e.g., 834). After about 20 s of counting backwards, ask the person to recall the letters. It is doubtful whether he or she will be able to do so. The reason is that the act of counting backwards prevents a person from paying attention to the letters in working memory; that is, it prevents rehearsing the letters. This same phenomenon occurs when an instruction is given to an employee, and before the instruction can be carried out, the employee is distracted or receives other instructions. Without time to encode and rehearse the instruction, it is very likely that it will be forgotten.

Working memory also has a finite capacity for holding information. It is generally recognized that the limit is seven, plus or minus two (i.e., five to nine) pieces of unrelated information. This means that, from working memory, people can recall five to nine unrelated digits, five to nine unrelated words, or five to nine unrelated sentences. If materials can be grouped into meaningful "chunks," then more items can be recalled. But again, people would be expected to recall only five to nine chunks. For example, ask someone to recall the letter string FB-IJF-KTV. If the letters are grouped into meaningful chunks, the task is much simpler; i.e., FBI-JFK-TV. For remembering letters and digits (e.g., equipment part numbers), the optimum size of a chunk appears to be three to four items. Errors can be reduced if part numbers or numeric codes are divided into optimum sized chunks. For example, a designation such as 834-431-212 is better remembered than 8-344132-12.

Some tasks involve receiving or processing a continuous sequence of stimuli. An operator must make a different response to each stimulus or series of stimuli, and he or she is not expected to remember the entire string. Most equipment operations are of this sort where a constantly changing sequence of stimuli require different responses. This situation is called a running memory task. If an operator is asked to recall the last few stimulus items, the memory span will be much smaller than five to nine items, and is often no more than two prior items. When trying to reconstruct an accident scenario, it is common for the people watching the sequence of events to be unable to recall what actually happened. (Often, what they relate is what they think should have logically happened, which may or may not be what actually happened.)

Long-term memory is vast, yet imperfect. No computer in existence can store as much information as is contained in the long-term memory of an average adult. The problem is that much of what is learned is forgotten and much of what is recalled was never learned. What ultimately is stored in long-term memory must first be stored in working memory where it is coded and organized for effective storage in long-term memory. This coding and organization requires that attention be paid to the information in working memory.

Methods for organizing and coding information can enhance long-term memory. For example, one method called the method of loci is useful for remembering a list of sequential items (tasks to perform, instructions to follow). The idea is to attach the items to a spatial map in memory. The first step is to picture a sequence of actions that are performed daily; for example, your coming to work. You form a mental map; that is, you picture the sequence of events and their location in your mind. You enter the company gate, park the car in the parking lot, walk to the change room, change clothes, get a cup of coffee at the coffee machine, read the bulletin board, etc. The next step is to tie each thing you need to remember to a location on your mental map. This is done by visualizing the thing you need to remember at that location. If the visual images are bizarre, the sequence of things will be easier to remember. When the items need to be recalled, you have only to mentally traverse your route to work and recall each chunk of information stored at each location. With practice, this technique is very effective because it uses visual imaging to organize information in long-term memory.

Decisionmaking

Decisionmaking is a complex process by which people evaluate alternatives and select a course of action. This process involves seeking out information, estimating probabilities of outcomes, and attaching values to the potential outcomes. Examples of common types of decisions include deciding what make and model of haulage truck to buy, deciding whether to set a temporary roof support before checking the integrity of the roof, deciding what caused an electrical malfunction in a piece of equipment, and deciding whether to come to work in the morning.

Unfortunately, people are not optimal decisionmakers and often do not act "rationally;" that is, they do not act according to objective probabilities of gain and loss. There are a number of biases inherent in the way people seek information, estimate probabilities, and attach values to outcomes, and these biases produce what, to some, may appear to be irrational behavior. The following is a short list of some of these biases (*33*)

1. People give an undue amount of weight to early evidence or information. Subsequent information is considered less important.

2. People are generally conservative and do not extract as much information from sources as they optimally should extract.

3. The subjective odds in favor of one alternative or another are not assessed to be as extreme nor given as much confidence as they optimally should be given.

4. As more information is gathered, people become more confident in their decisions, but not necessarily more accurate. For example, people engaged in troubleshooting a mechanical malfunction are often overly confident that they have entertained all possible diagnostic hypotheses.

5. People have a tendency to seek far more information than they can adequately absorb.

6. People often treat all information as if it were of equal reliability, even though it is not.

7. People appear to have a limited ability to entertain more than a few (three or four) hypotheses at one time.

8. People tend to focus on only a few critical attributes at a time and consider only about two to four possible choices that are ranked highest of those few critical attributes.

9. People tend to seek information that confirms the chosen course of action and to avoid information or tests whose outcome would contradict the chosen course of action.

10. A potential loss is viewed as having greater consequence, and therefore exerts a greater influence over decisionmaking behavior than does a gain of the same amount.

11. People believe that mildly positive outcomes are more likely than are mildly negative outcomes, but that highly

positive outcomes are less likely than are mildly positive outcomes.

12. People tend to believe that highly negative outcomes are less likely than are mildly negative outcomes.

These biases explain, in part, why some workers will engage in obviously dangerous behaviors to get a job done faster or with less effort. These people do not perceive the probability of serious injury to be as high as it might actually be, but are certain that they will gain by reducing the time and/or effort required to do the job. They also tend not to seek information that would contradict their perceptions of the situation.

Attention

Attention in human information processing is used in two different ways. The first is as a searchlight in which various features of the environment are attended. In some situations, one aspect or task must be attended and other distracting stimuli ignored; this is called focused attention. In other situations, numerous sources of information or multiple tasks must be attended; this is called divided attention. In both cases humans have limitations. Distractions are caused by irrelevant stimuli, or not everything can be attended, thereby important information, is missed. Under stress or high levels of arousal (e.g., during an emergency), fewer sources of information are attended, concentration is given those thought most important.

A special problem related to maintaining attention occurs when operators must perform a monotonous, repetitive task, yet stay alert to infrequent but critical events. This type of situation is called a vigilance task. The classic example is a control room operator who monitors dials and displays for hours on end, waiting for something to go wrong. As time passes, the probability increases that the operator will miss a signal or critical event. This inability to maintain alertness is evident after the first 30 min. This decrement is made worse if the operator is tired, or the task is performed in an unfavorable environment of high temperature and humidity. It was recognized (*19*) that surface mine haulage-truck drivers work in a situation that is conducive to a decrement in vigilance performance. The load-haul-dump-return cycle is highly repetitive, and little stimulation is received from driving in circles in an open-pit mine (fig. 3-8). This lack of alertness makes the driver unable to quickly respond to an unexpected situation and more likely to make inappropriate actions to maintain the truck on the roadway (e.g., steering corrections).

The second use of the term "attention" is as a resource. When performing any task, different mental operations require some amount of a person's limited processing resource. Doing more than one task at a time (e.g., divided attention) requires more resources than doing a single task. Attention, as a resource, is required to keep information in working memory, to obtain information from environmental sources, and to perform mental operations on that information. It is in this sense that attention is the "glue" that holds the entire information-processing function together.

In general, the more similar two tasks are, the more they compete for the same resources and the greater the interference. It is much harder to read two different messages at the same time than it is to read one and listen to the other. The more difficult the tasks, the greater the demand on resources, and the less efficient is the ability to do both tasks at the same time. A trolley operator can drive the trolley and easily converse with a dispatcher on a

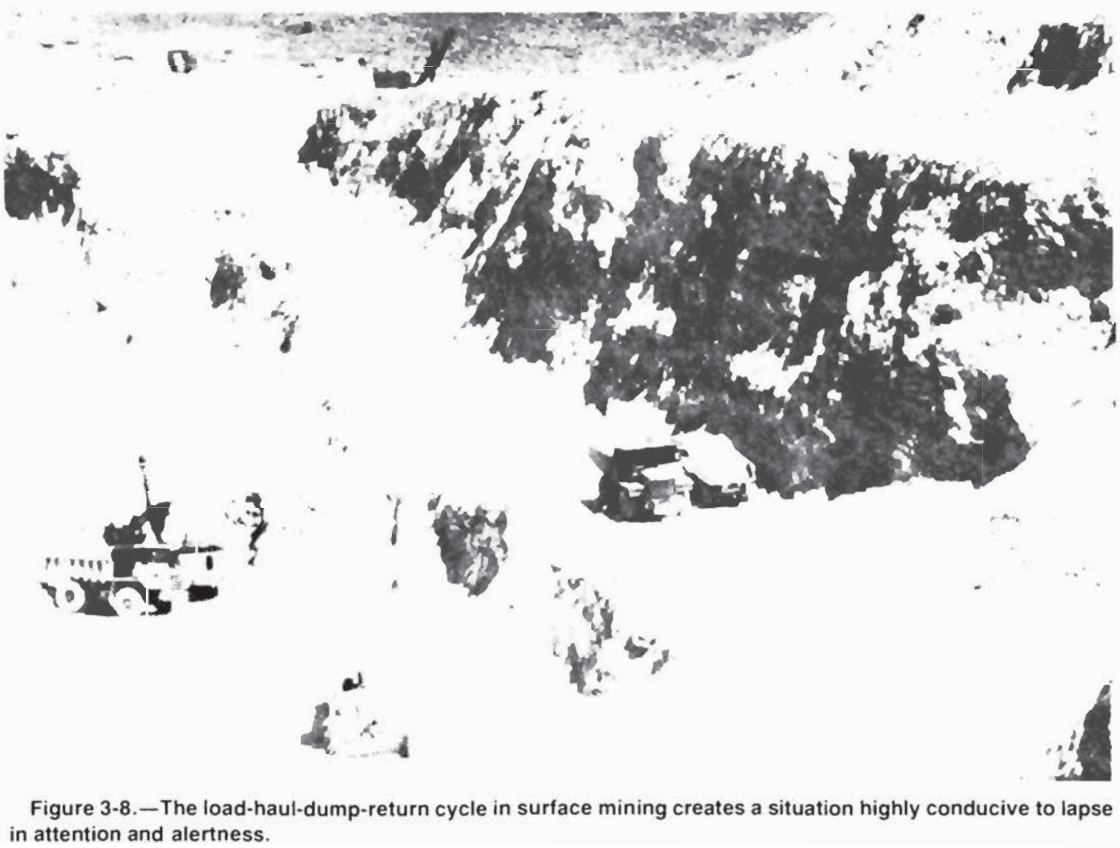


Figure 3-8.—The load-haul-dump-return cycle in surface mining creates a situation highly conducive to lapse in attention and alertness.

straight, clear track. As the operator goes through intersections, multiple switches, or dangerous sections of track, however, his or her conversation with the dispatcher will deteriorate.

Mental workload is a concept that relates to the difference between the attentional resources available and the demands placed on those resources by the tasks being performed. Hence, mental workload can increase if an operator's capacity is reduced or if task demands are increased. There have been numerous studies aimed at developing measures of mental workload, including subjective evaluations of workload, physiological measures, and performance measures. Although many seem promising, no single measure has emerged as the standard, nor is this likely to happen. Mental workload appears to be a multifaceted concept that probably cannot be adequately captured by a single measure.

HUMAN AS ACTION TAKER

When humans react to stimuli by making responses, they are concerned with the speed with which the response is made and the accuracy of that response. Response time can be divided into two components: reaction time and movement time. Reaction time is the time from onset of a stimulus to initiation of a response. Movement time is the time from initiation of response to completion of the response. For example, a person stepping into the path of a vehicle would be a stimulus to the driver of that vehicle. The driver must sense the stimulus, process the information, and select a response (e.g., turn the wheel or hit the brake). These activities take time and constitute reaction time. The driver must then execute the action, e.g., lift his or her foot and depress the brake pedal. The time required to lift the foot, move to the brake, and depress the brake would be the movement time.

Reaction Time

Reaction time is influenced by numerous factors. To organize the discussion of some of the more important ones, reaction time will be divided into three components: stimulus reception time, processing time, and response selection time. The overall mean reaction times of coal miners to a stimulus light was found to be 0.259 s (*3*). The coal miners were alerted before the light came on, and hence, this value probably represents the lower bound estimate for overall reaction time to a simple stimulus among miners. Under more realistic conditions, however, reaction times can be 10 times as long.

Stimulus Reception Time

The time it takes to perceive a stimulus depends only slightly on the sense modality (seeing, hearing, touching, etc.), but depends heavily on the intensity of the stimulus. Auditory and touch reaction times are approximately 0.15 s; vision and temperature reaction times are 0.2 s; smell reaction time is 0.5 s; and pain and task reaction times are 1.0 s.

For visually presented stimuli, the location in the field of vision is also an important determinant of reaction time. Reaction time is much faster to stimuli in the line of sight than it is to stimuli located in the periphery of the visual field. Anything that can make the stimulus more conspicuous, such as increased size, brightness, contrast, and duration, will decrease reaction time. Flashing lights are also responded to faster than are steady lights, especially if they are located in the periphery of the visual field.

Processing Time

Once a stimulus is received, it must be processed and a decision made to respond or not to respond to it. A major variable affecting processing time is the temporal uncertainty of the stimuli; that is, if a person knows when a stimulus will occur, reaction time is faster. For example, one study found that reaction time for braking an automobile in response to an anticipated auditory stimulus was 0.54 s, while braking in response to an unanticipated stimulus was 0.73 s (*15*). Another factor that influences processing time is whether a person is engaging in another task that could compete for attentional resources. In one study (*26*), reaction times of up to 2.5 s were found for responding to warning lights in the periphery while simultaneously performing a tracking task. This is very close to the results obtained by Summala (*27*), wherein the steering response to the onset of a light at the side of the road was measured. Subjects were not aware that they were in an experiment and were totally unexpectant of the stimulus. The average steering response (toward the center of the road) started less than 2 s after the onset of the light, reached its halfway strength at 2.5 s, and reached its maximum response at a little more than 3 s. Thus, reaction times in the operational environments should not be expected to be less than 2.5 s, and design should probably be for reaction times of 3.0 s. A haulage truck, for example, going 20 mph will travel about 90 ft in 3 s.

Response Selection Time

Once a stimulus has been processed, an appropriate response must be selected. The more choices available to a person, the longer the reaction time. Figure 3-9 shows the results of one study (*5*) that measured reaction time as a

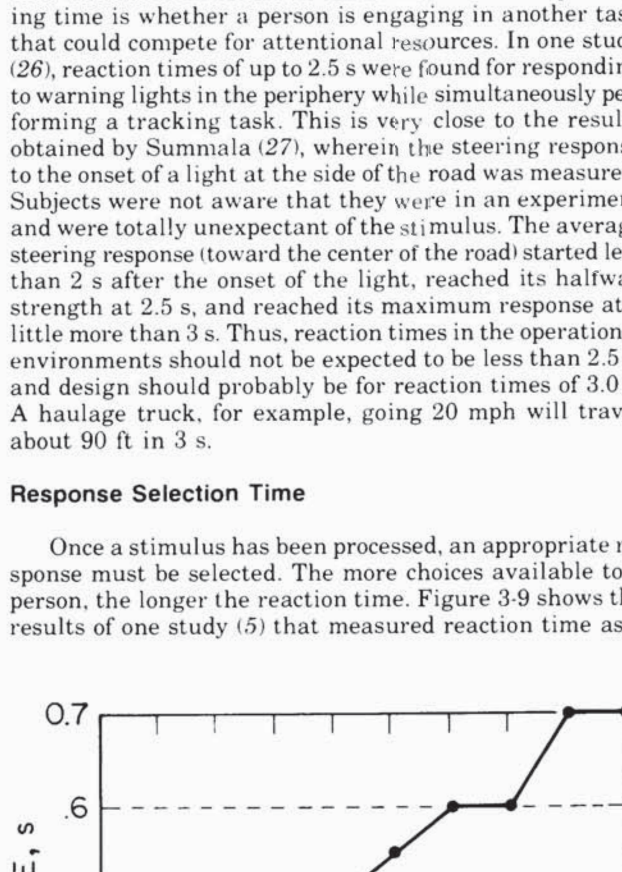


Figure 3-9.—Reaction time as a function of the number of response choices available. (Based on data presented by Damon (5).)

function of the number of choices available. Another variable that is important is whether a response is compatible with a stimulus. The more compatible a response is to a stimulus, the faster the reaction time. (Compatibility is discussed in more detail in chapter 6.)

Movement Time

Factors affecting movement time include the distance traveled, direction and type of movement, load being moved, and type of action taking place at the end of the movement. It has been estimated (*32*) that a minimum movement time of about 0.3 s can be expected for most control activities. If one adds this time to the simplest reaction time of about 0.2 s, the minimum control activation time (reaction plus movement time) is approximately 0.5 s.

Generally, horizontal hand movements are faster than vertical hand movements, and continuous curved motions are faster than abrupt direction changes. Movement time is not linearly related to distance traveled because higher movement velocities (inches per second) can be attained with longer movements than with shorter movements. Generally, reaction time using the hand is approximately 20% faster than using the foot, and the preferred hand is approximately 3% faster than the nonpreferred hand (*14*). These sorts of considerations, of course, have implications for the layout of equipment controls where speed of operation is critical.

Movement Accuracy

Several types of movements can be distinguished: positioning movements, continuous movements, and repetitive movements.

Positioning Movements

Reaching for something or moving an object to another location are examples of positioning movements. Accuracy of blind positioning movements was assessed by Fitts (*7*), and the results indicated that people are most accurate in blind positioning if a target is straight ahead. Accuracy decreased as the target moved to more peripheral positions and was better for targets at and below shoulder height than for those above shoulder height. In many mining situations, operators are required to reach for a control without looking at where they are reaching. To avoid groping or contacting the wrong control, controls that will be operated blindly should be placed in front of the operator, at a below-shoulder height.

Continuous Movements

Continuous movements require accurate control over the entire movement, as for example in drawing a line on a piece of paper. One study of tremor in arm movements (*20*) found that tremor was significantly greater (four to six times) if the arm movements were in-out (away from-toward the body) than if they were up-down or right-left.

Repetitive Movements

Repetitive movements involve successive performance of the same action over and over, such as in crank turning or tapping. Probably the most important aspect of repetitive movements is that such work requires pauses from time to time, and it is difficult to maintain a constant rhythm over time without rest breaks.

ANATOMICAL CHARACTERISTICS

It is no surprise to anyone that human bodies come in a variety of sizes and shapes. The science of measuring body dimensions is called anthropometry. Anthropometric data are essential for designing equipment and workspaces that will accommodate the worker population. Anthropometric data include body dimensions and range of movement. Before presenting some of the basic anthropometric data, a review of some basic concepts and some of the limitations of using such data is given.

Percentiles

Anthropometric data are usually reported as percentiles; e.g., the 95th percentile standing height for male low-seam coal miners is 73.7 in. Percentiles indicate the percentage of a particular population that have values less than the value given. Thus, it is known that 95% of male low-seam coal miners are less than 73.7 in tall and 5% are 73.7 in or taller. The most commonly reported percentiles are the 5th, 50th, and 95th. The 5th percentile value is the small person, as only 5% of the population have values smaller than the 5th percentile value. The 50th percentile value represents the "average" person; half the population have values less than the 50th percentile value and half have values equal to or greater than the 50th percentile value. The 95th percentile value, of course, represents the large person.

When equipment or workstations are designed, they are usually designed for the 5th to 95th percentile values, that is, the middle 90% of the population. The reasons for this is that accommodation of the extreme 5% at each end of a distribution requires a disproportionate range of adjustability in a workspace. For example, the 5th to 95th percentile sitting height spans a range of 4.2 in. The 1st to 99th percentile sitting height, however, spans a range of 6.0 in. Therefore, to accommodate the extra 10% of the population, vertical seat height adjustment would have to be increased almost 43%.

Fallacy of the "Average" Person

The term "average size" is often used, but in reality no one is average on more than one or two body dimensions. That is, a person who is average in overall standing height may have short legs and a long upper torso, or long legs and a short upper torso. Short people may have long arms, and tall people may have short arms. In a classic study (*10*), not a single person among 4,000 Air Force men could be found within ±30% of the mean on 10 body dimensions.

The fact that the smallest person is not necessarily the smallest on all dimensions, that the average height person is not necessarily the average on all dimensions, and that the largest person is not necessarily the largest on every dimension has important implications for using anthropometric data in design. First, one cannot simply add dimensions together and expect to arrive at the correct percentile value. For example, adding the 5th percentile fingertip-to-elbow length to the 5th percentile elbow-to shoulder length will not yield the 5th percentile fingertip-to-shoulder length. The correct procedure is more complicated, requires additional information, and is beyond the scope of this report.

Second, if individual dimensions are used to design workspaces, a larger proportion of the population will be excluded than would be expected. For example, if an operator's compartment was designed so that hand controls and foot controls could be reached by the 5th percentile person, more than 5% of the population would not be able to reach either the foot controls or hand controls, or both. The reason, of course, is that the 5% excluded from reaching the foot controls are not necessarily the same 5% excluded from reaching the hand controls. If several individual 5th and 95th percentile dimensions are used, the proportion of the population that would be excluded could be over 50%.

Other Limitations of Anthropometric Data

There are two classes of anthropometric data: static and dynamic. Static anthropometric data are collected on subjects who assume erect, rigid postures and are wearing no clothes or only the minimum required for modesty. These postures are not often those actually assumed in the work environment. People do not sit erect when operating equipment. Arm length is not an accurate measure of reach distance because it does not take into consideration extending the shoulder, bending the waist, and twisting the torso. Thus, one must be careful in applying static anthropometric data to designing a real workplace. Dynamic anthropometric data take into account normal work postures and the interaction between body parts that affect movements and reaches. Unfortunately, there are far less dynamic data available than there are static data.

Virtually all static anthropometric data are collected on people clothed in less than normal working attire. Winter garments, gloves, heavy boots, etc., are usually not worn when the measurements are taken. The designer, therefore, must increase dimensions to accommodate any additional clothing and any restriction in movement caused by the wearing of such clothing.

There is an enormous amount of static anthropometric data available on all sorts of populations, including truck drivers, coal miners, and flight attendants. By far, the most comprehensive data base is from the military. The important point is that there can be systematic differences in body dimensions between different occupational groups. For example, underground low-seam coal miners were measured and the results were compared with those of military personnel and long-distance truck drivers (*1*). The results showed that male miners were significantly heavier and tended to have larger circumferences of the torso, arms, and legs than did the comparison populations. The miners, however, did not differ reliably from the comparison groups in terms of linear dimensions (i.e., height, arm length, leg length, etc.). Female low-coal miners were found to have larger shoulder, waist, biceps, and thigh circumferences than did the comparison populations, but again linear dimensions did not differ.

It is important, therefore, that the designer choose a data base that closely represents the worker population for which he or she is designing. Based on Ayoub (*1*), it seems safe to use military personnel data for most design problems, keeping in mind the increased circumferences for miner populations.

Static Anthropometric Data

Appendix A contains static anthropometric data for male and female military populations (*30*). In using the data for mining applications, one must keep in mind its limitations. Allowances must be made for clothing, including heavy jackets, hardhats, battery packs and self-rescue units (for underground miners), and boots. Standing and sitting heights will be increased, and clearance spaces will have to be enlarged to accommodate the added bulk from clothing and personal protective equipment. The data in appendix A, therefore, should be considered as estimates and used as rough indicators for equipment and workspace design.

Range of Movement

The human body is not infinitely flexible. Joints impose limits on the range of movements possible—elbows pivot in one direction only but shoulder joints can rotate in all directions. The range of a joint movement is measured in degrees of angular motion. Appendix B contains data on common joint movements, including the 5th and 95th percentile range of movement for both males and females (*31*). The data are based on college-aged subjects. From ages 20 to 60, the decline in range of movement is only about 10%.

Reach Envelopes

The combination of joint mobility and anthropometric dimensions define the envelope within which a person can reach objects. In addition to mobility and anthropometrics, the posture assumed by a person, the clothes worn, and the actual manipulative task to be performed influence the reach envelope. For example, the more reclined the sitting posture, the shorter the arm reach envelope in the forward direction. If a person simply has to activate a pushbutton with his or her fingertips, the reach envelope will be 2 to 3 in. longer than if a knob must be grasped. A hand-grasp manipulation reduces the reach envelope an additional 2 to 3 in (*4*). A winter jacket, zipped up, can also reduce reach envelopes by 2 to 3 in (*25*).

Figure 3-10 shows a representative three-dimensional reach envelope (*18*). Several hand positions were used to generate the data. The cross-hatched areas represent those areas that were reached by all hand motions studied (*6*).

In addition to reaching controls with the arm, the foot is also used to activate controls. Foot-reach envelopes are much more constraining than are arm-reach envelopes. Figure 3-11 shows optimal and maximal vertical and forward pedal-reach envelopes for seated operators (*18*). The data assume a horizontal seat pan and pedals that do not require excessive force for activation. If high levels of force are required, the pedals should be moved closer to the seat reference point, the point of intersection of the centerline of the seat back and the centerline of the seat pan. The maximum areas indicated in figure 3-11 require quite a bit of thigh and/or leg movement and hence should be avoided for frequently used pedals.

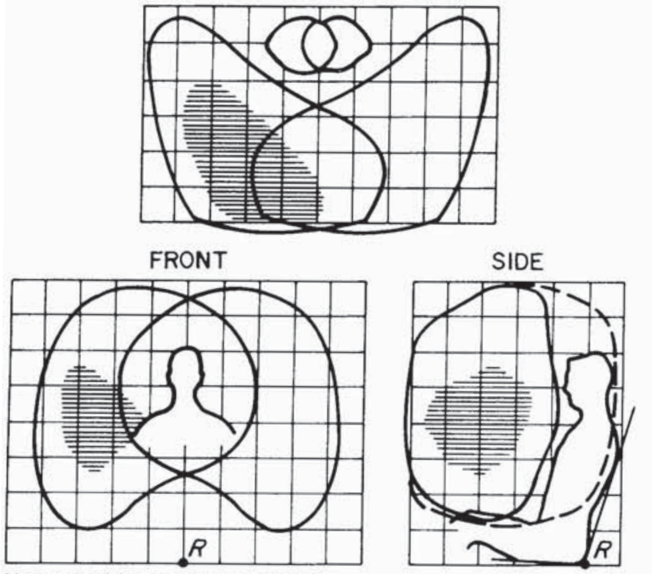


Figure 3-10.—Arm reach envelope for movements using a number of hand-grasp positions in three-dimensional space (cross-hatched areas depict regions reached under all conditions studied). (Adapted by McCormick and Sanders (18) from reference 6, courtesy of McGraw-Hill)

Strength

Strength is defined as the maximal force muscles can exert isometrically (against a fixed object) in a single, voluntary effort (16). The measured strength depends on the intrinsic muscle strength of a person, as well as the person's motivation and the specific instructions given the person as to how to exert the force. Figure 3-12 presents 5th percentile arm strength data for four directions of motion at five arm positions (13). As can be seen, pull-and-push movements are strongest, and up-and-down movements are weakest.

Strength data are important to designers so that controls and manual tasks are not designed to require more force than can be exerted by workers. Traditionally, 5th percentile values are used for design standards to insure that a task can be performed by 95% of a population.

Strength is related to age and sex. Maximum strength is reached in the middle to late twenties and declines slowly but continuously from then on. At age 65, strength is about 75% of what it was in the prime years. Women generally have less muscle strength than men. Overall, women's strength is about 66% of that of men; the exact percentage, however, is dependent on the specific muscle group measured and ranges from 50% to 80%.

It is important to keep in mind that most muscular actions relevant to a job require the integrated exertion of many muscle groups. For example, pushing a pedal requires turning the ankle and extending the knee and hips, while

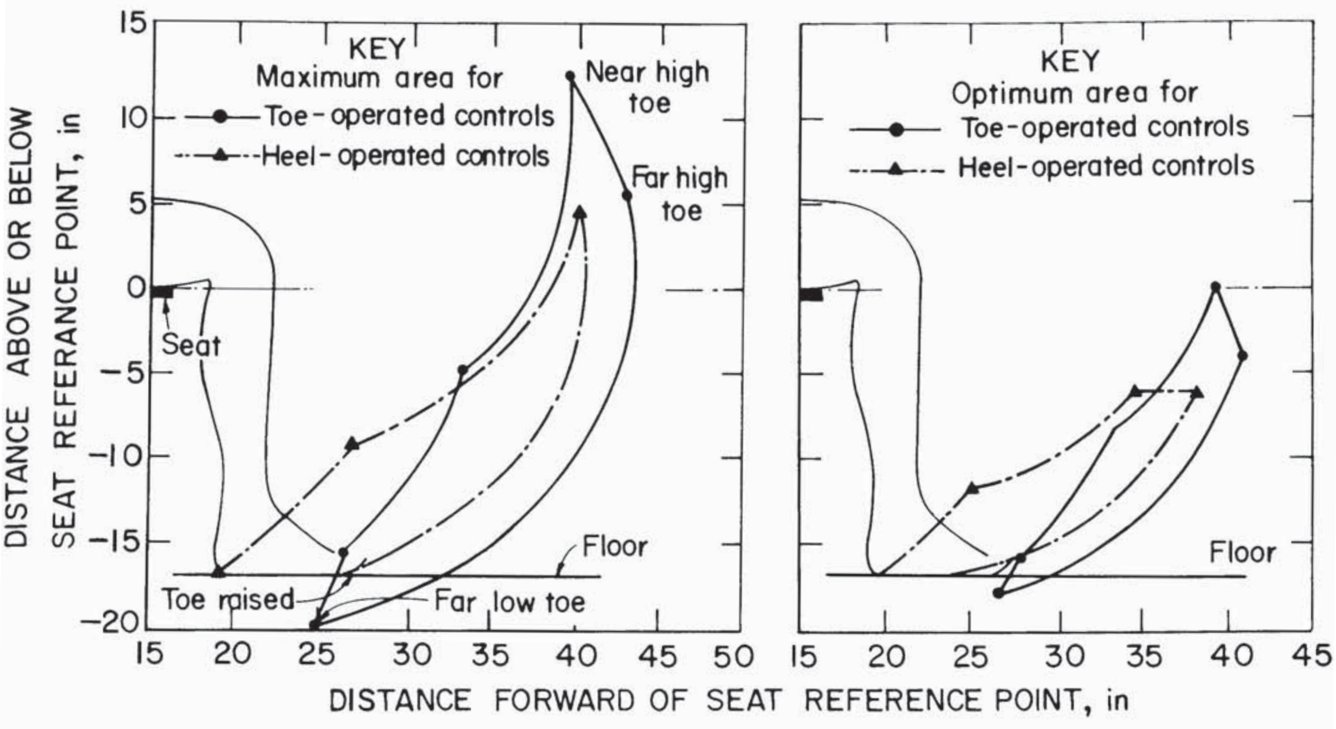


Figure 3-11.—Foot reach envelopes for various types of pedal operations. (Adapted by McCormick and Sanders (18) from reference 6, courtesy of McGraw-Hill)

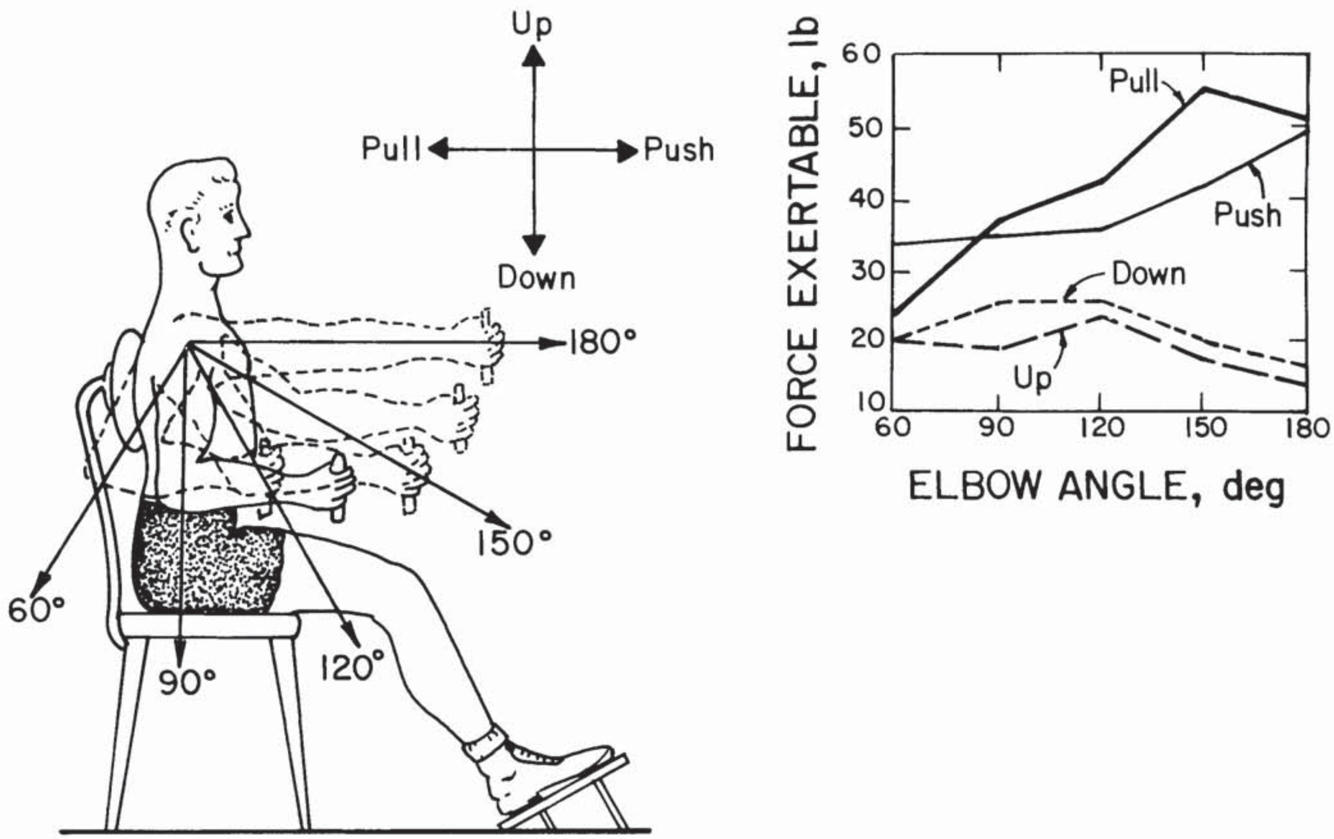


Figure 3-12.—Arm strength data. Shown are 5th percentile values for four directions of movement (up, down, pull, push) at five arm positions. (Adapted by McCormick and Sanders (*18*) from reference 13, courtesy of McGraw-Hill)

stabilizing the pelvis and trunk on the seat. Reference 25 collected the maximum forces that truck drivers could exert on pedals and the maximum torque that could be exerted on a 22-in-diameter steering wheel. Figure 3-13 summarizes the data as a function of time. Drivers were told to hold their maximum exertion for 15 s.

Endurance

Endurance refers to the ability to continue exerting a force over time. Unfortunately, the ability to hold maximum forces is rather limited. The higher the force applied, relative to the maximum force possible, the shorter the endurance time. Maximum exertions can only be held for a few seconds, but an exertion that is 25% of maximum can be held for several minutes. This relationship is shown in figure 3-14. Reference 25, for example, found that the mean maximum force dropped 12% to 15% in just 5 s, and after 15 s had decayed 21% to 24%.

Circadian Rhythms

The human body, contrary to popular belief, does not maintain an utterly constant, homeostatic internal environment. It is now generally accepted that there are regular, significant fluctuations througout the day in almost every physiological measure. These fluctuations take on a rhythm that repeats roughly each day, and therefore the term "circadian rhythms" has been coined to describe them. (The term "diurnal rhythms" is also used.)

One of the more easily measured circadian rhythms is that of body temperature. Body temperature does not remain constant at 98.6° F, but fluctuates about 1° F throughout the day. Figure 3-15 shows the typical temperature circadian rhythm with the minimum value occurring in the early hours of the morning, followed by a pronounced rise over the early working hours, with a slower rise over the rest of the day, and finally reaching a peak in the early evening.

These biological circadian rhythms are internally regulated, but can be influenced by the external environment. For example, the temperature rhythm can be shifted by altering the sleep-wake cycle. The important fact about these circadian rhythms is that they are correlated with performance. For simple perceptual and motor skills, performance closely follows the body temperature rhythm, with lower performance between midnight and 8:00 a.m. and peak performance in the late afternoon and early evening. Tasks that show this cycle include visual scanning tasks where a person is searching for targets (e.g., the type of task

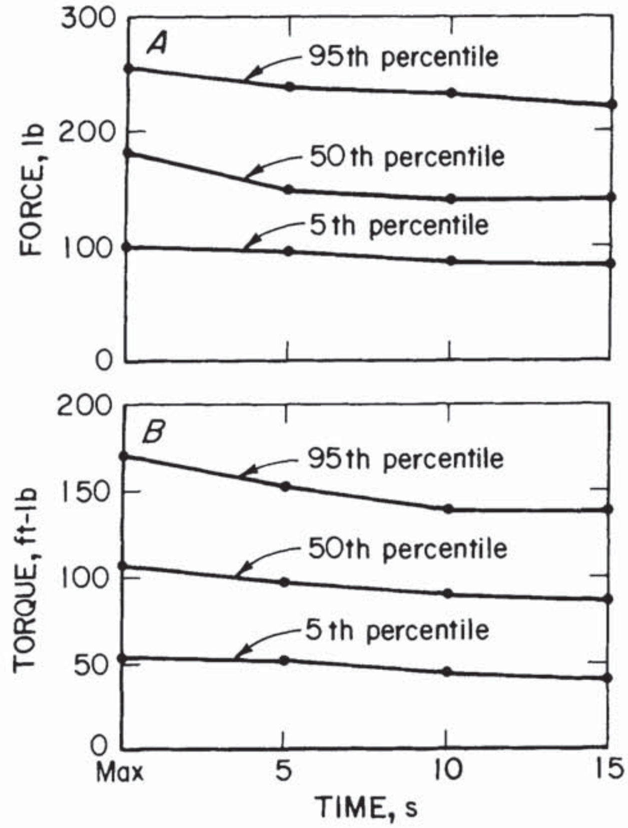


Figure 3-13.—Maximum force exerted on a foot pedal and maximum torque applied to a 22-in-diameter steering wheel by truck drivers. (Adapted from reference 25)

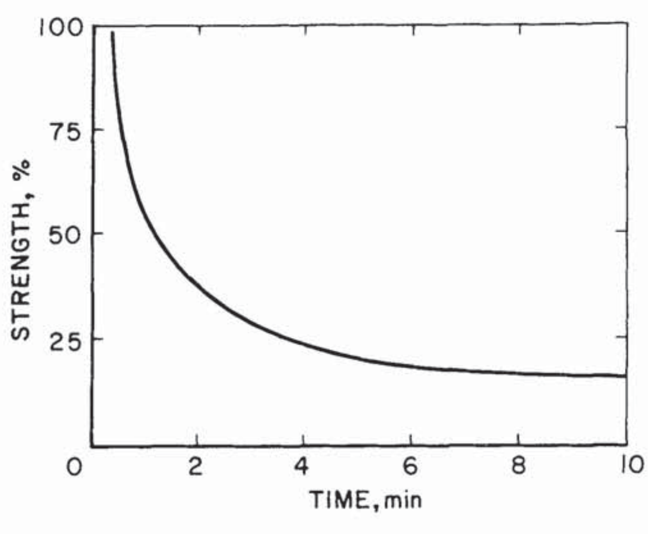


Figure 3-14.—Endurance time as a function of the force maintained (*16*). (Copyright 1970, by the Human Factors Society, Inc., and reproduced by permission)

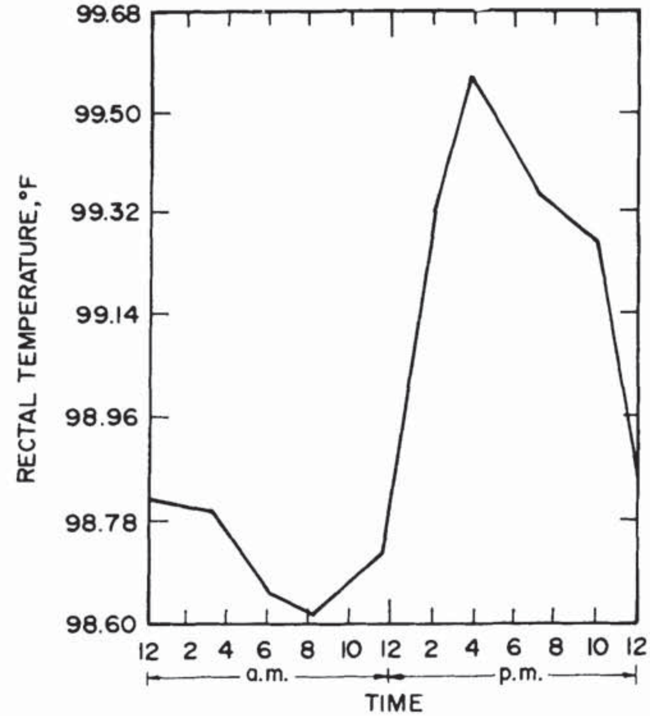


Figure 3-15.—Typical circadian rhythm for body temperature. (Adapted from reference 22, copyright 1983, by John Wiley & Sons Ltd., and reprinted by permission)

a haulage truck operator would perform); physical tasks such as manual materials handling; and reaction time tasks. It was found by Monk and Folkard (*22*), however, that tasks involving high working memory loads show a very different time-of-day trend. These sorts of tasks would include immediate recall of materials presented as prose (as in a book). In the case of these tasks, performance declines over the normal working day, with poorest performance in the early evening—almost the exact opposite of that found for simple perceptual motor tasks. This indicates that different biological clocks may be involved with these two types of functions.

Physiological Adjustment

When people alter their sleep-wake patterns, as when they change work shifts, the circadian rhythms slowly adjust to the new schedule. This process of adjustment takes a considerable amount of time, up to 12 days in the case of the temperature rhythm. However, it does not take much time to readjust the temperature rhythm to a normal day-wake, night-sleep pattern. This readjustment can occur in 1 or 2 days. There is evidence that the biological clock related to simple perceptual motor performance adjusts to change slowly, while the clock related to complex mental activity changes rapidly.

Shift Work

Circadian rhythms impose certain biological limitations on performance. These limitations are most important in the context of shift work. It was reported by Tasto and Colligan (*28*) that 30% of miners were shift workers. Among metal miners, the percentage on late shifts (second or third) was approximately 40%.

Three basic types of shift schedules can be distinguished: (1) permanent, where people always work the same shift; (2) rapidly rotating, where people never have more than one or two shifts in a row before changing to a different time; and (3) slowly rotating, where people work one shift for a week or more before changing. There seems to be two schools of thought with regard to which system is preferred. One school of thought advocates permanent shifts to maximize physiological adjustment. To be effective, however, the workers must maintain their sleep-wake habits during their days off. The second school of thought advocates rapidly rotating shifts so that no adjustment of the rhythms occur. It is believed that the constant adjustment and readjustment in permanent shift workers who revert to a normal day shift during their days off is more harmful than if they work a few days totally out of synchronization with their circadian rhythms. The disadvantages of this approach are (1) night-shift performance involving simple perceptual motor skills will be impaired; and (2) a sleep debt may quickly build up, thus requiring 2 or 3 days off after each short run of night work. It should be pointed out that if the work at night involves complex memory and mental processing tasks, a rapidly rotating shift would result in better performance than a permanent shift schedule because performance on such tasks is best when out of synchronization with the circadian rhythm.

With respect to mining, most tasks are probably of a simple perceptual motor nature. For example, field studies of shift work performance have found that error frequency in reading meters (*2*), in nodding off while driving (*22*), and in train drivers missing warning signals (*8*), is higher on night shifts than it is on day shifts. Permanent shift schedules would probably be best under such conditions, given that workers try to maintain their sleep-wake patterns during their days off, and that adequate sleep is obtained. It should be pointed out that none of the experts endorse a slowly rotating shift system. This is considered the worst of both worlds.

The major detrimental effects of shift work are sleep loss, disruption of social and family life, and increased gastro-intestinal problems. It must be pointed out, however, that not all studies are unanimous on these disadvantages. Some report advantages of being home during the day with family, and some report no gastro-intestinal problems. Sleep loss, however, appears to be fairly common. As with so many situations, shift work appears to take a heavy toll on some workers, while others appear unaffected or may even prefer it to "normal" work hours. For mining companies using shift work, it is important to recognize the potential negative effects and select workers and a shift schedule to minimize these negative aspects. Shift workers, for example, get about 25% less sleep than their day-working counterparts (*29*). There appears to be little evidence, however, that life expectancy is reduced by shift work, or that sickness is increased among shift workers.

DISCUSSION

In this chapter, an enormous amount of information and data have been presented concerning limitations and capabilities of humans as information receivers, processors, and action takers. Some of this information has direct relevance to mining, while much of it forms the basis for the design recommendations contained in subsequent chapters.

The intent was not to provide an exhaustive discussion of human capabilities and limitation, but rather to illustrate the range of factors and abilities that affect human performance. This basic background information should aid in appreciating the following chapters on information displays, controls, tools, equipment design, physical work, etc. When people's capabilities are exceeded because of the task, equipment, and/or environment, errors increase, accident frequency increases, and productivity declines. People are not infinitely adaptable; they have limitations, and recognition of these limitations is a step toward designing for increased productivity and safety.

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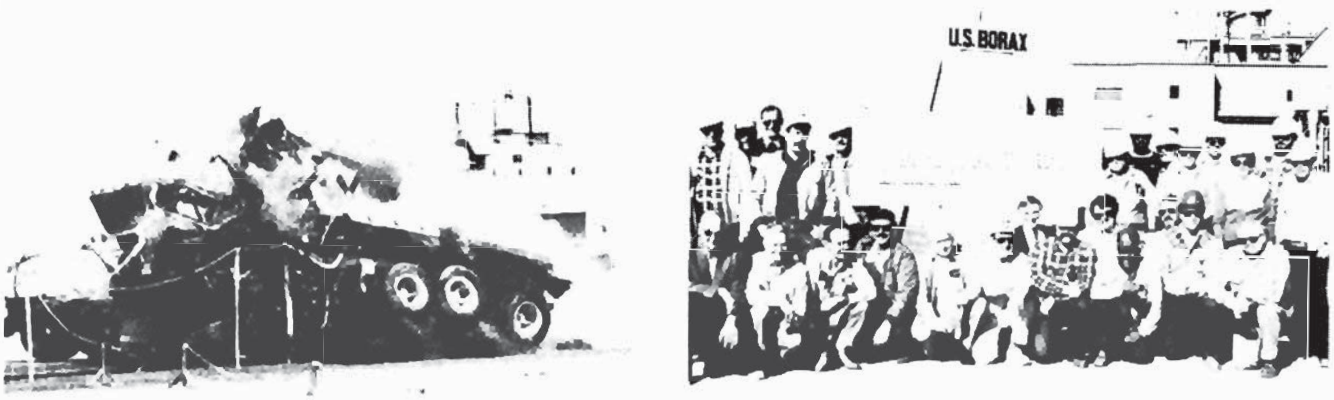
CHAPTER 4.—HUMAN ERROR AND ACCIDENTS



Accidents may happen but they can be avoided.

On Monday, July 11, 1983, the 5 right section crew arrived at the working section. Because of absenteeism, most of the crew was composed of miners from the 18 left section. Richman,[1] a shuttle car operator, was in the No. 2 entry with Nystrom, a maintenance worker. According to Nystrom, Richman was going to move the shuttle car but could not do so because the brake lock was set. Richman asked Nystrom where the lock was located and Nystrom pointed it out to him and released it. Richman also told Nystrom that he had never operated this particular model of shuttle car. The shuttle car he normally drove, although manufactured by the same company, was structurally different. He trammed the shuttle car to the section feeder to become familiar with its operation.

After the test run, Richman moved the shuttle car behind the continuous miner and asked Upton, the continuous miner helper, to check his cable reel. Richman then angled his car beneath the continuous miner tail conveyor and loading began. Shortly thereafter, Richman got out of the operator's compartment, swiveled the seat to tram outby, and got back in. As he was looking toward the continuous miner over his right shoulder, the car started to move; he said that he could not hold it. Richman saw Upton on the opposite side of the shuttle car, along the rib, and began yelling for him to get out of the way while trying to brake and hit the panic bar. The shuttle car pinned Upton against the rib and completely severed both his legs. Upton died shortly thereafter.

What was the cause of this accident? Was it human error? Was it equipment failure? Was it a combination of both? Why was Upton standing where he was? Why couldn't Richman stop the shuttle car?

As it turned out, the shuttle car showed no evidence of brake failure or any other malfunction. It was the consensus of the investigating team that when Richman became aware of the machine's movement toward Upton, he attempted to brake, but he engaged the tram rather than the brake pedal. Here then is a clear case of human error; or is it? The accident report also noted that the shuttle car's brake and tram control pedals were the exact opposite of those on the shuttle car Richman normally operated. Both cars were made by the same manufacturer but were different models. Perhaps Richman made an error, but is he to blame for it?

In this chapter the concepts of human error and accident will be explored. Theories of accident causation will be discussed, and an analysis of mining accident statistics will be made.

HUMAN ERROR

Human error is often used as a synonym for operator error, although there are obviously other humans in the system besides the operator. The operator's immediate supervisor and the mine's manager are human, and they too can err. Improper work procedures, poor management policies, and inadequate supervision could all be causal factors in an accident, and all are caused by humans. Maintenance personnel are human, and their errors can be the cause of accidents. The designer of the equipment may also have erred, as perhaps was the case with Richman and Upton previously described. Thus, to think of human error only in terms of operator error is rather narrow and may be counterproductive with respect to accident investigation and prevention.

When some people talk of human error, there is a connotation of blame or cause, rather than considering human error as simply an event whose cause is yet to be determined. One danger with the causal interpretation of human error is that the resultant emotional atmosphere often makes it difficult to rationally determine appropriate corrective action.

In this chapter the term "human error" is considered to be an event that can occur anywhere in the system. The following definition is suggested by Conway and Sanders (*7*):[2] An inappropriate or undesired human decision or behavior that reduces, or has the potential to reduce effectiveness, safety, or system performance.

[1] Names have been changed.

[2] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

In addition to defining human error, numerous investigators have attempted to develop classification systems to describe the nature of human errors. Some of these systems are simple, two-part classifications, while others are more elaborate and follow from the basic components of human information processing and performance.

Broad Classification of Human Error

One investigator (*17*) attempted to classify human errors into the following broad categories: operator-induced errors, design-induced errors, and system-induced errors. Operator-induced errors are incorrect conscious or unconscious actions or decisions on the part of personnel who have the training, experience, and tools necessary to make correct decisions and actions. Design-induced errors are errors induced by poor equipment design, fabrication, installation, or operating procedures. System-induced errors result from such things as system integration, operational practices or procedures, management policies, and selection and training procedures.

An important point was made by Meister (*17*) with respect to this classification of errors. Many errors made by operators are not operator-induced errors, but could be design- or system-induced errors. The accident described at the beginning of this chapter is an example of just such a case.

Action Classification of Human Error

Action models focus on the output of the human in terms of decisions made and actions taken. The simplest classification is that suggested by Swain and Guttman (*27*): errors of omission, errors of comission, sequence errors, and timing errors.

Errors of omission involve failure to do something. The following is an example of an error of omission that resulted in a mining fatality (MSHA *Fatalgrams*, Jan. 2, 1981, 81-09).

> An electrician was electrocuted while attempting to position himself on the steel framework of a substation. There were several points to disconnect in order to shut off power completely to the substation. In this case something was missed.

Errors of commission involve the incorrect performance of an act. The following is an example from MSHA *Fatalgrams* (Sept. 29, 1980, 80-039).

> The victim, sitting on the conveyor belt, called for his partner to hit the start button just lightly to jog the belt forward a few inches. The helper lost his balance momentarily, hit the button hard and actually started the belt, rather than just jogging it forward. The victim was drawn between the belt and a steel support member 9 inches above the belt.

A sequence error occurs when a person performs some task or step in a task out of sequence. A good example is the following (MSHA *Fatalgrams*, July 25, 1980, 80-033).

> A helper was killed when the crane he was operating overturned. The victim lifted a 24 ton block with the boom extended 80 feet at a low angle. Instead of raising the boom first, the victim rotated the crane to the right 90 degrees, resulting in positioning the near-flat extended boom at right angles to the crawler tracks. This caused the crane to overturn.

A timing error occurs when a person fails to perform an action within the allotted time, either too early or too late. An example would be a shot firer who does not vacate a blasting area fast enough after lighting fuses and is caught by the blast.

Actually, both sequence and timing errors are errors of commission, but are listed separately because their causal factors are frequently different. As can be seen, this classification focuses on operator errors as defined by Meister (*17*).

Information-Processing Model of Human Error

Several authors use an information-processing model to classify human errors. These models use an input, decision, and output classification scheme. The output element overlaps the action classification discussed previously. One information-processing model is shown in table 4-1. A problem with applying such a taxonomy is that often the same objective error can be classified into several categories, depending on the details of the situation. Such details are not often obvious from the description of the error or accident. For example, a loading machine helper was scaling down broken roof. Two temporary supports had been set. A large piece of rock broke from the roof, drove out the two supports, and fell on the miner. How does one classify this based on table 4-1? Did the worker not detect the loose rock? Did he detect it, but not classify it as dangerous? Did he incorrectly estimate the protective capability of the supports? As can be seen, such classification systems often require more information than is available in an error situation.

Table 4-1.—Information-processing model of human error (*8*)

Inputs	Sensing.
	Detecting.
	Identifying.
	Coding.
	Classifying.
Decisions	Estimating.
	Logical manipulation.
	Problem solving.
Outputs	Chaining.
	Omissions.
	Insertions.
	Misordering.

Warning-Hazard Classification of Human Error

Closely related to the information-processing model of human error is the classification scheme (*15*) used to investigate human errors in South African gold mining accidents. Table 4-2 presents the classification scheme and lists causes of the various types of human errors. This classification stressed the importance of perceiving and recognizing warnings about hazards in the work environment.

Error classifications, such as those described, can serve several useful purposes: (1) facilitate the tabulation of error frequencies, (2) provide a general frame of reference for studying human error, and (3) direct efforts at reducing the incidence of errors. The classifications that have been developed, however, are crude at best and have not served the needs of either the scientist or the practitioner. Further efforts at developing an error classification scheme could probably be better spent in identifying the causes of human error, and developing and validating preventive and remedial strategies.

Table 4.2—Human error classification of accidents in South African gold mines (*15*)

Human error	*Cause*
Failure to perceive a warning	Inadequate inspection technique. Neglecting to inspect. Obstruction to line of sight. Masking noise. Other. Mixture of these. Inadequate information.
Failure to recognize a perceived warning.	Lack of training. Lack of experience. Other. Mixture of these.
Underestimation of hazard	Causes unknown.
Failure to respond to a recognized warning.	Underestimation of hazard. Other.
Responded to warning but ineffectively.	Negligence or carelessness. Standard practice inappropriate. Well-intended but ineffective direct action. Other. Mixture of these.
Inappropriate secondary warning ...	Causes unknown.

WHAT IS AN ACCIDENT

Before anything can be scientifically studied, it must be defined. Although this may sound easy with respect to accidents, in fact, definition has been a stumbling block to accident research since its inception. Consider the following example. A haulage truck operator fails to visually inspect the area in front of his or her truck before starting out. In one case, the operator drives off and nothing happens. In another case, the operator runs over a person standing in front of the truck; and in yet another case, he or she crushes a small vehicle as shown in figure 4-1, but no one is hurt. Is the first case an accident? One might consider it an error; but when does an error become an accident? Must there be injury or property damage in order for an accident to be considered an accident?

In defining the term "accident" it is necessary to distinguish between the act itself and the consequence of that act. Two extreme definitions can be identified, but there are many shades and blends of definitions between them. For example, 200 different definitions of accidents were collected by Benner (*2*). At one extreme, definitions take no account of the consequences of the act, but rather define an accident in terms of the characteristics of the act itself. For example, a list of accident indicators was produced by Suchman (*26*); the more indicators that were present, the more the event was likely to be called an accident. The indicators were

1. Low degree of expectedness.
2. Low degree of avoidability.
3. Low degree of intention.

At the other extreme are definitions that stress the consequence of the act. For example, acts that result in injuries are considered to be accidents. For the most part, the mining industry has adopted the consequence-type definition, and for all practical purposes defines accidents as synonymous with injuries.

If consequence is considered the principal element in the definition of an accident, then the following consequences must be distinguished:

1. Fatal injury.
2. Nonfatal injury that results in days lost from work.
3. Nonfatal injury that results in restricted work days.
4. Nonfatal, no-days-lost injuries (also called first-aid injuries).
5. Property damage.

One might think that such categories would be clear and unambiguous. However, when 14 mine safety personnel were asked to classify four injury cases as disabling, nondisabling, or neither, the results indicated disagreement with respect to whether an injury was disabling or nondisabling (*20*).

One common belief is that chance or luck distinguishes a fatal accident from a nonfatal accident. A little reflection, however, reveals that some activities are more likely to cause one type of consequence than another. For example, a study of coal mine accidents in Great Britain over a 3-yr period (*19*) found that, as would be expected, a greater proportion of fatalities occurred in haulage and transport than in handling materials and using handtools. The results were just the opposite for nonfatal injuries.

Serious accidents (all those that resulted in at least 1 day of restricted or missed work activity) in underground and surface mines from 1975 to 1982 were investigated by Bennett and Passmore (*3*). The probability that an injury would be severe increased in each succeeding year studied; was lower for supervisory and maintenance personnel than for all other job classifications; and was not any greater for younger or more inexperienced miners than for older or more experienced miners.

Several investigators have urged the use of near-miss accidents as a source of information on accident causation. The logic behind this is that there are more near-miss accidents than injury-producing accidents, and therefore more data are available for study. It is assumed that only chance and luck discriminate a near-miss accident from an actual accident. An investigation of near-miss accidents in British coal mines (*23*) was made by asking miners once per month to describe any near-misses they experienced. Two problems with this approach are (1) there may be selective recall, e.g., the miners may tend to recall near-misses that they felt responsible for and may tend to forget those that were caused by forces over which they had no control; and (2) the definition of a near-miss is vague, i.e., how near a miss does it have to be to call it a near-miss. These types of problems make it difficult to use near-miss data to estimate the relative contribution of various causal factors because only a sample of all near-misses are reported, and this sample is very likely unrepresentative of the population of near-misses actually occurring.

HUMAN ERROR AND ACCIDENTS

What percentage of accidents is caused by human error? This is a question that has vexed researchers for years. Probably the most common answer one hears is that approximately 85% of accidents are due to human error. This

Figure 4-1.—One consequence of operator error.

figure came from an analysis of insurance company records conducted by Heinrich (*11*). This percentage, however, should not be taken too seriously. The percentage of accidents one attributes to human error depends on how one defines human error; the data source used to compile the statistics; and the alternative causes, other than human error, included in the tabulation.

If one assumes that human beings are responsible for their own actions and are therefore responsible for the errors they make, then a higher percentage of accidents will be attributed to operator error. On the other hand, if the view is adopted that errors can be anticipated and they should therefore be planned for and designed for, and that when they do occur the fault should be traced to the designer, then fewer accidents will be attributed to operator error.

The typicial human-error-in-accident investigation classifies cause as either due to unsafe acts (i.e., operator error) or unsafe conditions, or as due to operator error or equipment failure. Such a simple classification results in a foregone conclusion that a high percentage of accidents will be attributed to the operator. Such analyses leave out the all important question of what caused the operator to err. Often the cause can be traced to faulty equipment design, inadequate or improper instruction and training, or dangerous management policies.

A review of the literature reveals widely disparate estimates of the percentage of accidents due to human error. For example, in 12 studies reviewed by Conway, Muckler, and Peay (*6*), percentages were found ranging from 4.3% to 90%. Half reported percentages equal to or exceeding 80%, while the other half reported percentages less than or equal to 50%

A few studies have attempted to estimate the proportion of accidents in the mining industry attributable to human error. A study of underground transport accidents in Great Britain (*10*) revealed that 44% of the accidents were due to "lack of discipline or ordinary caution" and "bad operator practice." Sims, Graves, and Simpson (*23*) categorized haulage near-misses as caused by "man factors" (i.e., human errors), "vehicle/load factors," or "environmental factors." They reported that 49% of the incidents were caused by "man factors." On the other hand, it was reported by Snyder (*24*) that, based on Mine Safety and Health Administration accident investigations, 63% of the 43 fatal accidents involving supervisors from 1981 through July 1983 involved the victims doing things they knew, or should have known, were unsafe. These acts included the victims placing themselves in a hazardous position; standing or working in areas where the roof was not supported or where an approved roof control plan was not being followed; repairing machinery in motion or electrical equipment that was known to be energized; supervising improperly conducted blasting operations; or overseeing work in operations with inadequate ventilation.

From an analysis of 92 underground mining accident investigations, it was found by Sanders and Shaw (*21*) that operator error was involved to some degree in 93% of the cases, but was the primary cause of only 39% of them. Across all 92 cases, the average percentage of cause attributed to operator error was 30.5%.

Lawrence (*15*), in his investigation of 405 South African gold mining accidents, identified 794 errors associated with the perception of, recognition of, and response to warnings. His investigative model assumed that *all* accidents were due to human errors, and his task was to categorize the errors by type. These error classifications and causes are shown in table 4-2. A careful reading of the causes listed for a human error indicate that some of them would be considered, according to Meister (*17*), as design errors (e.g., obstruction to the line of sight or masking noise), or system errors (e.g., lack of training or inappropriate standard practice). The percentages of accidents assigned to his classification of errors by Lawrence (*15*) were as follows:

Failure to perceive a warning	36%
Failure to recognize a perceived warning	4%
Underestimation of hazard	25%
Failure to respond to a recognized warning	17%
Responded to warning but ineffectively	14%
Inappropriate secondary warning	4%

It appears that there is probably no one answer to the question of the contribution of human error to accidents. The best that can be said is that the answer depends on what human error is considered to be, and whether the cause of the error is taken into account. Overall, however, it can probably be said that operator error is the primary cause in no more than half of the accidents occurring in underground mining. This conclusion is based on the results of the studies by the Health and Safety Executive (*10*), Sanders and Shaw (*21*), and Sims, Graves, and Simpson (*23*).

THEORIES OF ACCIDENT CAUSATION

There has been a wide array of accident causation theories proposed. Each theory emphasizes the orientation of its author, be it psychological, sociological, or statistical. The varying theories can, however, be grouped into three broad classes: accident proneness theories, job demand versus worker capability theories, and psychosocial theories.

Accident Proneness Theories

The oldest and probably the most influential accident causation theory is that of accident proneness. In its pure form it hypothesizes that some people are more prone to have accidents than others because of a peculiar set of constitutional characteristics. Further, accident proneness is considered to be a relatively permanent feature of the individual.

The support for this theory has come from statistical comparisons between the distribution of accidents in a population of workers and the distribution expected by pure chance. What was often found was that more people than would be expected had multiple accidents. More recent authors have challenged these early statistical studies, pointing out that to accept accident proneness one must accept the underlying assumption that all people in a population of workers are exposed to the same job and environmental hazards. The fact that more people have multiple accidents than would be expected because of chance may only indicate that some people are exposed to more hazards on the job than others.

A more restricted view of accident proneness is that people are more or less prone to accidents in given specific situations, and that this proneness is not permanent but changes over time. This has been called the accident liability theory. Thus, person A may be more accident prone than person B in situation 1; but in situation 2, person B may be more accident prone than person A. Further, person A may be more accident prone than person B in situation 1, but this proneness may decrease with time.

Two prime variables that relate to this formulation of accident liability are age and experience. The problem, however, is that it is often difficult to separate the effects of the two variables; younger workers usually are also the most inexperienced. Little relationship was found among underground coal miners between age and either fatality rates or permanent disabling injury rates (*18*). There was, however, a very strong correlation between age and nonpermanent disabling injury rates. Figure 4-2 depicts the relationship found. A young miner (18-24 yr old) was about three times more likely to be injured than a miner 45 yr of age or older, and about twice as likely to be injured than a miner 25 to 44 yr of age.

A number of researchers have suggested that younger workers have accidents for reasons other than experience. For example, inattention, lack of discipline, impulsiveness, recklessness, misjudgment, overestimation of capacity, and

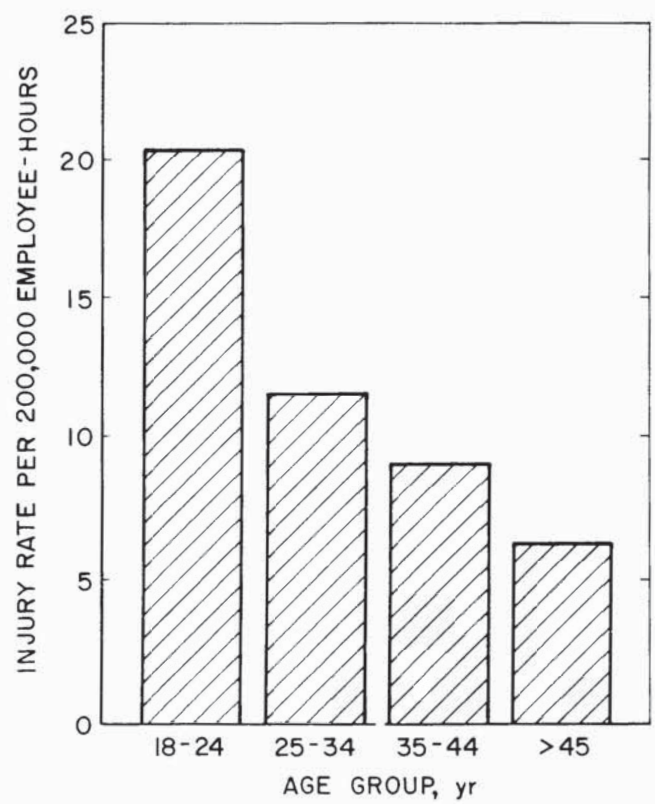


Figure 4-2.—Relationship between age and disabling injury rate (*23*). (Courtesy of National Academy Press)

pride were implicated by Lampert (*14*) as factors that may account for higher accident rates among younger workers.

Although not investigated by the National Academy of Sciences (*18*), other investigators have found that accident liability increases among older workers (e.g., over 50 or 60 yr of age). This increase may be due to deterioration in motor skills, sensory functions, and mental agility (*9*). It should be pointed out that Schaffer, Gavan, and Woodward (*22*) found no such rise in accident liability at the upper age range for operators of surface front-end loaders, haulers, or trucks, nor for operators of underground shuttle cars or roof bolting machines.

The amount of job experience is another transient factor that changes an individual's accident liability over time. Virtually all investigators have found experience to be closely related to accident liability. Further, it appears that specific job experience is more important than general mining experience. The number of days of experience at a new job element (new mine, new job, new piece of equipment, new task, etc.) were found to be related to fatal accidents (*28*). The accident frequency on the first day was nearly three times higher than the average frequency for the next 4 days. This conclusion was supported by Studenski (*25*) when he found that 40% of mistakes that resulted in accidents at work occurred on rarely performed or entirely new tasks.

Even among supervisors, experience is an important factor in accidents. Among coal mine supervisors who were killed in the 9-yr period from 1973 through 1981, 31% had 2 yr or less of supervisory experience. Figure 4-3 shows a more detailed analysis of 49 supervisors who died in coal mine accidents from 1981 through July 1983. As can be

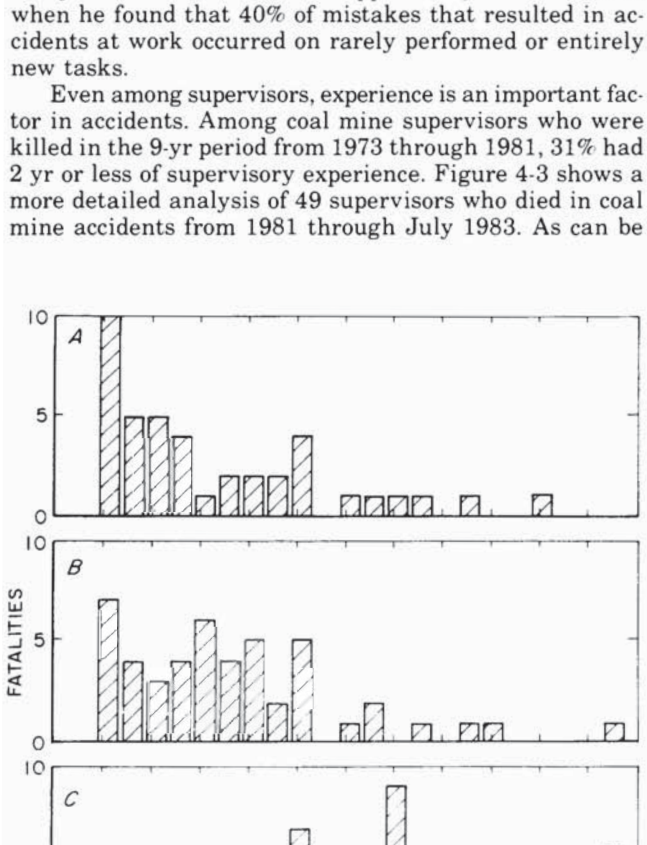


Figure 4-3.—Supervisor fatalities in coal mining as a function of experience at mine (*A*), experience in job classification (*B*), and total mining experience (*C*) (*24*). (Courtesy of U.S. Mine Safety and Health Administration)

seen, experience in job classification and experience at mine are highly related to accident frequency, while the relationship of total mining experience to accident frequency is less discernible. It indeed appears that accident liability fluctuates with time, especially as related to age and specific job experience. The notion that some people are naturally more accident prone than others across all situations and at all times is probably a less tenable position.

Job Demand Versus Worker Capability Theories

This class of theories is related in part to the accident liability notion previously introduced. Simply put, accident liability increases when job demands exceed worker capabilities. For example, if a job requires greater psychomotor skills than workers have, accidents are expected to increase. The relationship between job experience and accident rates can also be considered as examples of job demands exceeding worker capabilities. With more experience, capabilities increase and, hence, one would expect accidents to decrease.

Another line of evidence used to support this class of theories is the relationship of fatigue to accidents. The assumption is that with increased fatigue, capabilities are reduced. Because it is difficult to measure fatigue, investigators have correlated accident frequencies with factors believed to be related to fatigue, such as day of week, time of day, and time since shift started.

The problems with studies that have investigated day of week, time of day, etc., are that they do not attempt to equate the number of people actually working on each day of the week, the hour of the day, etc.; and they do not attempt to equate the type of work being performed on each day of the week, the hour of the day, etc. For example, it was noted by Adams, Barlow, and Hiddlestone (*1*) that fewer accidents occur on Mondays and a greater number of accidents on Wednesdays. It may well be that absenteeism is higher on Mondays than in the middle of the week. They also reported a steady increase in the number of accidents occurring 40 to 70 min after a break, with a consistent and steady drop thereafter. One factor affecting this steady drop after 70 min may be that another break may be in progress because there are not many workers who fail to take a break of some sort after 90 min of work.

Unfortunately, then, this line of research cannot be used to support the job demand versus worker capability theories. Some tangential evidence, however, came from a study by Kephart and Tiffin (*12*) who investigated the visual requirements of 12 jobs and compared them to the workers' visual capabilities. In 11 of the 12 jobs, the percentage of safe workers (low-accident employees) was higher among those whose capabilities exceeded the requirements than among those whose capabilities did not exceed the requirements.

Related to the job demand-worker capability class of theories is the adjustment to stress theory. This theory states that accident rates will be higher in situations where stress (physical or physiological-psychological) is placed on the worker. In essence, the additional stress overloads the workers and adds to the demands of the job so that their capabilities no longer match the job demands. Physical stressors include noise, poor illumination, and temperature extremes. Physiological-psychological stressors could include anxiety, lack of sleep, illness, anger or remorse from having a fight with a spouse, etc. The research data are mixed with respect to the effects of these variables. Undoubtedly, some of the confusion arises because the jobs performed, even with the stressors, are not demanding enough to exceed the worker' capabilities; or the workers slow down and this reduces the overall demands of the job.

Psychosocial Theories

One theory, goals-freedom-alertness, holds that greater freedom among workers to set reasonably attainable goals is accompanied by high-quality work performance, and accidents are viewed as examples of low-quality work performance. The idea is that by raising the level of alertness, accidents will be reduced; and this alertness can be sustained only within a rewarding psychological climate *(13)*. Kerr contends that in industry, both management and unions interfere with this climate by telling people what to do and what not to do, without asking them their ideas about relevant and attainable goals. Sanders, Patterson, and Peay *(20)* found some evidence supporting this theory among underground coal miners. This study will be discussed further in chapter 10.

In addition to the goals' freedom-alertness theory, there are some psychoanalytical theories that view accidents as self-punitive acts caused by guilt, aggression, etc.

Overall, then, there does not appear to be any one really good theory of accident causation. All have a ring of truth to them, but by themselves do not explain the complexity of the accident situation.

INJURY STATISTICS

Numbers seem to be so objective; it is possible to compute the number of trip-and-fall injuries, compare them to back injuries, look for trends over several years, and make recommendations based on the "statistics." For some unknown reason, putting a number on something makes it more believable. Nothing is inherently wrong with this, as long as the limitations of the numbers used are understood. Consideration must be given to how the data were collected, and what factors could have influenced the numbers obtained.

Mining companies may collect, tabulate, and analyze their own accident data. The Mine Safety and Health Administration (MSHA) of the Department of Labor requires mining companies to report accidents and fill out accident forms so that MSHA can collect, tabulate, and analyze the resulting data. The entire accident-reporting process, from accident occurrence to reporting, is at best an unreliable process that almost always fails to capture all the accidents that actually occur. In addition, the data collected about the accidents are often inaccurate and incomplete.

As already discussed in this chapter, the term "accident" has many definitions, and the definition accepted will obviously influence the type and the number of incidences reported. Even if accident and injury are accepted as synonymous terms, there is still plenty of opportunity to lose data.

Sanders, Patterson, and Peay *(20)* traced the injury-reporting process to the last step, transmitting the data to MSHA, and revealed several areas where injury data may be lost.

Workers commit unsafe acts, a proportion of which lead to injuries. Workers must then decide to report the injuries to management. In cases of serious injuries, there is little choice. With less serious injuries (e.g., cut or bruised fingers, strained back, or dust in the eye), however, workers may decide not to report injuries for any number of reasons (e.g., they know management does not like workers who bellyache, they are afraid they may be laid off, their pride keeps them from admitting to injuries, they feel they can treat the injuries themselves, etc.).

After a worker reports an injury, management decides if it is really an injury. Again, with minor injuries, management may question whether an injury really occurred (e.g., back strain) or may say, "Put a bandage on it and forget it." If an injury is considered bona fide, management then decides whether it is a lost-time injury. Surprisingly, there is some ambiguity here. A worker can be told to go home and take a few days off to recuperate, creating a lost-time injury; or the worker can be given a temporary assignment in the office or topside where recuperation can take place while the employee is on the payroll, without a lost-time injury. This practice often exists in industry.

At each of the steps in this process, an injury may drop out and not be reported. Some companies may report more injuries than do others because of differences in reporting policies rather than in the underlying safety of the mines. If injury statistics are used in a punitive fashion, then companies are more likely to underreport incidences.

The accident data collected on an injury can also be a problem area. There is considerable confusion as to how an accident should be classified. Especially ambiguous is the source of injury category that identifies the object, substance, exposure, or bodily motion that directly produced or inflicted an injury. Often, the nature of injury can be ambiguous, especially in the case of multiple injuries. The specification of accident type becomes difficult when the accident sequence comprises a series of associated events. One worker drops a wrench. The wrench strikes another worker who is standing on a ladder. This worker falls off the ladder, and the ladder in turn falls on him or her. Should this accident be classified as struck by falling object, and if so, by wrench or ladder, or as fall from ladder?

The data collected usually concentrate on the individual injured, recording his or her age, experience, activity at time of injury, job title, etc. This is done whether or not the victim was the cause of the accident or simply the recipient of another person's error. For example, if a continuous miner operator (50 yr old with 15 yr of job experience) crushes his or her helper (21 yr old with 1 yr of job experience) against the rib with the tail conveyor of the continuous miner, the victim's injury is attributed to youth and inexperience, when it may well be the fault of the older, more experienced operator.

With these limitations in mind, a review is made of some of the following basic injury statistics in the mining industry.

Industry-wide Comparisons

The major sectors of the mining industry can be grossly categorized within a two-dimensional matrix: commodity by type of mine. Although these dimensions can become complex, as far as injury statistics are concerned, the situation is simplified by dividing commodity into coal, metal, and nonmetal categories, and type of mine into underground and surface. This rough classification scheme is used by MSHA to tabulate its injury statistics. MSHA does, however, include finer breakdowns within each of these categories.

Figure 4-4 presents injury data for 1983 *(29)* for the various segments of the mining industry. Shown are the percentages of fatal, nonfatal-days-lost (NFDL), and no-days-lost (NDL) injuries occurring in each industry segment. As can be seen, underground coal mining accounted for approximately 65% of all fatal injuries, 70% of all NFDL injuries, and 50% of all NDL injuries occurring in the mining industry during 1983. These values are typical; similar values can be found in other years as well. It is not surprising then that much more research effort has been directed toward understanding the causes of injuries in underground coal mining than in any other segment of the industry.

Figure 4-5 shows the injury rates (per 200,000 employee-hours) for each segment of the industry for 1983 (*29*). As can be seen, the main distinction is between underground and surface mines, with smaller differences among commodities. This is reinforced in figure 4-6, which shows the percentage of NFDL injuries attributed to the five main accident-producing categories for each segment of the industry (metal and nonmetal have been combined). These five categories (handling materials, machinery, powered haulage, slips and falls, and handtools) accounted for the following percentages of NFDL injuries in 1983:

Underground coal 83%
Underground metal-nonmetal 79%
Surface coal 93%
Surface metal-nonmetal 91%

For some categories, there is no apparent relationship among the segments of the industry, such as for handtool, powered haulage, and materials handling accidents. A greater proportion of accidents involved machinery in underground mining than in surface mining, probably due in part to the proximity of people to machinery, often in cramped work areas. A greater percentage of NFDL accidents were slips and falls in surface mines than in underground mines. This is due in part to slips and falls while mounting and dismounting large surface mining equipment. The large percentage of "other" accidents in underground mining was due to roof fall injuries. The analogous situation in surface mining would be an injury due to failure of a highwall, to which fewer people are exposed.

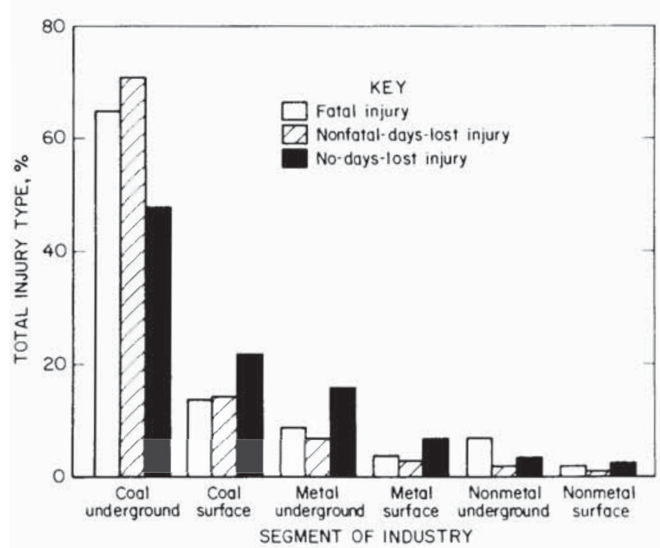


Figure 4-4.—Percent of fatalities, nonfatal-days-lost, and no-days-lost injuries occurring in 1983 for each of the major segments of the mining industry (*29*). (Courtesy of U.S. Mine Safety and Health Administration)

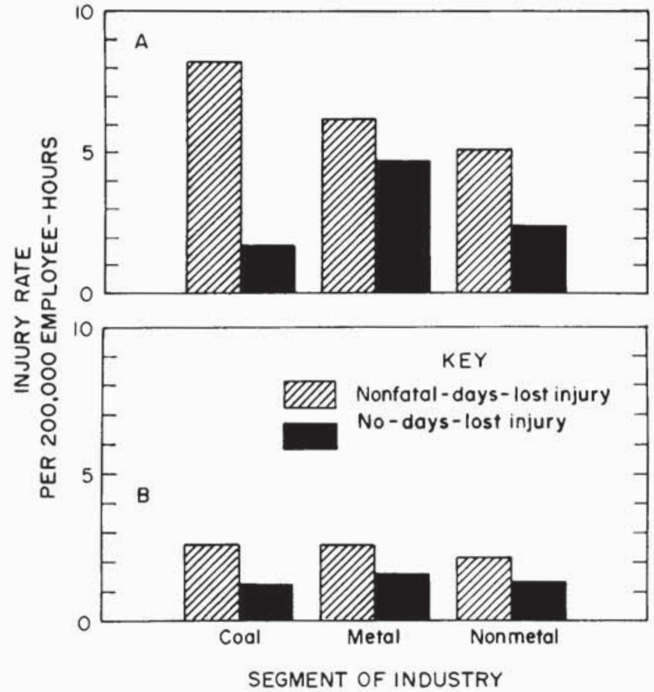


Figure 4-5.—Nonfatal-days-lost and no-days-lost injury rates for 1983 for each of the major segments of the underground (*A*) and surface (*B*) mining industry (*29*). (Courtesy of U.S. Mine Safety and Health Administration)

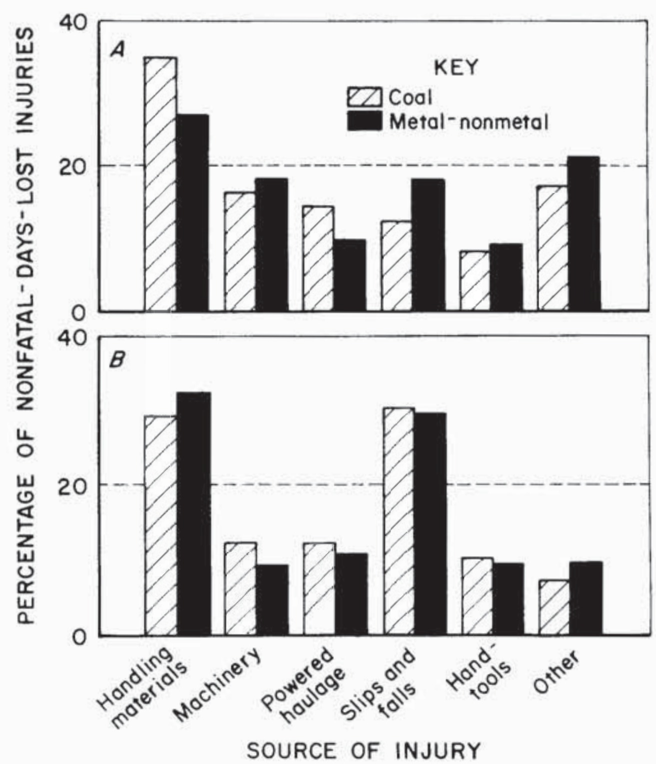


Figure 4-6.—Comparison of nonfatal-days-lost injuries from major accident catagories for the major segments of the underground (*A*) and surface (*B*) mining industry in 1983 (*29*). (Courtesy of U.S. Mine Safety and Health Administration)

It appears that much of the variance in injury statistics is due to the type of mine (underground or surface), and that underground mining is more hazardous than surface mining. Further, underground coal mines account for the majority of mining industry injuries. For this reason, statistics from underground coal mining will be concentrated on and data from other segments of the industry will be addressed only where appropriate.

Underground coal mines have been traditionally viewed as having high fatality rates. Compared with fatality rates of other industries, this is true. Compared with other types of underground mining, it may not be so. In 1983, for example, the fatality rate was higher in both metal and nonmetal underground mining than in underground coal mining. Figure 4-7 shows the fatality rate for underground coal mining from 1932 to 1983 (*18, 29-32*). As can be seen, the general trend has been one of declining fatality rates over the recent past.

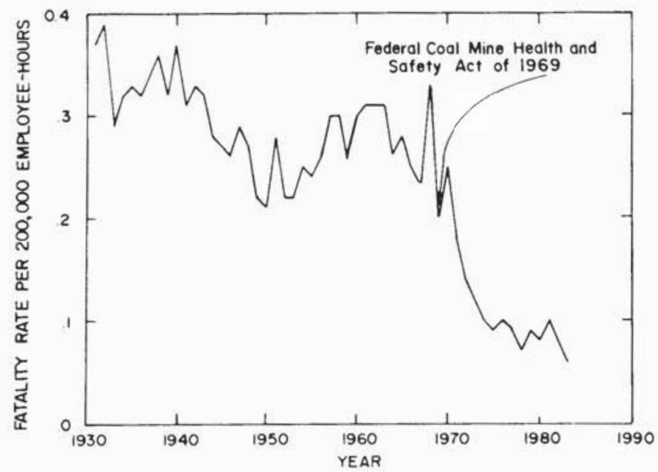


Figure 4-7.—Fatality rate per 200,000 employee-hours for U.S. underground coal mines from 1931 through 1983 (*18, 30-32*). (Courtesy of National Academy Press and U.S. Mine Safety and Health Administration)

Comparisons With European Countries

It is difficult to make meaningful comparisons of U.S. injury rates with those of European countries. For one thing, mining conditions and methods are different. U.S. mines are generally less deep than European mines; room-and-pillar method is predominant in the United States, while longwall is predominant in Europe; labor is distributed differently in European mines than in U.S. mines; and the social systems and market conditions are different. Another problem is that reporting differences exist among countries. A disabling injury in the United States, is an injury that results in 1 day of missed work. In some European countries, an injury is not classified as disabling until 3 days of work are missed.

The number of fatalities is the only measure, therefore, that is directly comparable among countries. Even comparing the number of fatalities, however, can be tricky because of the need to take exposure into account. Comparing the number of fatalities per 1,000 workers among countries assumes that there are the same number of hours per shift in different countries, which is not true (*16*). If one compares U.S. underground coal mine fatalities per 100 million labor hours with those of European countries, one finds that the United States has a poorer record. This is shown in figure 4-8*A*. It should be mentioned that the fatality rate in the United States has been dropping more rapidly than in European countries, and is now approaching the European levels.

What these statistics fail to present is the fact that U.S. mines are more productive than European mines. Therefore, when fatalities are computed per 100 million st of coal mined, the picture is radically different, as shown in figure 4-8*B*. Here, the U.S. record is better than that of most European countries, but more rapid improvements in productivity are occurring in European mines, so that the differences are becoming smaller.

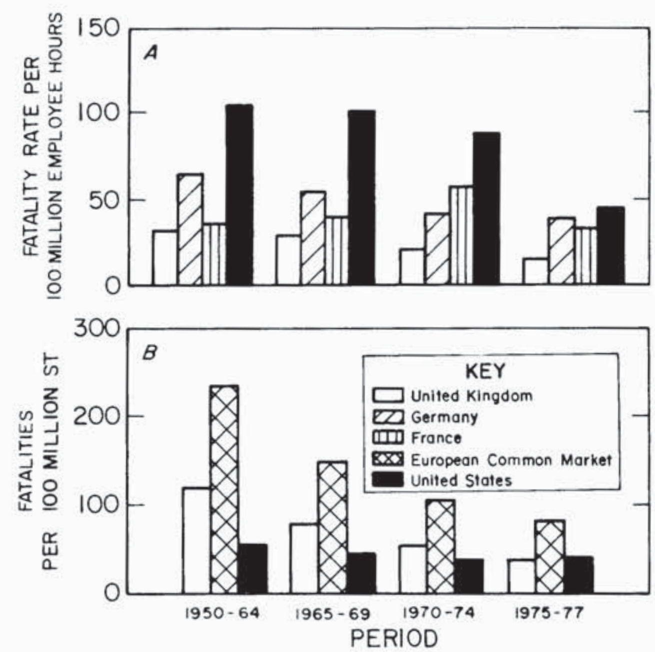


Figure 4-8.—Comparison of fatality data between U.S. and European underground coal mines (*18*). (Courtesy of National Academy Press)

COST OF ACCIDENTS

Determining the cost of accidents can be a complex and unending process. The problem is determining which cost factors to include in the calculations. One end of the spectrum could consider only the immediate medical compensation costs associated with various types of injuries. For example, medical expenses connected with underground coal mine injuries over an 18-month period for one large company were reported by Cain and Pettry (*4*). Table 4-3 shows the dollar amounts paid for various types of injuries. The 558 incidents cost this mining company approximately $217,950 or an average of $390.58 per incident in medical expenditures alone.

Anyone who thinks such figures represent the total cost of injuries is naive. The most comprehensive analysis of accident costs was carried out by FMC Corporation under a Bureau contract. A review of that effort was given by Chi

Table 4.3—1982-83 medical compensation costs paid per incident by a major coal company, by type of injury sustained (4)

	Incidents	Cost per— Incident	Type[1]
Abrasion	15	$178.25	$2,675
Bruise	154	219.47	33,800
Bruise and cut	35	90.89	3,180
Burn (minor)	15	61.22	920
Fracture:			
Simple	26	2,601.17	67,630
Compound	4	3,416.37	13,665
Irritation-inflammation	29	36.59	1,060
Laceration	46	135.95	6,255
Puncture	10	80.84	810
Sprain	32	299.25	9,575
Strain	168	406.18	68,240
Other	24	422.48	10,140
Total or average	558	390.58	217,950

[1] Rounded.

and DiCanio (5). The study and resulting predictive model considered the following cost factors:

1. Loss of personal income.
2. Compensation of wages from State, Federal, and union funds for disabling injuries.
3. Benefits for injuries resulting in death or permanent disablity.
4. Medical treatment and hospital care.
5. Immediate and postaccident production losses as a result of a fatality or amputation injury.
6. The costs incurred by the investigation of a fatal accident.

The cost elements excluded were loss of life, fines, costs of lawsuits, loss of equipment, production loss due to a permanent shutdown, immediate loss of production due to the disruptive effect of an injury serious enough to require medical attention, potential postaccident loss of production due to temporary replacement of an injured miner by a less experienced one, and cost of long-term followup treatment. The reason for these exclusions was simply that such costs are not readily available for analysis. Thus, the FMC model must be considered conservative at best.

Figure 4-9 presents the findings on the average cost of a fatality for the various segments of the mining industry, and figure 4-10 presents the average cost of a disabling injury. As can be seen, the average cost of injuries has been increasing faster than the inflation rate for the last several years. The average industry cost in 1981 for a fatality was $674,000 and the cost of a disabling injury was $177,000.

A significant portion of the costs incurred was due to postaccident declines in production. In the case of fatalities, all underground cases lost production from mine and section closures immediately following the accident. Further, in 73% of the cases, postaccident production level was significantly lower than preaccident production level for up to 5 months after normal operations resumed. Figure 4-11 shows a typical example of the effect of an accident on productivity. In the majority of cases, the largest decline in productivity was not in the section that had the accident. After underground fatalities, for example, production declines in a majority of the sections. This demonstrates that a fatal accident affects all crews in a mine.

The immediate and long-term production loss for cases involving fatal accidents in underground coal mining ranged from 0.5% to 9.4% of annual mine production, with a mean of 2.7%. At a price of $25.00 per short ton of coal,

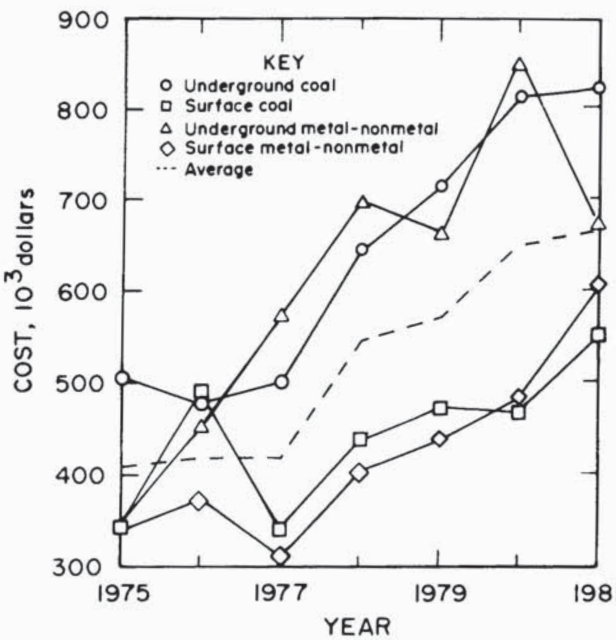


Figure 4-9.—Average cost of a fatality in the mining industry 1975-81 (5). (Courtesy of American Mining Congress)

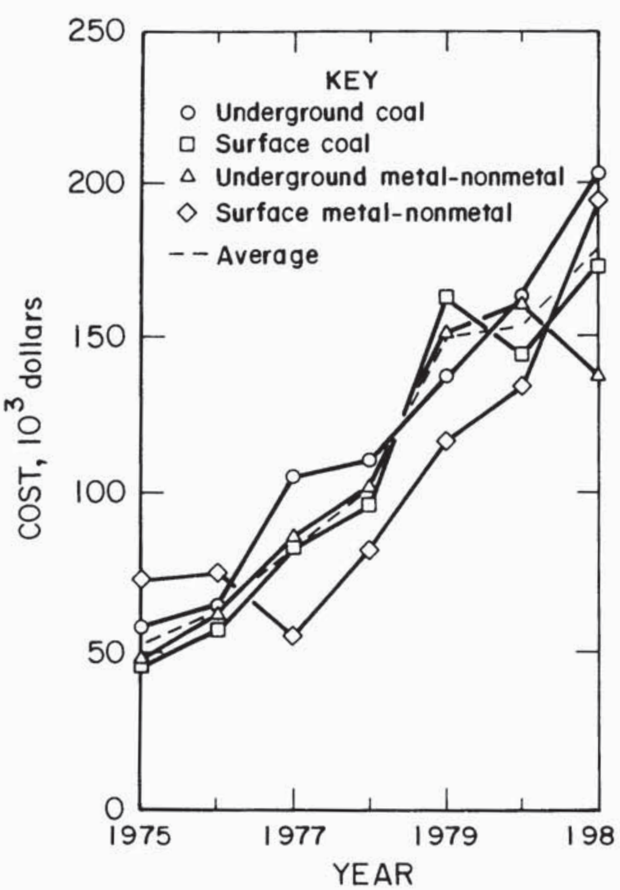


Figure 4-10.—Average cost of a disabling injury in the mining industry, 1975-81 (5). (Courtesy of American Mining Congress)

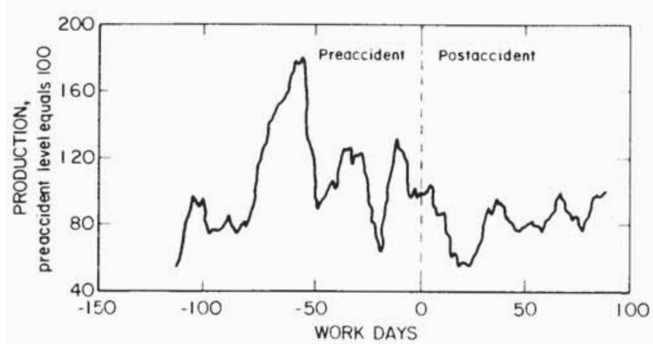


Figure 4-11.—Example of characteristic effect of a fatal injury on production in an underground mine, where the vertical axis represents production over preaccident levels and the preaccident level equals 100 (*5*). (Courtesy of American Mining Congress)

the average mine lost $450,000 in production value from a fatality. One case resulted in a loss of $2,000,000.

For fatal cases in underground metal mines, the production loss ranged from 0.5% to 4.0% of annual production, with a mean of 1.8%. There was no significant postaccident loss observed after fatalities in surface mines.

DISCUSSION

This chapter stressed the complexity of accidents and the role of human error in accidents. A total systems perspective was stressed in which human error itself could be caused by inadequate equipment designs, management policy, and the like. The need to dig deeper to uncover these root causes was emphasized. A review of the major classes of accident causation theories revealed no one really good theory that accounts for all the data. Although accidents appear to be decreasing in the mining industry, there will continue to be a level of accidents and injuries considered by many to be unacceptable. Unfortunately, there is still much not known about the causes of mining accidents, and there remains more questions than answers in the field.

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CHAPTER 5.—INFORMATION DISPLAYS

Information displays can be simple or complex.

Humans receive information from the environment, process it, and take actions based on their judgments about the information; thereby making information central to everything they do. Information is received by humans either directly or indirectly. Directly perceived information would be involved when a shovel operator looks out his or her cab window and sees the position of the shovel over a haulage truck, or when an underground coal miner hears the creaks and groans of the roof "working." Although a great deal of information is received directly, we must often rely on indirect sources of information because some stimuli are beyond human sensing limits or can be sensed better or more conveniently if converted to another type of representation. Examples of indirect information include a sign warning of dangers that might not be perceived, a temperature gauge on a piece of equipment indicating the temperature of a fluid that cannot be seen or touched, a map showing the overall layout of an underground mine that could not be directly seen without removing 800 ft of overburden and boarding an airplane, or a buzzer warning of a dangerous level of methane that cannot be sensed.

The concern in this chapter is with the choice and design of indirect sources of information, i.e., information displays. A display, therefore, is considered to be any technique or process for presenting indirect information. The information can be conveyed through the visual, auditory, olfactory, or tactual senses. Because most information displays are visual and auditory in nature, this chapter will concentrate on these types.

CHOOSING A DISPLAY

In evaluating various information displays for human use, several criteria are relevant.

1. Speed at which humans can receive and process the information presented.
2. Accuracy of interpretation.
3. Speed in learning to use the display.
4. Comfort.
5. Absence of fatigue from long-term use.
6. Performance level under degraded environments and stress.

The choice and design of information displays that maximize these criteria depend greatly on the type of task or tasks for which the information is required. People need information to perform the following seven generic tasks. Each task places unique demands on a display to present information in a manner that will facilitate its use.

1. *Quantitative reading.*—Must determine a specific numeric value, such as pressure, weight, or speed.
2. *Qualitative reading.*—Need only approximate a value, trend, rate of change, or direction of change. For example, an operator might only have to know that pressure is rising or holding constant, but not the specific pressure value.
3. *Check-reading.*—Compare one or more displays to a standard. For example, are the tensions on two lines equal?
4. *Setting an indicator.*—Set an indicator to a desired value. For example, setting a timer to 90 s.
5. *Tracking.*—Must follow or compensate for a continuously fluctuating stimulus. For example, maintaining a constant flow by opening and closing a valve in response to varying hydraulic pressures.
6. *Spatial orientations.*—Must determine location in physical space. For example, determining where one is in a mine and how to get back to the lift.
7. *Receiving instruction or warning.*—Must obtain information about how or why to do something. For example, a worker needs to know how many bags of rock dust to leave at each of five sites in a mine.

It is common for a display to serve multiple purposes. An operator may have to read a specific value from display (quantitative), but may also need to know if there has been a change, over time, in the value and in what direction the change has occurred (qualitative). The same display may also be used for check-reading when comparisons are made with other similar displays. Further, the operator may have to use the information on the display to set an indicator, if it is out of tolerance. Such multiple-use situations present interesting tradeoffs for a designer of displays. A display designed for check-reading, for example, may not be optimum for quantitative reading or vice versa.

A fundamental decision in display design is the choice of display mode, i.e., visual, auditory, olfactory, or tactual. Actually, in all but the most unusual circumstances, the choice is between the visual and auditory modes. In general, visual displays are more appropriate than auditory displays when the information has the following characteristics:

1. Long.
2. Complex.
3. Will be referred to later.
4. Deals with locations in space.
5. Does not call for immediate action.

Visual information can usually be read and reread, and can be read at the receiver's pace. Auditory information, once presented, is usually gone and is presented at a pace set by the sender rather than by the receiver.

Further, visual displays are more appropriate than auditory displays in the following situations:

1. Auditory system of a person is overburdened with too many auditory information sources.
2. The receiving location is too noisy.
3. The receiver remains in one position rather than moving about continually.

Auditory displays, on the other hand, are more appropriate than visual displays when the information has the following characteristics:

1. Simple.
2. Short.
3. Will not be referred to later.
4. Deals with events in time.
5. Calls for immediate action.

The best situations for auditory displays include the following:

1. The visual system of a receiver is overloaded with too many visual displays.
2. The receiving location is too bright or too dark for visual information to be seen.
3. The information needs to be received regardless of the position of the operator's head, i.e., you do not have to look at an auditory display.

As can be seen, auditory signals are especially appropriate for presenting warnings that are usually simple, short, and require immediate action.

VISUAL DISPLAYS

Estimates are that humans receive as much as 90% of the information originating outside their bodies through their visual senses. How this information is presented is extremely important (*7*).[1] Advances in technology, including remote sensing devices, video displays, and even wristwatch televisions, hold both promise and challenge for the designer and user of future systems. The mining industry is making advances in the utilization of advanced technology, but for the most part still depends on the tried and true, "medium" technology equipment and displays it has used for years. There are some good reasons for this hesitation by the industry to embrace high-technology equipment. For one thing, currently designed mining equipment is rugged, lasts a long time, and is expensive to replace. In addition, it is used in some of the most inhospitable environments, which can adversely affect the reliability of some high-technology equipment

The emphasis of this chapter, therefore, will be on the design of more traditional visual displays still being used and introduced in mining equipment.

[1] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

Quantitative Displays

Quantitative displays are intended to convey to a user the specific numerical value of some underlying variable being measured by a device. This variable can be changeable, e.g., speed, pressure, flow; or it can be essentially static and unchanging, such as a ruler used to measure length.

There are three basic types of quantitative displays: (1) fixed scale with moving pointer; (2) moving scale with fixed pointer; and (3) digital displays, also called counters. Examples of these are shown in figure 5-1. There are strong indications that a digital display is usually superior to an analog display (moving pointer or moving scale) if a precise numerical value is required and if the value presented remains visible long enough to be read (*12*). But, if an operator were required to report a precise pressure value during an emergency where pressure was dropping rapidly, a digital display would not be the choice. Given ample opportunity to read the numerals on a digital display, however, both speed and accuracy can be greatly improved upon that obtained with a moving pointer display, as shown by the following data from Zeff (*21*):

	Response time, s	*Errors*
Digital display	0.94	0.5%
Circular, fixed scale, moving pointer	3.54	6.5%

Fixed scale, moving pointer displays, however, are superior to digital displays for qualitative readings, such as when an operator needs to sense the direction or rate of change in a variable. In general, fixed scale, moving pointer displays are better than moving scale, fixed pointer displays; this is especially true when a control is used to set a value under the fixed pointer. The reason for this is that with a moving scale, fixed pointer, the scale has to

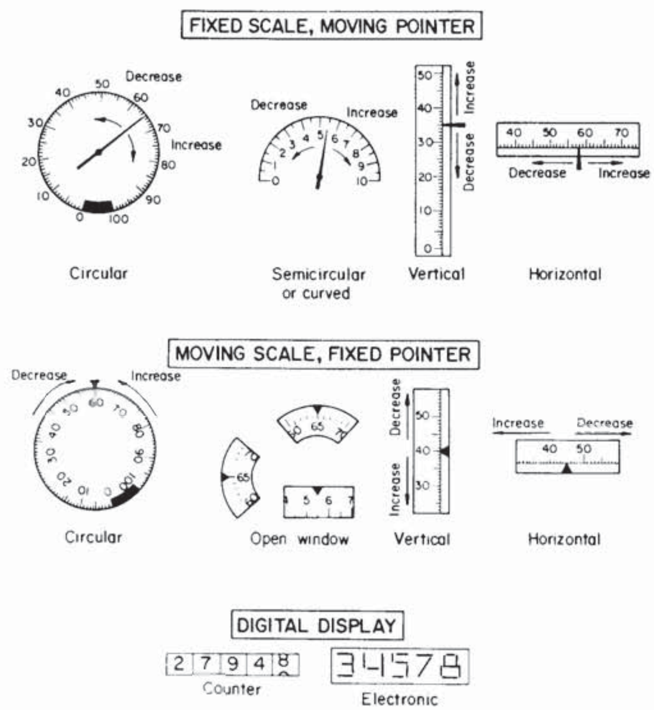

Figure 5-1.—Examples of quantitative displays (*12*). (Courtesy of McGraw-Hill)

move in a direction opposite to that in which the values are changing. Look at the moving scale, fixed pointer vertical display shown in the middle row of figure 5-1. To increase the value, the scale must move down, yet "down" is usually associated with decreasing values. The principal advantage of moving scale, fixed pointer displays can be seen in the open window displays in the middle row of figure 5-1. Such displays take up a minimum amount of panel surface area, yet can display a very large range of values. Often, the scale is moved around spools behind the panel face.

Design Features of Quantitative Displays

Figure 5-2 illustrates several important concepts in the design of quantitative displays:

1. *Scale range.*—The numerical difference between the highest and lowest value on a scale.
2. *Numbered value interval.*—The numerical difference between adjacent numbers on a scale.
3. *Graduation interval value.*—The numerical difference represented by adjacent graduation values.
4. *Scale unit value.*—The smallest unit to which the scale is to be read. This may or may not correspond to the graduation-interval value. The scale in figure 5-2 is to be read to the nearest pound; therefore, 1 lb would be the scale unit value.

The following design recommendations were gleaned from Bailey (*1*), McCormick and Sanders (*12*), and Oborne (*13*).

Scale Markers

It is generally considered a good design practice to provide scale markers for every scale unit value. Figure 5-3 illustrates the recommended dimensions for scale markers under both normal and low illumination conditions, assuming a viewing distance of 28 in. In some circumstances, placing a marker at each scale unit produces a cluttered scale with inadequate space between markers. In such cases it is usually better to require an operator to interpolate between markers. Interpolation to fifths yields satisfactory accuracy in many situations.

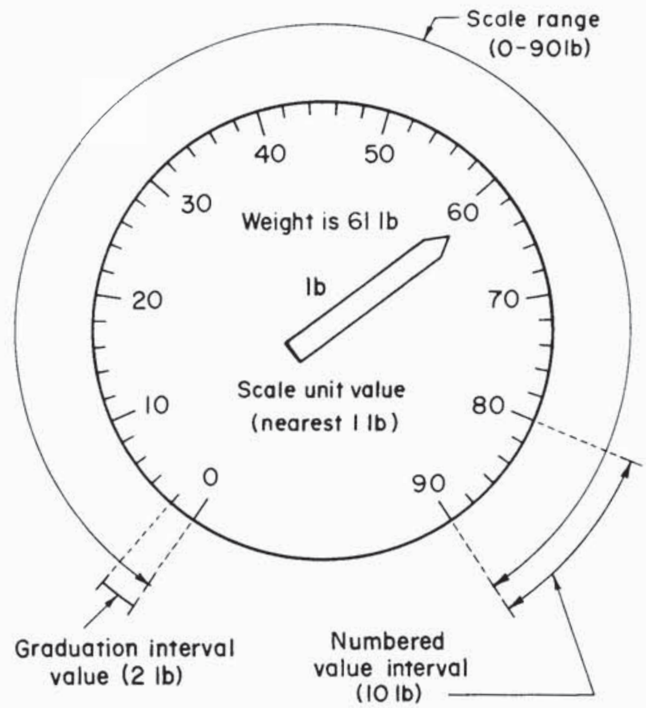

Figure 5-2.—Illustration of several numeric scale concepts.

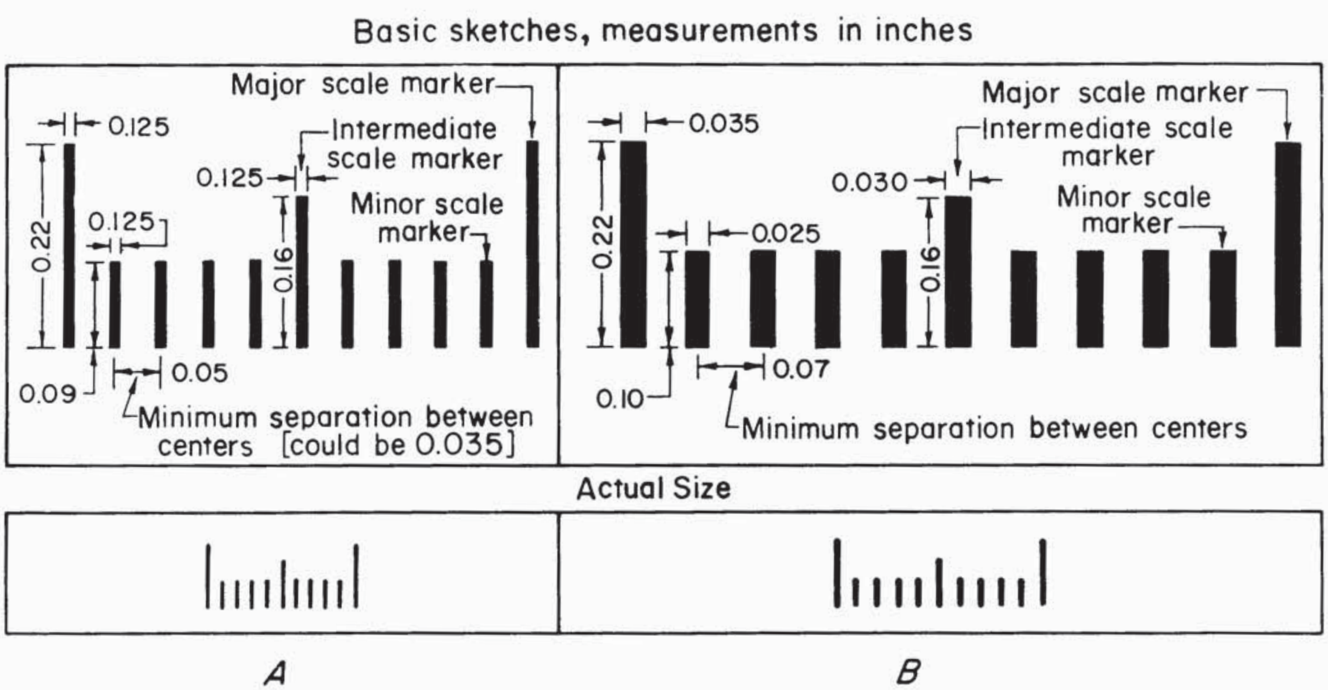

Figure 5-3.—Recommended format for quantitative scales under normal (*A*) and low (*B*) illumination conditions (adapted by McCormick (*12*) from reference 7). (Courtesy of McGraw-Hill)

If a normal viewing distance greater than 28 in is expected, the dimensions given in figure 5-3 must be increased to maintain the same visual angle to the observer. The following formula will correct the dimension of interest:

Dimension at X in. = (dimension at 28 in.) × (X/28).

Numerical Progression of Scales

The numbered intervals on a scale should be in ones, twos, or fives, and multiples of 10. For example, 10-20-30, 20-40-60, 50-100-150, or .5-1.0-1.5 would be acceptable. Progression by threes, fours, and sixes should be avoided. Decimals make scales more difficult to use; but if used, the zero before the decimal should be omitted.

Design of Pointers

There is general agreement that pointers should—

1. Have a tip angle of about 20°.
2. Meet, but not overlap, the smallest scale marker.
3. Be colored the same as the scale markings from the tip to the center, and be colored the same as the background from the center to the tail.
4. Be as close to the dial face as possible to minimize parallax.

Relative Importance of Design Features

The effects of the following seven factors on speed and accuracy of dial reading (fixed scale, moving pointer) were assessed by Whitehurst (*19*):

Numerical progression	By 8 or by 10.
Scale unit length	3.2 or 6.4 mm.
Pointer width	6.4 or 0.8 mm.
Marker width	0.8 or 1.6 mm.
Scale number location	Same side as pointer or opposite side.
Scale orientation	Vertical or horizontal.
Clutter	Added words or nothing added.

It was also found in this study that the two most important factors affecting reading speed and accuracy were numerical progression (by 10 was better than by 8) and scale unit length. (The more widely spaced arrangement was better than the narrowly spaced arrangement.) The other factors had little effect on performance.

Qualitative Displays

The task of a user in obtaining qualitative information from a display is to assess the appropriate value of some quantitative variable or to estimate its trend or rate of change. Often, the display that is best for obtaining a quantitative reading is not the best for obtaining a qualitative reading. For example, three displays for the speed of making both qualitative readings (pointer above 60, say "high;" pointer 40-60, say "OK;" and pointer below 40, say "low") and quantitative readings were compared by Elkin (*6*). The three displays compared were an open-window fixed pointer, moving scale; and two moving pointer, fixed scales, one circular and the other vertical. The results of this study are shown in table 5-1. The open-window display resulted in the fastest times for quantitative reading and the slowest times for qualitative reading.

Table 5-1.—Average times for qualitative and quantitative reading, with three types of scales (*6*), seconds

(Courtesy of U.S. Wright Air Development Center)

Type of scale	Qualitative	Quantitative
Fixed pointer, moving scale:		
Open window	115	102
Fixed scale, moving pointer:		
Circular	107	113
Vertical	101	118

If a quantitative scale can be divided into a limited number of zones or ranges, color coding or shape coding can be added to the dial to demarcate the regions, as shown in figure 5-4. Response time for three dial designs, two of which used coding techniques to represent danger zones, were compared by Kurke (*11*). The task was to respond when the pointer was in a danger zone. Figure 5-5 shows the designs and the relative response times using the uncoded display as the base (100%). As can be seen, a substantial decrease in response time is realized by the addition of simple color coding, and an even more dramatic decrease is effected by using the more complex wedge design.

Check-reading an array of dials to determine if all conditions are normal is really just a special class of qualitative information seeking. Several persons have investigated arrangements of dials to facilitate such check-reading activities, such as the study by Dashevsky (*4*). The general wisdom is that such dials should be arranged in neat rows and columns, with the normal positions of the pointers all aligned in the 9 o'clock or 12 o'clock position (*4*). This arrangement yields more accurate detection of deviant dials than if the normal positions are not consistent. It was found by Elkin (*6*), for example, that people made 350% more errors when the dials were subgrouped as shown in figure 5-6 than when all the normal pointer positions were at 12 o'clock.

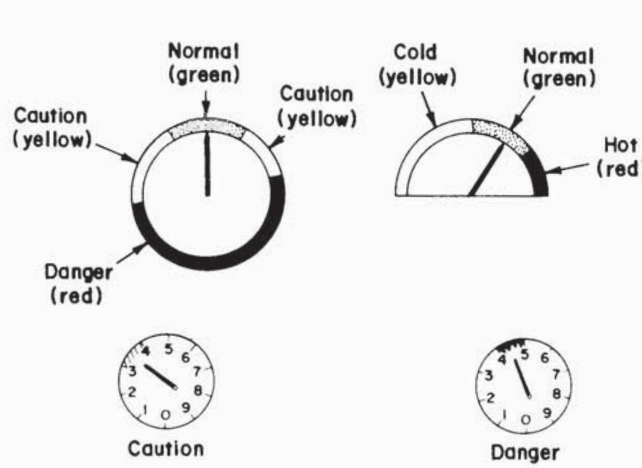

Figure 5-4.—Illustrations of coding methods for marking zones of instruments that are to be read qualitatively (*12*). (Courtesy of McGraw-Hill)

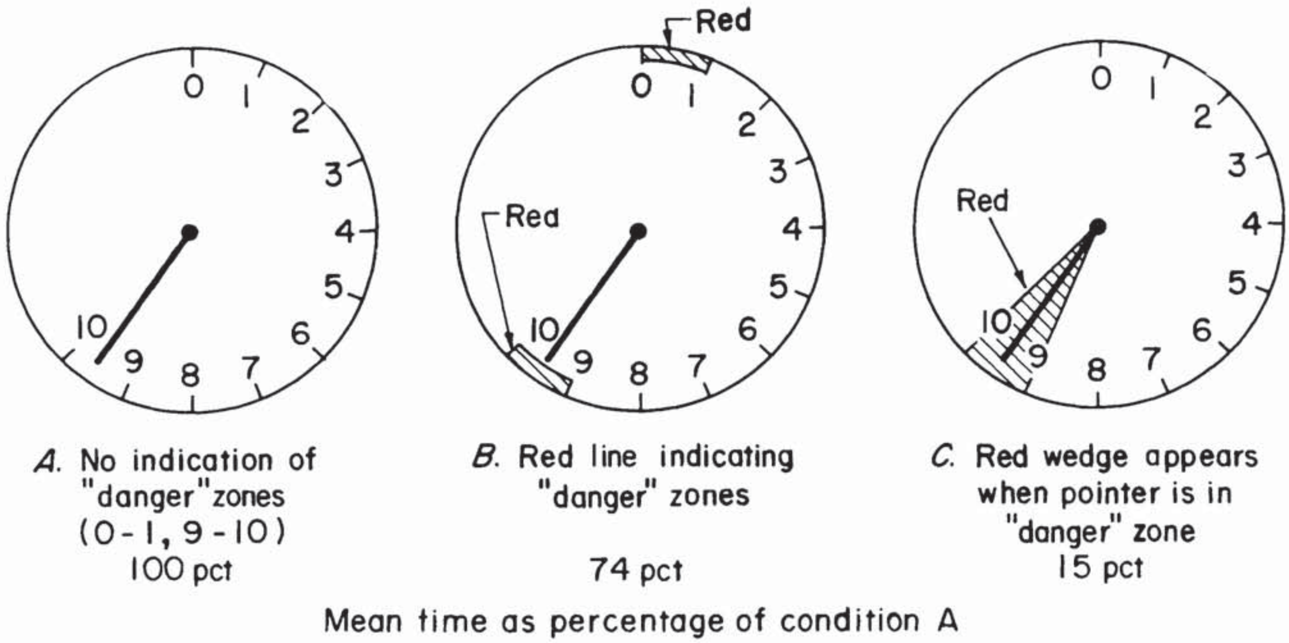

Figure 5-5.—Mean response time for detecting pointer in danger zone for three dial displays, where the mean response time is shown as a percentage of dial design. (Adapted by McCormick and Sanders (*12*) from reference 11, courtesy of McGraw-Hill)

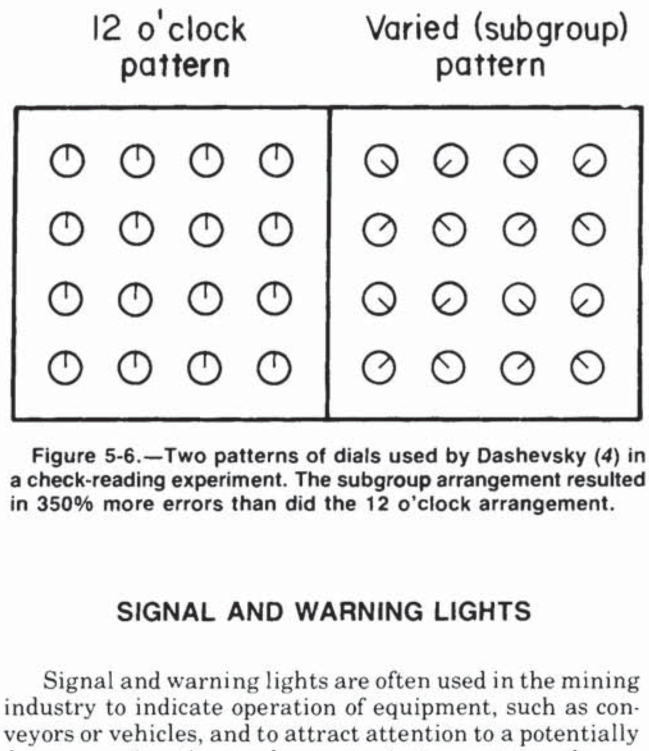

Figure 5-6.—Two patterns of dials used by Dashevsky (*4*) in a check-reading experiment. The subgroup arrangement resulted in 350% more errors than did the 12 o'clock arrangement.

SIGNAL AND WARNING LIGHTS

Signal and warning lights are often used in the mining industry to indicate operation of equipment, such as conveyors or vehicles, and to attract attention to a potentially dangerous situation, such as on an instrument panel or on a barricade around a newly dug hole. Unfortunately, there is little research relating to such signals, but some general conclusions can still be made.

The detectability of a light depends on its size, luminance (i.e., brightness), contrast with its background, and time available to detect it. A number of recommendations were offered by Heglin (*8*) regarding the use of signal and warning lights on instruments panels.

When should they be used.—To warn of actually or potentially dangerous conditions.

How many warning lights.—Ordinarily only one. (If several warning lights are required, use a master warning or caution light and a word panel to indicate the specific danger condition.)

Steady-state or flashing.—Because they are distracting, flashing lights should be reserved for emergencies.

Flash durations.—If flashing lights are used, flash rates should be from 3 to 10 per second (4 is best), with equal intervals of light and dark.

Warning-light intensity.—The light should be at least twice as bright as its immediate background.

Light size.—The warning light should ordinarily be 1.5 times the size of other indicators on a console. Master warning or extreme emergency light should be twice the size of other console indicators.

Location.—The warning light should be within 30° of the operator's normal line of sight.

Color.—Warning lights are normally red because red means danger to most people. (Other signal lights in the area should be other colors.)

An extension of the idea of using lights to warn is using retroreflective material to draw attention to a potential danger. Retroreflective material (or paint) contains minute glass spheres that return light directly back to the light source. The amount of light that is reflected to the eye, however, becomes less as the angle from the eyes to the object and from the object to the light source increases. A particularly good application of retroreflective material is to make underground miners more visible to equipment operators. The effect of various configurations of retroreflective material on detectability was tested by Beith, Sanders, and Peay (*2*). A one-fifth scale simulator was used in the study Dolls with miniature functioning caplamps and retroreflective material on their helmets served as miners to be detected at various viewing angles in various body postures.

At the most severe viewing angle (i.e., 45° from the line of sight), probability of detection almost doubled when retroreflective armbands and/or belts were added to the dolls.

SIGNS AND LABELS

Warning and information signs and labels are common in the mining industry and some are even mandated by the Code of Federal Regulations. Usually, signs convey important safety information or warn of potential hazards and dangers. It is important, therefore, that signs and labels be designed and displayed to maximize their effectiveness. Three attributes that are important in evaluating the effectiveness of signs and labels are visibility, legibility, and comprehension.

First, a sign or label must be seen and distinguished from its surroundings (visibility). The size, color, and placement of a sign or label are important determinants of visibility. Once a sign or label has attracted the attention of the viewer and has been seen, its alphanumeric or symbol characters must be easy to read or identify (legibility). This depends on such features as the size and form of the characters, and the contrast and illumination of the sign or label. Finally, the message presented must be understood by the viewer (comprehension). As will be seen. this can pose a real problem with pictorial-symbol signs.

Typography

Two important characteristics of alphanumeric characters depicted in figure 5-7 are stroke width to height ratio and width to height ratio. Various stroke width to height ratios are illustrated in figure 5-8 for black letters on a white background and for white letters on a black background. Under good viewing conditions (normal illumination, no time constraint), most people can adequately discriminate alphanumeric characters over a wide range of stroke width to height ratios. Under adverse conditions, however, this variable becomes more important. The optimum ratio is smaller (i.e., thinner letters), for white characters on a black background (1:8–1:10) than for black characters on a white background (1:6–1:8). This is due to a phenomenon called irradiation in which white features appear to spread into adjacent black areas.

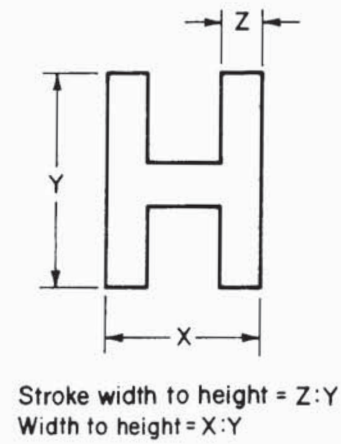

Figure 5-7.—Definition of stroke width to height and width to height ratios for alphanumeric characters.

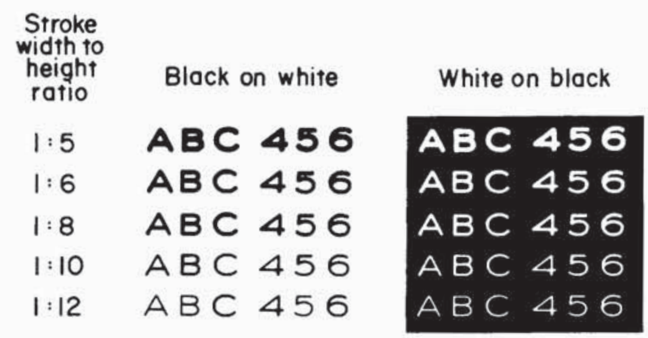

Figure 5-8.—Illustrations of stroke width to height ratios of letters and numerals (*12*). (Courtesy of McGraw-Hill)

Experimental evidence suggests that for capital letters, a width to height ratio of about 1:1 is optimum, but that it can be reduced to about 3:5 without serious loss in legibility. In general, alphanumeric characters that have uniform stroke widths and strokes that do not have serifs (flourishes and embellishments) are more legible than fancy nontraditional styles.

An important variable affecting legibility of a sign or label is the size of the characters or symbols used in relation to the anticipated viewing distance. To be equally legible, a sign or label must be made larger if it is moved farther from the viewer. A simple formula for determining the height of letters, given the viewing distance, importance of the sign or label, and illumination and reading conditions was developed by Peters and Adams (*14*). The formula, however, should probably not be applied to viewing distances beyond 60 in, because the correction for importance and reading condition may be inadequate. The formula is as follows:

$$H = 0.0022D + K_1 + K_2,$$

where H = height of letter, in,
D = viewing distance, in,
K_1 = correction factor for illumination and viewing condition;
0.06 (above 1.0 fc, favorable reading condition),
0.16 (above 1.0 fc, unfavorable reading condition),
0.16 (below 1.0 fc, favorable reading conition), and
0.26 (below 1.0 fc, unfavorable reading condition),
and K_2 = correction factor for importance;
0.075 for emergency and warning signs,
0.000 for all other signs.

Table 5-2 uses this formula to compute letter heights for various representative viewing distances from 14 to 60 in. For viewing distances beyond 60 in, under varying illumination conditions, letters on emergency signs should subtend approximately 30′ of visual angle. Table 5-3 summarizes the recommendations.

Table 5-2.—Recommended letter heights for labels and signs for various distance conditions,[1] inches

Distance ..... in..	14	28	48	60
Unimportant, K_2 <0.0:				
K_1 <0.06	0.09	0.12	0.17	0.19
K_1 <0.16	.19	.22	.27	.29
K_1 <0.26	.29	.32	.37	.39
Important, K_2 <0.075:				
K_1 <0.06	.17	.20	.24	.27
K_1 <0.16	.27	.30	.34	.37
K_1 <0.26	.37	.40	.44	.47

[1] Based on formula by Peters (*14*).

Table 5-3.—Recommended heights of letters on emergency signs

Viewing distance, ft	*Letter height, in*
10	1.04
20	2.08
40	4.16
100	10.44

Pictorial Signs and Labels

Although written signs and labels are probably the most commonly used method of providing safety and hazard information, pictorial or symbolic signs are becoming more and more common in industry. The following advantages of pictorial signs over written signs were cited by Collins (*3*). They provide essential information—

1. More rapidly,
2. More accurately,
3. At a greater distance,
4. In less space,
5. Without being language specific, and
6. Without the need to read written language.

All these advantages, however, do not come free. The development of pictorial signs that will be understood by a viewing population is a difficult task. For example, 72 symbols to depict 40 different hazard and safety messages appropriate to the mining industry were developed. The comprehension of these symbols was tested among a diverse group of 271 underground and surface mine employees (*3*). Only 44% of the symbols were comprehended correctly by more than 90% of the people. More than 25% of the symbols were correctly comprehended by less than 75% of the people. Similar difficulties and results were obtained by Woo (*20*) in his evaluation of pictorial hazard signs on surface mobile mining equipment. Figure 5-9 shows a few examples of pictorial signs that were not readily understood by the mining population tested by Collins (*3*). In some instances, workers interpreted the sign to mean the opposite

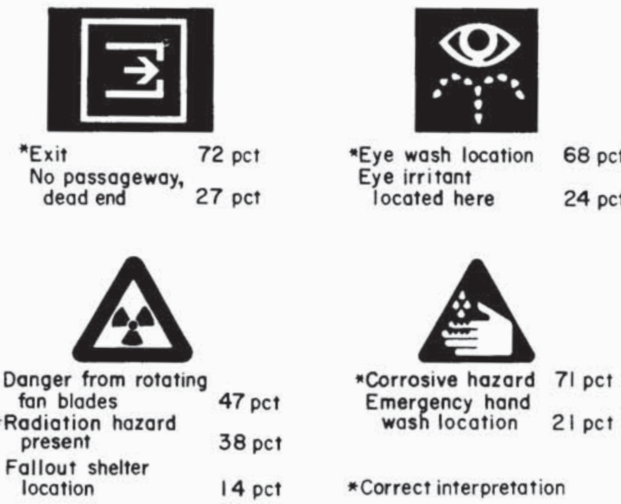

Figure 5-9.—Examples of pictorial signs that caused confusion among mining industry employees. Most frequent interpretations are given below each figure with the percentage of subjects choosing each response given (*3*).

of what it was intended to mean. Appendix C presents the pictorial warning signs recommended by Collins (*3*) for use in the mining industry, based on her tests of underground and surface mine employees.

AUDITORY DISPLAYS

As pointed out at the beginning of this chapter, the auditory channel is especially effective for presenting warning information. Such information is usually short, requires immediate action, and must be received by people even if they move about from one location to another.

To be effective, auditory information must be detected by a listener. That is, an auditory signal must be heard above any background noises in an environment. If there is more than one auditory signal that must be responded to, then a listener must discriminate between them. In some cases, a listener must specifically identify a signal, such as identifying a sound as a sticky intake valve or a loose fan blade.

In addition to discussing auditory alarms, the topic of speech communication is also addressed as a form of auditory display.

Alarms

There are numerous types of auditory alarms available today; table 5-4 lists some characteristics of various generic types. To insure that an alarm will be heard above an ambient noise environment, the intensity of the alarm must be higher than the intensity of the noise.

A procedure and rule of thumb for specifying the optimum intensity for a signal or an alarm was suggested by Deatherage (*5*). First, adjust the intensity of the signal until it is just barely detectable in the noise environment at

Table 5-4.—Characteristics and features of certain types of audio alarms (*5*)

(Copyright 1972 by John Wiley and Sons, and reprinted by permission.)

Alarm	Intensity	Frequency	Attention getting ability	Noise-penetration ability
Diaphone (foghorn)	Very high	Very low	Good	Poor in low-frequency noise.
Horn	High	Low to high	do	Good.
Whistle	do	do	Good, if intermittent	Good, if frequency is properly chosen.
	do	do		
Siren	do	do	Very good if pitch rises and falls.	Very good with rising and falling frequency.
Bell	Medium	Medium to high	Good	Good in low-frequency noise.
Buzzer	Low to medium	Low to medium	do	Fair if spectrum is suited to background noise.
Chimes and gong	do	do	Fair	Do.
Oscillator	Low to high	Medium to high	Good, if intermittent	Good if frequency is properly chosen.

normal operator work positions. Turn the noise off and measure the intensity of the signal at the entrance to the ear (called the masked threshold). Repeat this with several people and average the results. The rule of thumb is to set the intensity of the signal midway between the masked threshold and 110 dB. Thus, if a signal could just barely be heard in noise at 50 db, then one would be confident of its detection in noise if it were set at 80 dB.

In addition to setting the intensity of a signal above the background noise level, the frequency of the signal can be selected to maximize its detectability. The idea is to select a signal frequency that corresponds to the lowest intensity frequency region of the background noise. Also, where possible, it is best to select a signal frequency below the dominant frequency of the background noise; this is because loud noise of a given frequency tends to mask signals higher than its frequency more than it masks signals lower than its frequency.

Under some conditions, especially those involving very high intensity noise, the use of hearing protectors can increase the detectability of a signal. This occurs because the hearing protection brings the noise and signal intensity down so that the signal can be more easily detected.

McCormick and Sanders (*12*) provided the following list of general design recommendations for auditory warning and alarm signals which were gleaned from various sources:

Use frequencies between 200 and 5,000 Hz, and preferably between 500 and 3,000 Hz, because the ear is most sensitive to this middle range.

Use frequencies below 1,000 Hz when signals have to travel long distances (over 1,000 ft), because high frequencies do not travel as far.

Use frequencies below 500 Hz when signals have to "bend around" major obstacles or pass through partitions.

Use a modulated signal (1 to 8 beeps per second or warbling sounds varying from 1 to 3 times per second), because it is different enough from normal sounds to demand attention.

Use signals with frequencies different from those that dominate any background noise to minimize masking.

If different warning signals are used to represent different conditions requiring different responses, each should be discernible from the others, and moderate intensity signals should be used.

Where feasible, use a separate communication system for warnings, such as loudspeakers, horns, or other devices, not used for other purposes.

It should be pointed out that some of these recommendations can create conflicting situations. For example, because mining noise tends to be of low frequency, it would be best to use a high-frequency signal, despite the fact that high frequencies do not carry as far as low-frequency sounds.

Speech

Speech is the most common method for transmitting information between humans. With the development of reliable, inexpensive speech synthesis and recognition systems, it may also become a common method for transmitting information between humans and machines. Speech is one of the most complex, yet suitable forms of communication. Although there are only about 40 speech sounds in the English language, these can be put together to convey the most complex of messages.

Intensity of Speech

Different speech sounds have different levels of speech power (intensity). In general, the vowel sounds contain more speech power than do the consonant sounds. The *a* as pronounced in *talk* has approximately 680 times the speech power of *th* as pronounced in *then*. Unfortunately, the less powerful consonant sounds are the most important for understanding speech.

The overall intensity of speech, of course, varies from person to person. The following, however, are representative intensities averaged over large samples of speakers:

Talking as softly as possible .... 46 dBA
Lecture or telephone conversation........ 66 dBA
Talking as loudly as possible .... 86 dBA

Intelligibility of Speech

Intelligibility is the extent to which a spoken message is understood by a listener. How much of a message is understood depends, among other things, on the nature of the message and the expectation of the listener. The English language is very redundant; one does not have to hear every syllable to understand a word, nor every word to understand a sentence. Further, if a listener has some idea about what a message will pertain to, the probability of understanding the message increases.

In the mining industry, speech communication often takes place in noisy environments, such as processing plants, or near large mining machines. Intelligibility under such conditions is of critical importance for maintaining productivity and safety. One way to increase intelligibility, especially in the presence of noise, is to limit the size of the vocabulary and make a list of words known to both the listener and speaker. Rather than use them interchangeably, one of several words to mean the same thing, agree on one term and use it consistently. For example, the words "increase," "raise," "up," "advance," "augment," and "intensify" can all mean the same thing. Rather than use them interchangeably, one word should be selected and used consistently. When selecting standard vocabulary words, consider potential confusion between words. For example, rather than using "increase" and "decrease," it would be better to use "raise" and "lower" because they are less likely to be confused in a noisy environment.

In general, complete sentences have higher levels of intelligibility than do single words, and long words are more intelligible than short words. Words commonly used every day are more intelligible than uncommon words. A classic example of increasing the length of a word to increase its intelligibility is the use of the International Word-Spelling Alphabet. Rather than telling a mechanic to get part number ABE-136, one would say "Alpha-Bravo-Echo-one-three-six." In a noisy environment, ABE is easily confused with APE.

Preferred Octave Speech Interference Level (PSIL)

This index, reported by Peterson and Gross (*15*), gives a rough evaluation of the effect a noisy environment has on the transmission of speech. It is relatively easy to assess and compute if the right equipment is available. A sound pressure meter is needed that can measure intensity (sound pressure in decibels) in three octave bands centered at 500, 1,000, and 2,000 Hz. The PSIL is simply the average of the decibel levels of the noise in the three octave bands. This technique is appropriate where the noise is relatively continuous and its spectrum (intensity at various frequencies) is relatively flat. Given the PSIL, table 5-5 can be used to determine the maximum distance that two people can be apart and converse in a normal voice, raised voice, very loud voice, or shouting voice. These limits represent distances where 98% of the speech would be heard. Thus, in a processing plant where the PSIL was 80 dB, two people could converse in a raised voice at 0.5 ft apart, in a very loud voice at 1 ft, in a shouting voice at 2 ft, and with maximum vocal effort at 16 ft.

Table 5-5.—Maximum distance between speaker and listener to carry on a satisfactory conversation in various intensity voices under ambient noise conditions defined by the preferred octave speech interference level (PSIL) (*18*), feet

(Courtesy of National Academy Press)

PSIL, dB	Normal	Raised	Very loud	Shout	Max vocal effort
40	32	>32	>32	>32	>32
45	16	32	>32	>32	>32
50	8	17	>32	>32	>32
55	5	10	23	>32	>32
60	3	6	12	24	>32
65	1.75	3	7	13	>32
70	.75	2	3.5	7	>32
75	.5	1	2	4	30
80	NAp	.5	1	2	16
85	NAp	NAp	.6	1.25	8
90	NAp	NAp	NAp	.75	5
95	NAp	NAp	NAp	NAp	3
100	NAp	NAp	NAp	NAp	1.5
105	NAp	NAp	NAp	NAp	1
110	NAp	NAp	NAp	NAp	.5
120	NAp	NAp	NAp	NAp	NAp

NAP Not applicable.

Hearing Protection and Speech

It was found by Howell and Martin (*9*) that hearing protection did not degrade speech intelligibility for a listener. This was confirmed in high-noise environments (90 dBA), but a decrease in intelligibility in low-noise (70 dBA) environments was found (*17*). Reference 9, however, found that if those talking wore hearing protection, their speech was reduced in both intensity and quality, and intelligibility actually decreased for the listener. The lesson here is that, in noisy situations where people wear hearing protection, extra effort must be made to speak loudly and clearly. People will think they are speaking more loudly than they really are, and therefore must be made aware of this to compensate for their misperceptions.

Underground Loudspeaker System: A Case Study

Results of adding a loudspeaker telephone system to an underground longwall coal face in the Netherlands were reported by Koene and Ruwette (*10*). The particular face was approximately 790 ft in length with a working height of approximately 3 ft. The face was equipped with the following communication systems prior to installation of the loudspeaker phones:

1. Dial telephones at the ends of the face.
2. Telephone sets at a number of points on the actual coal face. (Face lights were flashed to signal a call, but there was no way to determine which telephone should be answered or who was being called.)
3. Elaborate signaling by flashing the face lights.
4. Messages transmitted verbally from person to person.

The loudspeaker telephones were installed every 60 to 70 ft. Each set incorporated two loudspeakers and a microphone. Pressing of the microphone switch enabled transmission of a message through all the loudspeakers on the coal face. A whistle signal could also be transmitted.

Problems During Introduction of the System

Koene and Ruwette (*10*) also indicated the following social-psychological communications problems caused after the system was installed:

1. Personnel were initially timid about using the system.
2. Because of the public nature of the communications, greater control of language, criticism, and negative remarks was required.
3. Supervisory staff had a tendency to intervene when a lower ranking supervisor gave an instruction, thereby undermining his or her authority.
4. There was a temptation to transmit messages encouraging workers to work harder. This reduced the credibility of the system.
5. The system was used like a regular telephone; the person to whom the message was addressed was required to reply.
6. Supervisors sought more information than was needed to conduct proper operations.

These investigators indicate that, with proper instruction, these initial problems were reduced or eliminated.

Results of Installation

With the loudspeaker system, one supervisor did the work of the two required before the system was installed. This was accomplished without increasing the distance traveled by the supervisor to perform the job. The major finding was that after installation, the duration of stoppages per shift decreased from 160 to 128 min, a reduction of 20%. Compared with all coal faces in the mine, the test site had a lower percentage of utilization rate before installation (i.e., percentage of time coal was being extracted). After installation, the percentage of utilization was higher than the overall mine average. There was clear evidence that the system reduced the duration of stoppages by supplying necessary information to everyone along the coal face. Better coordination of material transport and repositioning of props reduced the number and duration of such stoppages. Response times to emergencies were significantly reduced, and the responses were more coordinated.

OLFACTORY DISPLAYS

Although olfactory displays are not very common, there are applications where their use can be beneficial. In facilities served by natural gas, for example, an odorant is added to the naturally odorless gas to aid in the detection of leaks. Another example of an olfactory display is the use of stench systems in underground noncoal mines to warn of a fire or other emergency. Miners, upon smelling the stench, evacuate the mine according to a prearranged plan.

Stench systems have been used for 60 yr in underground mines. The odorant most commonly used, ethyl mercaptan, however, is highly toxic and sometimes causes nausea among the miners. In 1980, the Bureau embarked on a program to develop an improved stench system *(16)*. The chemical tetrahyprothiophane (THT) was selected as the odorant; it is widely used in Europe as a natural gas odorant and is not as toxic as ethyl mercaptan. In a field test of the new system, which included a new method for dispersing the odorant, average penetration time (time from release to detection at various locations within the mine) was 10.5 min compared to 19.6 min using the old system, a reduction of 46%.

DISCUSSION

Information is critical for safe, productive work; it is necessary for guidance of decisionmaking and actions. Many sources of information are not readily available so indirect sources of information are relied on—information displays. This chapter has reviewed some human factors considerations in the design of medium-technology visual and auditory displays, signal lights and signs, and has illustrated that speed and accuracy are affected by how these information sources are designed.

Although high-technology computer displays were not dealt with, as their use in mining is still relatively small, many of the same principles of design apply. Concern with detectability, legibility, and comprehension still remain. With many computer displays, information overload often is an additional problem. Operators are presented with a screen full of numbers and are expected to analyze and interpret the meaning of the information presented. Much can be done to improve such displays, including presenting only the information the operator really needs to do the tasks, use of color coding, and proper layout of information on the screen. The human factors literature has really only scratched the surface with regard to formatting computer-displayed information. It is anticipated that in the future more guidance on proper designs will be available. Until then, as with other medium-technology displays, existing human factors can be applied, keeping in mind the information needs of the operator, supplying neither less nor more than is required, and trying to do so in a manner that requires the least amount of mental processing.

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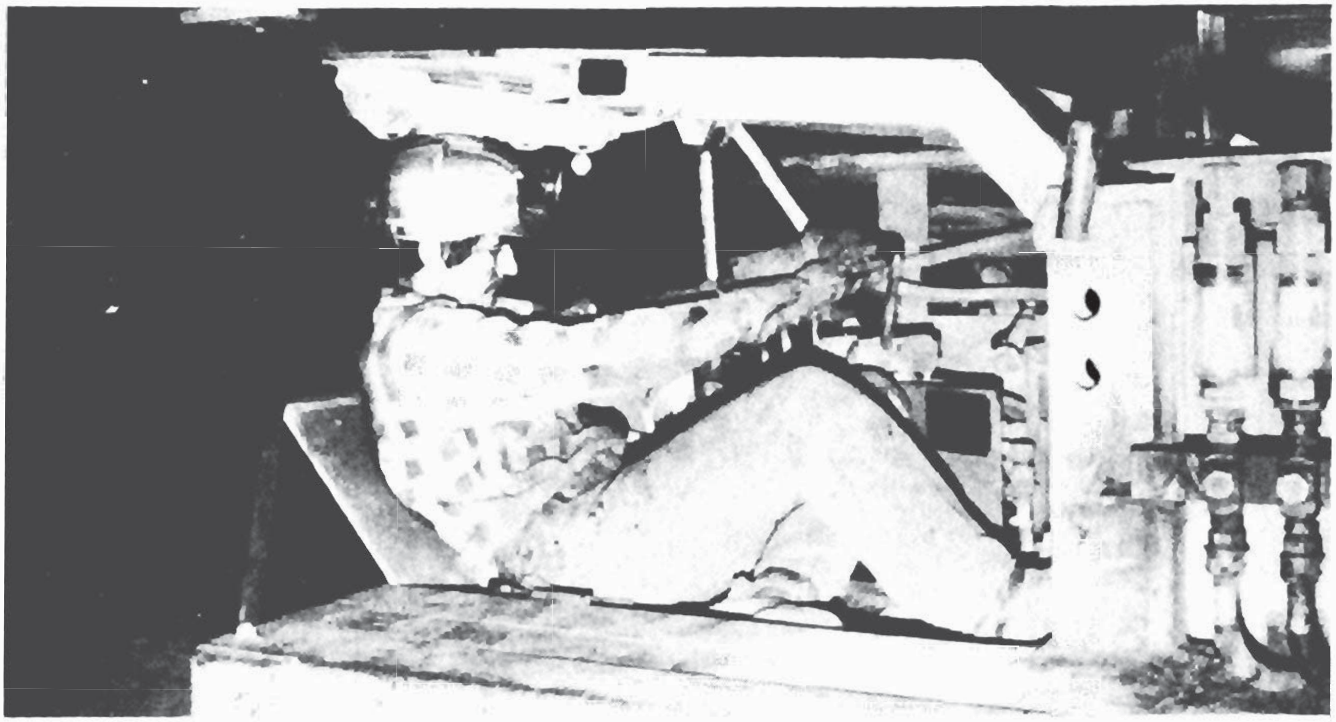
CHAPTER 6.—DESIGN OF CONTROLS, EQUIPMENT, AND TOOLS



Because of the unique operating requirements and environments of mining equipment, special attention must be given to human factors considerations, whether in the design of operating controls, tools and access for maintenance, or the equipment itself.

In this chapter a broad overview of major human factors considerations and issues in the design of controls, equipment, and tools will be presented. The benefits to be gained by incorporating human factors into the design of equipment, include increased safety, higher productivity, and worker satisfaction and comfort. Special attention will be given to the problems of seating on low-seam underground equipment, restricted field of vision in underground and surface equipment, egress and ingress in surface equipment, and designing for ease of maintenance in all types of mining equipment.

CONTROLS

Controls are the means by which humans communicate with equipment, and the proper design of controls helps ensure safe, productive operation of that equipment. The Mining Equipment Safety Laboratory of the Mine Safety and Health Administration (MSHA) analyzed all fatal accident reports involving underground coal mine mobile and electrical face equipment for the years 1972 through 1979 (*17*).[1] A total of 350 fatalities were investigated. Twenty-five fatalities (an average of three per year) were attributed to improper control design. Unknown is the number of nonfatal injuries caused, in whole or in part, by improper control design. It must be assumed, however, that it is higher than the number of fatalities.

[1] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

Types of Controls

There is a wide variety of control devices available, with certain types best suited for particular applications. Common control types were classified by McCormick and Sanders (*20*) as to the type of information they can most effectively transmit (discrete vs continuous) and the amount of force normally required to manipulate them (large vs small). Discrete information is information that can only represent one of a limited number of conditions, such as on-off; high-medium-low; crusher 1, crusher 2, crusher 3; or alphanumerics, such as A, B, and C; 1, 2, and 3. Continuous information, on the other hand, can assume any value on a continuum, such as speed (as 0 to 60 mph); pressure (as 1 to 100 psi); or direction of motion. Table 6-1 lists the common types of controls classified by this scheme. Figure 6-1 illustrates some of the more common of these controls.

It is important that the type of control used be suited to the type of information an operator wishes to communicate to the equipment. For example, speed is generally thought of as a continuous variable. Going slow or fast is thought of as slowing down or speeding up; yet many pieces of underground electrical equipment permit an operator to

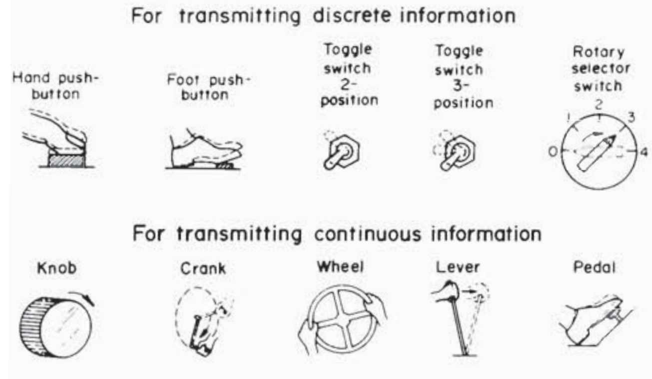


Figure 6-1.—Common types of controls classified by type of information they transmit most effectively (*20*). (Courtesy of McGraw-Hill)

Table 6-1.—Common types of controls, by type of information transmitted and force required to manipulate (*20*)

Information transmitted	*Manipulation force required*
Discrete:	
Pushbuttons, including keyboards	Small.
Toggle switches	Do.
Rotary selector switches	Do.
Detent thumb wheels	Do.
Detent levers	Large.
Large hand pushbuttons	Do.
Continuous:	
Rotary knobs	Small.
Multirotational knobs	Do.
Thumbwheels	Do.
Levers or joysticks	Do.
Small cranks	Do.
Handwheels	Large.
Foot pedals	Do.
Large levers	Do.
Large cranks	Do.

control speed only as a discrete variable: on-off. Slow speed is achieved by repeatedly activating the tram controls to inch the machine forward.

Factors in Control Design

Although controls differ in design, there are certain factors that apply to all types of controls and influence the overall performance of an operator. Well-designed controls that match the task requirements, and the capabilities and limitations of an operator are easier to learn to operate, are operated faster and more accurately, and result in fewer errors and better operator acceptance. The major factors that should be considered in the design or selection of controls are identification, control-response ratio, resistance, deadspace, and backlash. Spacing and general positioning of controls are discussed in another section of this chapter

Identification of Controls

The ability to quickly and accurately identify the proper control can often mean the difference between life and death, especially in the mining environment where massive pieces of equipment are set in motion with the flick of a lever. An operator, while reaching for a boom-sump control on a roof bolter machine, could accidentally activate the boom swing and crush a person against a mine rib. Identification of the proper control is really a problem of control coding, and the basic methods of control coding are shape, texture, size, location, color, and labels.

The choice of a coding technique and the specific coding values depend on the speed and accuracy requirements of a task, whether an operator can look at the controls, what the environmental conditions are (especially illumination), whether an operator is wearing gloves, and the number of controls that must be coded.

The most common method of control coding used on mining equipment is location coding. For example, on one particular model of a machine, the tram control is third from the outside, the boom swing is second from the outside, etc. Two deficiencies, however, are often present in mining equipment, which minimize the effectiveness of location coding. First, there is often no standardization in control placement from manufacturer to manufacturer, or even from model to model within a manufacturer's line. Second, controls are often very close together and are easily confused. A good example of this is shown in figure 6-2. Some manufacturers provide long and short lever controls, or bend levers so that the controls are positioned in different planes for easier discrimination as shown in figure 6-3.

Shape coding involves providing different shaped handles or knobs on the equipment. Figure 6-4 shows a case where operators had added a glob of electrical tape to one handle in an array of handles to aid in identification; an example of primitive shape coding. The shapes selected for shape coding must be different enough from one another to be identified by operators even when they are wearing gloves. Figure 6-5 presents a set of shapes that have been found by the U.S. Army to be identifiable by touch alone even when wearing gloves (*30*). Further, to facilitate the learning of a control function, it is helpful if the shapes selected connote, or relate to, the function being controlled. The shapes shown in figure 6-6 for the controls of roof bolting machines were suggested based on opinions of MSHA inspectors and equipment manufacturers (*15*).

One consideration often overlooked in the use of shape codes is that of maintenance. If a control knob can be removed or easily broken, it may be replaced by a dissimilar knob, thus destroying the coding scheme. The welding of knobs to control levels to prevent this problem is usually a good idea.

Coding by texture (i.e., smoothness, rippledness, or knurledness) and size is somewhat limited with respect to the number of different values that can be detected. Size coding probably has more application in the mining environment than texture coding because of the tendency of some texture codes to become obliterated by dirt and muck and the difficulty of identifying textures when wearing gloves. If size coding is being used, probably no more than three sizes should be employed. The largest size should be for either the most frequently used or the most important controls.

Figure 6-2.—Control station of a low-seam coal auger.

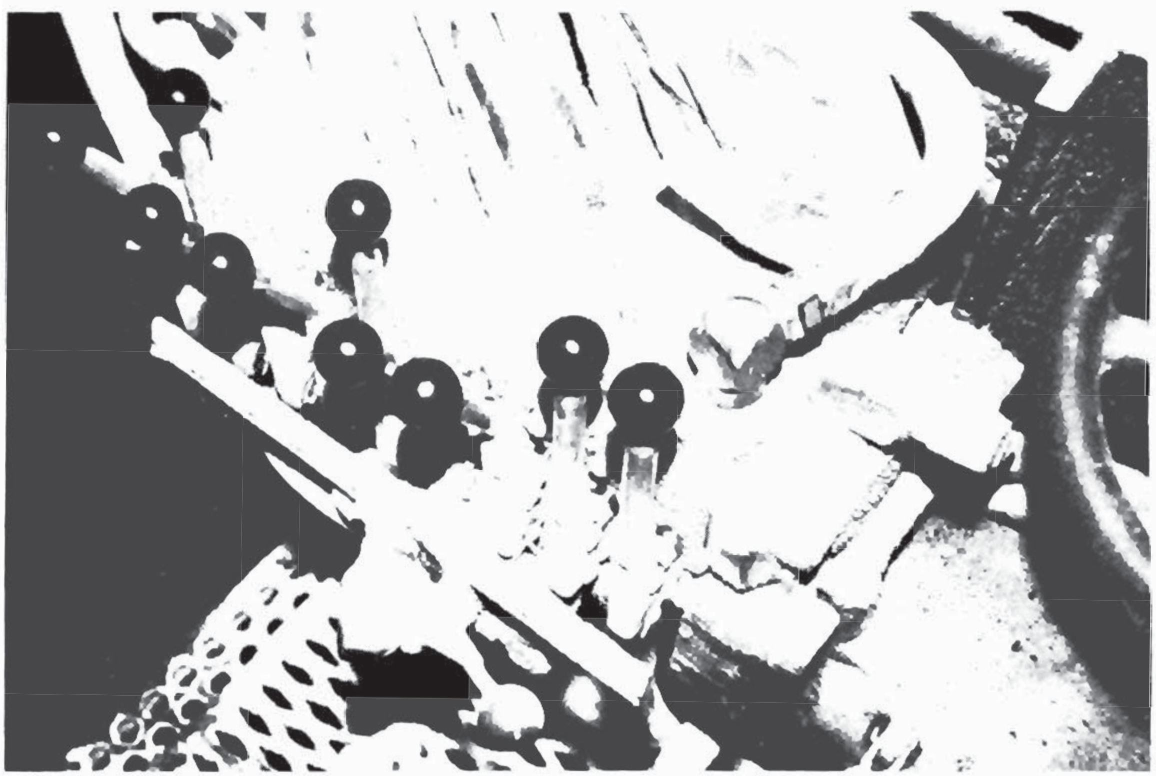


Figure 6-3.—Controls with different length lever controls, which provides easier location discrimination.

Figure 6-4.—Example of operator-provided shape coding. Electrical tape has been added to the fourth knob from the left to aid in identifying the control.

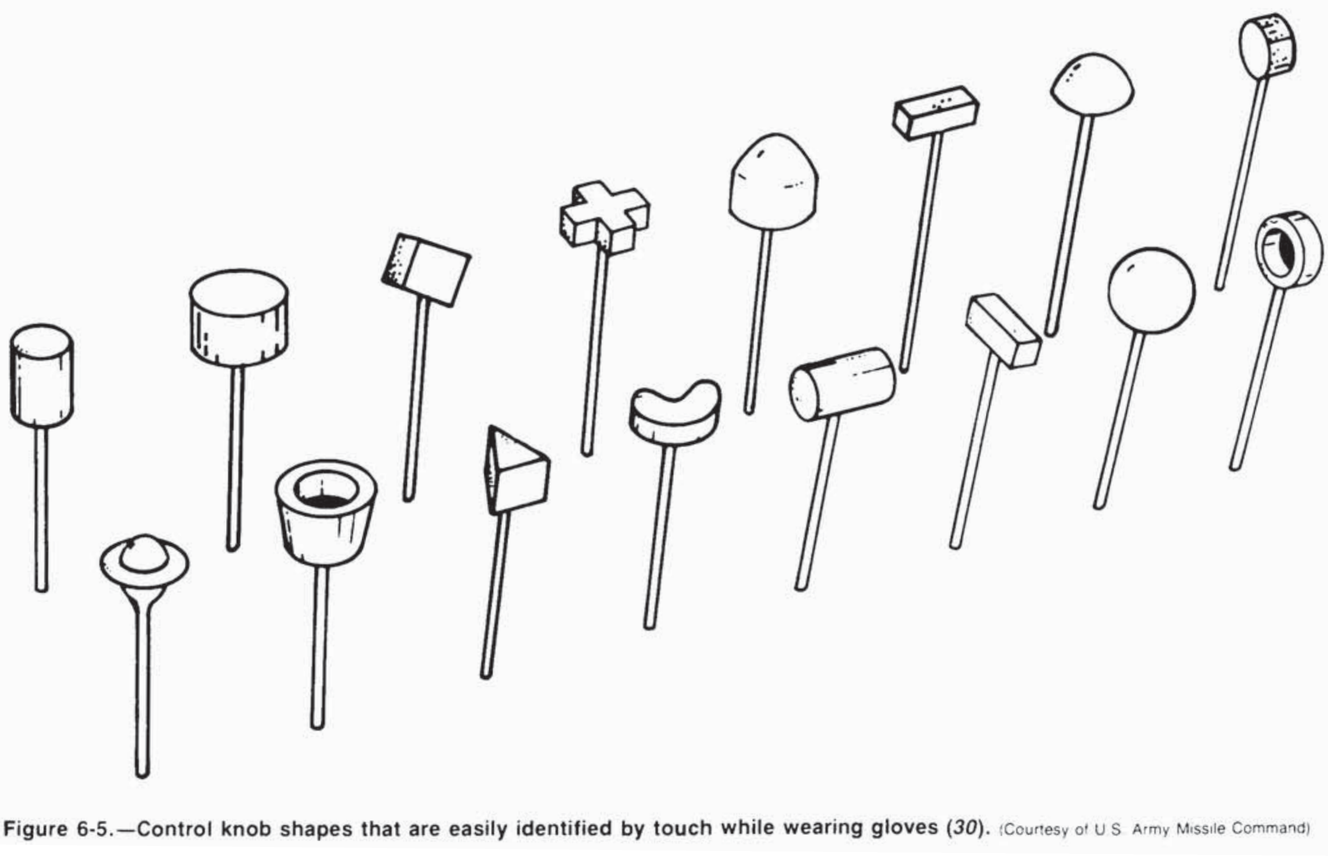


Figure 6-5.—Control knob shapes that are easily identified by touch while wearing gloves (*30*). (Courtesy of U.S. Army Missile Command)

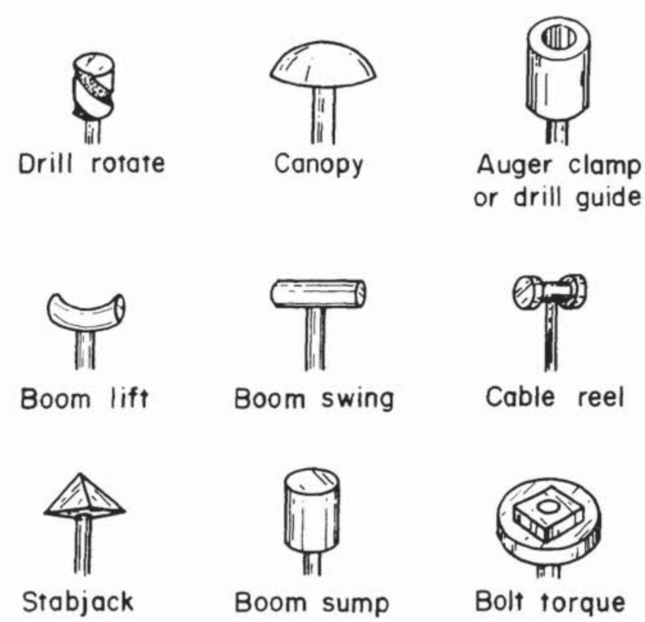


Figure 6-6.—Control shapes recommended for underground roof bolter (*15*).

Coding by colors and labels requires visual confirmation of the control choice. Operators do not often have the luxury of looking at the controls each time they have to activate them. One thing that everyone agrees on, however, is that, at a minimum, every control (and display for that matter) must be labeled. With labels, an operator can at least determine the function of a control if the function has been forgotten, although it is unlikely that an operator could rely on labels as the primary coding method during actual operation of the equipment.

If color coding is used, as for example on a control panel in a processing plant, it is important that the colors chosen are easily identified and that their meaning is the same everywhere in the plant. For example, if a red pushbutton means stop on one panel, it should not mean energize on another panel.

A well thought out coding scheme is especially important for complex equipment used in the mining industry. Inadvertent activation of the wrong controls can be reduced and often eliminated by the prudent application of control coding techniques.

Control-Response Ratio

The control-response (C-R) ratio is the ratio of the movement of a control device to the movement of a system response. A large C-R ratio would indicate that a control must be moved a large distance to cause a small system response. A small C-R ratio indicates that a small control movement results in a large system response.

Often, the problem with C-R ratios is that they are too small; that is, a slight movement of a control may cause a large swing of a boom conveyor or an abrupt increase in tram speed. Such controls are difficult and dangerous to use. One solution that is gaining acceptance is the use of proportional controls to replace the detent on-off controls commonly found in underground hydraulic equipment. An example of a proportional control is the accelerator pedal in an automobile; the more you depress the pedal, the faster you go.

The proper C-R ratio must be empirically determined by testing various ratios and determining the speed and accuracy of system control achievable with each ratio.

Resistance

There are several types of resistance that are inherent in, or can be built into, controls. The main types are listed in table 6-2. In general, a little elastic resistance is usually desirable, but inertial resistance often causes a decline in control precision.

Table 6-2.—Description of common types of control resistance

Type	*Description*
Elastic	Spring loaded—the greater the displacement of a control, the greater the resistance.
Static	Resistance to initial movement is maximum but drops off sharply as a control is moved (sticky).
Coulomb	Continued resistance to movement that is unrelated to the velocity or displacement of a control movement. Resists change in direction.
Viscous damping	Like moving a spoon through thick syrup. The faster one moves a control, the more resistance is encountered. Resists quick changes in direction and helps execute smooth control movements.
Inertia	Resistance to movement or change in direction caused by the mass of the mechanism. Resists quick control movements and any attempt to slow down or speed up control movements.

Deadspace

Deadspace in a control mechanism is the amount of control movement around the null position that results in no response of the device being controlled. A little deadspace is usually desirable, especially if vibration and buffeting of an operator are present. Too much deadspace, however, can be detrimental to operator performance.

Backlash

As described by McCormick and Sanders (*20*), the best way to think of backlash is to imagine operating a joystick or lever with a loose, hollow cylinder fitted over it. When the cylinder is moved to the right, for example, it touches the stick on the left. If you move the cylinder to the right and then reverse direction, the stick does not start to return to the left until the cylinder comes up against the right side of the stick. Until the cylinder contacts the stick, the operator's control movements have no effect on the system. In essence, then, backlash is deadspace at any control position.

Backlash is usually inherent in any system that uses gears, because the gear teeth rarely mesh perfectly. When a direction of movement is changed, there is a delay until the gear teeth contact the opposite side of the gear-teeth slots. Typically, operators do not handle backlash well, and performance deteriorates with increasing amounts of it.

Design of Specific Controls

There are several good sources of design recommendations for common controls, such as knobs, levers, cranks, pedals, and wheels (*8, 30, 32, 35*). No attempt will be made here to set forth all the detailed recommendations contained in these sources. Appendix D, however, presents recommended sizes, displacements, and resistances for many of the common controls, including pushbuttons, toggle switches, rotary selector switches, cranks, levers, and pedals.

EQUIPMENT DESIGN

The focus of this section is on the integration of controls and displays, and the layout of workstations, as aspects of equipment design. In addition, some special problems will be addressed, including operator field of vision, egress and ingress, and designing for maintenance.

The proper design of equipment that matches the capabilities and limitations of an operator, and provides the information and control functions needed by the operator to perform a task will pay dividends over and over. Reduced training time, less downtime, higher quality work, fewer errors and accidents, and greater user satisfaction accrue from well-designed equipment. The importance of such considerations is stressed by Grandjean (*11*) and U.S. Air Force Systems Command (*29*), for example.

There is a general misconception that people are adaptable; they can get used to anything. As with most misconceptions, there is probably a grain of truth buried somewhere in them. People are adaptable, but there is a cost associated with forcing them to adapt. It takes energy, both physical and mental, to adapt to the unfamiliar or unexpected, and this leads to both physical and mental fatigue—the ultimate consequences of which are obvious.

Consider the tradeoffs: Properly design a machine once or require every operator who uses it to accommodate and adapt. It is not easy but it is necessary to design equipment so that (1) controls operate as expected, (2) operators can reach controls and see displays, and (3) enough space exists to carry out the work in a safe and efficient manner.

Compatibility

Probably one of the most fundamental human factors design principles is to design to meet user expectations. Equipment should work in a natural, expected manner; that is, it should be compatible with a user's expectations.

There are several types of compatibility: conceptual compatibility, movement compatibility, and spatial compatibility. As pointed out by McCormick and Sanders (*20*), some compatible relationships are intrinsic in certain situations. Turning a wheel to the right in order to turn to the right is an example. Other compatible relationships are culturally acquired. In the United States, for example, a light switch is usually pushed up to turn it on, but in certain other countries it is pushed down.

Conceptual Compatibility

Conceptual compatibility deals with the meaning of symbolic information. For example, red means stop and green means go. This type of compatibility is most relevant for the design of coding systems and symbolic signs.

Movement Compatibility

Movement compatibility refers to the direction of control movement and the resultant system response. An example is turning a steering wheel to the right to cause a vehicle to turn right. Figure 6-7 shows compatible relationships for dial movement and display response where both the dial and the display are in the same plane. The situation becomes more complicated when the control and the display are in different planes as shown in figure 6-8. Both figures 6-7 and 6-8 represent directions of motion that a majority of people would expect without prior training or experience (i.e., population stereotypes). The expectation is stronger in some cases than in others. Figure 6-9 presents common meanings associated with lever movements in different planes and directions. Lever controls are very common on underground and surface mining equipment; yet, compatible relationships often are not observed. For example, up-down movement of a lever may cause a boom to swing left-right. Table 6-3 presents a list of common movement stereotypes grouped by function, without regard for spatial layout.

Table 6-3.—Compatible directions of movement associated with various control functions (*30*)

Function	*Direction*
On	Up, right, forward, clockwise, pull (push-pull type switch).
Off	Down, left, rearward, counterclockwise, push.
Right	Clockwise, right.
Left	Counterclockwise, left.
Raise	Up, back.
Lower	Down, forward.
Retract	Up, rearward, pull.
Extend	Down, forward, push.
Increase	Forward up, right, clockwise.
Decrease	Rearward, down, left, counterclockwise.
Open valve	Counterclockwise.
Close valve	Clockwise.

(Courtesy of U.S. Army Missile Command)

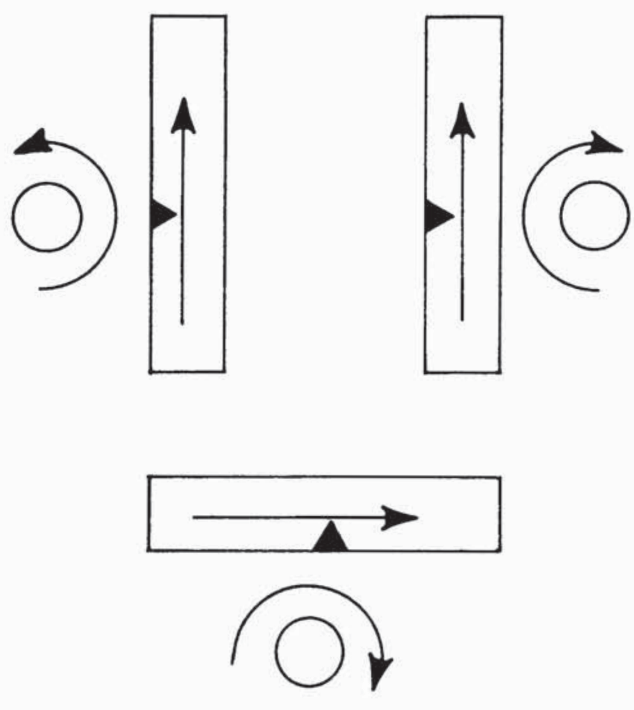


Figure 6-7.—Movement compatibility relationships where dial and display are in same plane.

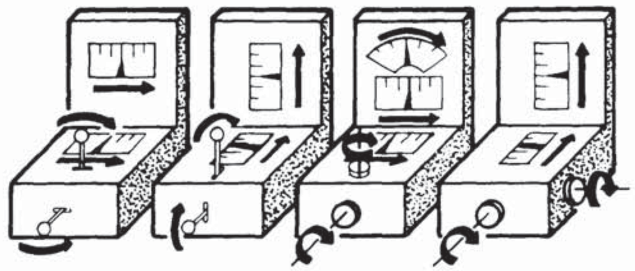


Figure 6-8.—Compatible control-display movements when controls and displays are in different planes (*11*). (Courtesy of Taylor and Francis Ltd.)

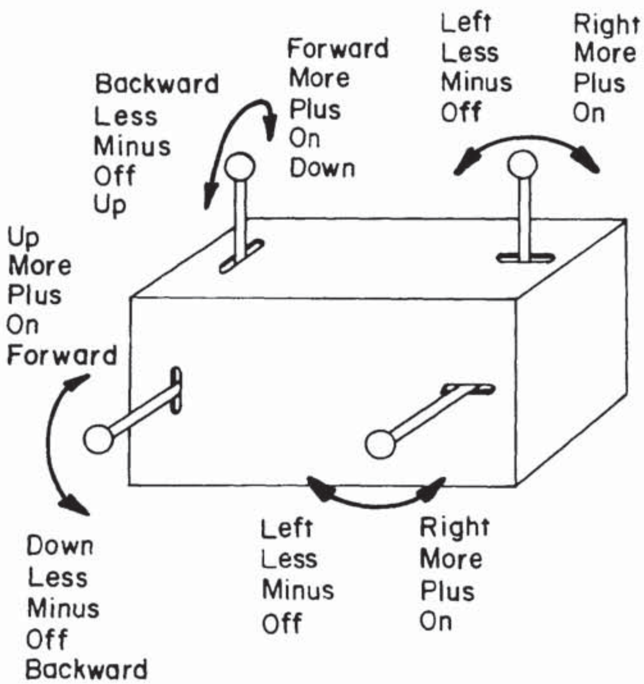


Figure 6-9.—Common meanings of lever movements (adapted from *11*). (Courtesy of Taylor and Francis Ltd.)

Spatial Compatibility

Spatial compatibility refers to the physical location and relationship between the controls and the displays they control. Figure 6-10 shows examples of arrangements of controls and displays. Where the relationship between controls and displays is not obvious, it is more likely that the wrong control will be activated, user response time will be slowed, and additional training time will be required to learn how to operate the equipment.

Placement of Displays and Controls

To determine display and control placement requires two questions to be answered. First, where in physical space is it best to place controls and displays; and second, within that space, how should the displays and controls be arranged.

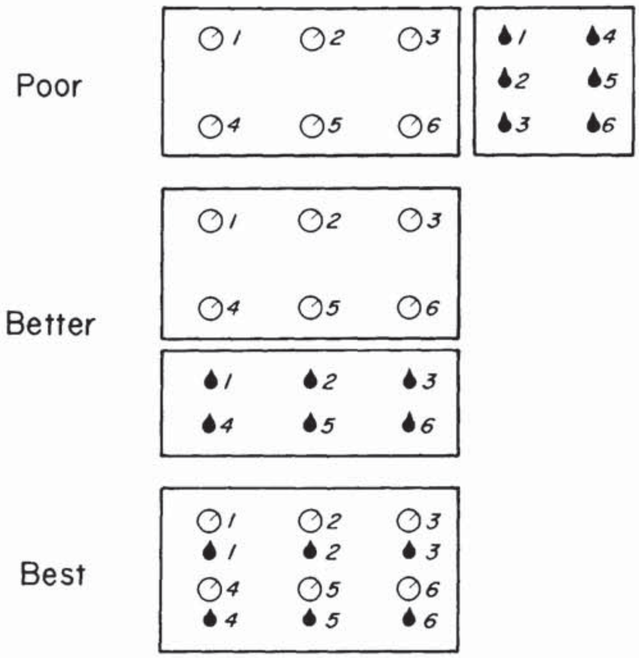


Figure 6-10.—Examples of spatial compatibility between a bank of controls and displays.

Arrangement of Controls and Displays

The arrangement of controls and displays obviously involves spatial compatibility; but, beyond that, consideration must be given to grouping displays and controls with regard to how they are used. There are four basic principles for arranging controls and displays: importance principle, frequency-of-use principle, functional principle, and sequence-of-use principle.

The importance principle states that controls and displays that are vital to the achievement of a task be placed in an optimum location. The frequency-of-use principle states that the most frequently used controls and displays be given priority in a workspace. The functional principle provides for the grouping of controls and displays by function, such as grouping together all controls that deal with the tail conveyor of a continuous miner. Finally, the sequence-of-use principle requires that controls and displays be arranged to take advantage of frequently used patterns or sequences of operation.

Obviously, one cannot satisfy all of these principles at the same time; tradeoffs must be made. In general, the importance and frequency-of-use principles are probably most applicable in determining the general area in a workstation to locate controls and displays, while the sequence-of-use and functional principles apply more to the arrangement of components within a general area. One thing does seem clear, however; where there is a fixed sequence of operation, the sequence-of-use principle should take precedence over the other principles.

Standardization

Transcending the preceding principles of arrangement is the principle of standardization. Once an acceptable layout of components has been achieved, every effort should be made to standardize that arrangement within a particular class of equipment and, where possible, across similar equipment. In chapter 4, a fatal accident was described that could be attributed to a lack of standardization between different models of the same manufacturer's equipment. Lack of standardization probably represents the most serious and pervasive problem with respect to equipment design in the mining industry.

Figure 6-11 shows different arrangements of roof bolter controls used by one manufacturer. A survey of surface mining haulage trucks and front-end loaders by Conway and Sanders (*6*) found eight different configurations for brake, clutch, and throttle controls on 120-st-capacity and smaller haulage trucks as shown in figure 6-12. In consideration of the many different braking systems employed, standardization of the major controls would be highly desirable, with recommended locations for other controls if they were employed.

Figure 6-13 shows the placement of the service brake relative to the steering wheel in four front-end loaders found at surface mines (*6*). Again, the need for standardization is obvious.

When equipment layout is not standardized, an operator must unlearn old habit patterns (e.g., hitting the brake with the left foot) and learn new patterns (e.g., hitting the brake with the right foot). The unlearning-learning is much more difficult than learning a habit pattern the first time. With practice, people can usually adapt; however, it is a well known fact that in panic or stress situations, people will often revert to old habit patterns or operate controls in the stereotypically expected manner. There are no reliable statistics available as to the number of accidents that were caused, in whole or in part, by lack of standardization in control-display layout. However, it was reported by White (*33*) that 72% of crane operators admitted to making control-input errors because of lack of standardization.

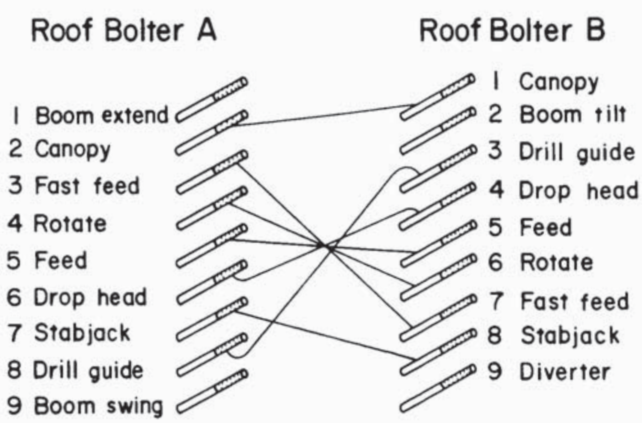
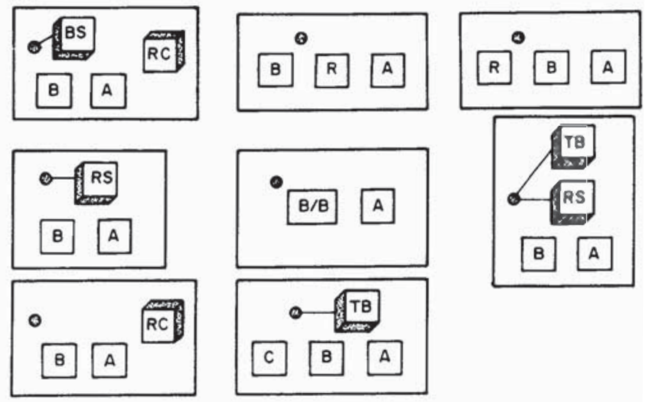


Figure 6-11.—Different arrangements of roof bolter controls from one manufacturer (*15*).



KEY

⊙	Steering column
A	Accelerator or throttle (floor pedal)
B	Service brake (floor pedal)
B/B	Dynamic or service brake (combination floor pedal)
BS	Rear brake (steering column mounted)
C	Clutch (floor pedal)
RC	Retarder (console mounted)
R	Retarder (floor pedal)
RS	Retarder (steering column mounted)
TB	Trailing unit brake (steering column mounted)

Figure 6-12.—Brake, clutch, and throttle control placement on eight 120-st-capacity and smaller haulage trucks (adapted from *6*).

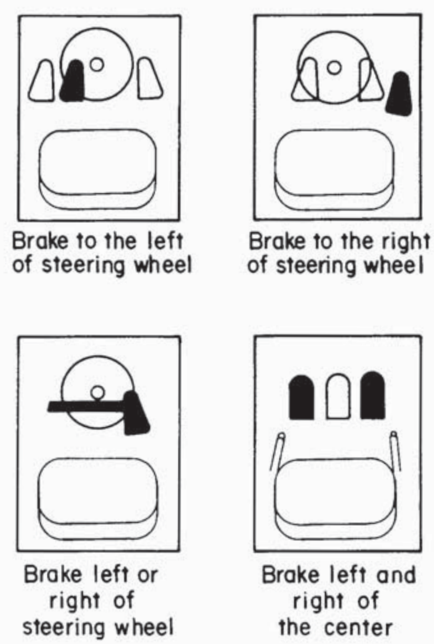


Figure 6-13.—Location of service brake relative to steering wheel on four front-end loaders (*6*).

Location of Controls and Displays

The optimum location for controls and displays depends on the posture assumed by an operator in a workspace. Most design recommendations deal with the seated operator. These recommendations assume an upright seated posture typical of that found in computer consoles or truck vehicles. Rarely dealt with are semireclining work postures often found on low-seam mining equipment. The reclining posture workstations are discussed in another section of this chapter.

Figure 6-14 presents a diagram showing the preferred vertical surface area for various classes of controls used by a seated operator. The dimensions are indexed from the seat reference point (SRP), which is at the midline of the seat at the intersection of the seat back and seat pan.

Figure 6-15 presents an integrated picture of data relative to the design of seated workstations, including fields of view, reach distances, and control and display placements. Placing displays and controls in these recommended areas helps insure that they can be seen and reached with minimal delay, discomfort, and errors.

Vehicle cab design is similar to, but has important differences from, the typical seated console workstation. Figure 6-16 presents recommendations for the design of vehicle cabs. The Society of Automotive Engineers (SAE) has published a recommended practice regarding the location for controls in heavy construction equipment (*27*) as shown in figure 6-17. This figure shows a 95th percentile male with the seat in the most rearward position. A 4-in forward adjustment range on the seat will accommodate 90% of the operator population. Figure 6-17 is indexed from the H-point of the seat. The H-point is determined by using an anthropometric, weighted device developed by SAE. Because most people in the mining industry do not have access to H-point data about truck seats, one can approximate the location of the seat reference in figure 6-17 as 4.0 in to the rear and 2.2 in lower than the H-point.

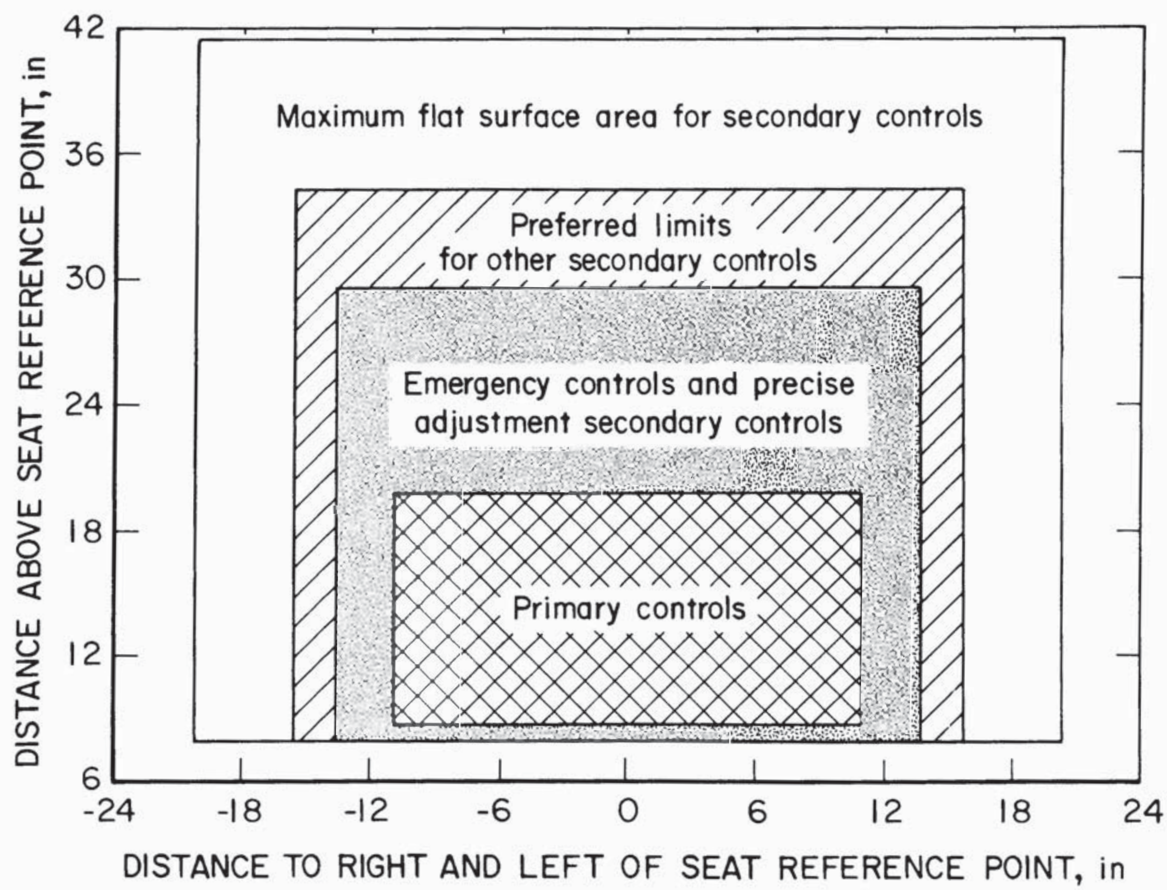


Figure 6-14.—Preferred vertical surface areas and limits for various types of control functions operated by a seated operator (adapted from *20*). (Courtesy of McGraw-Hill)

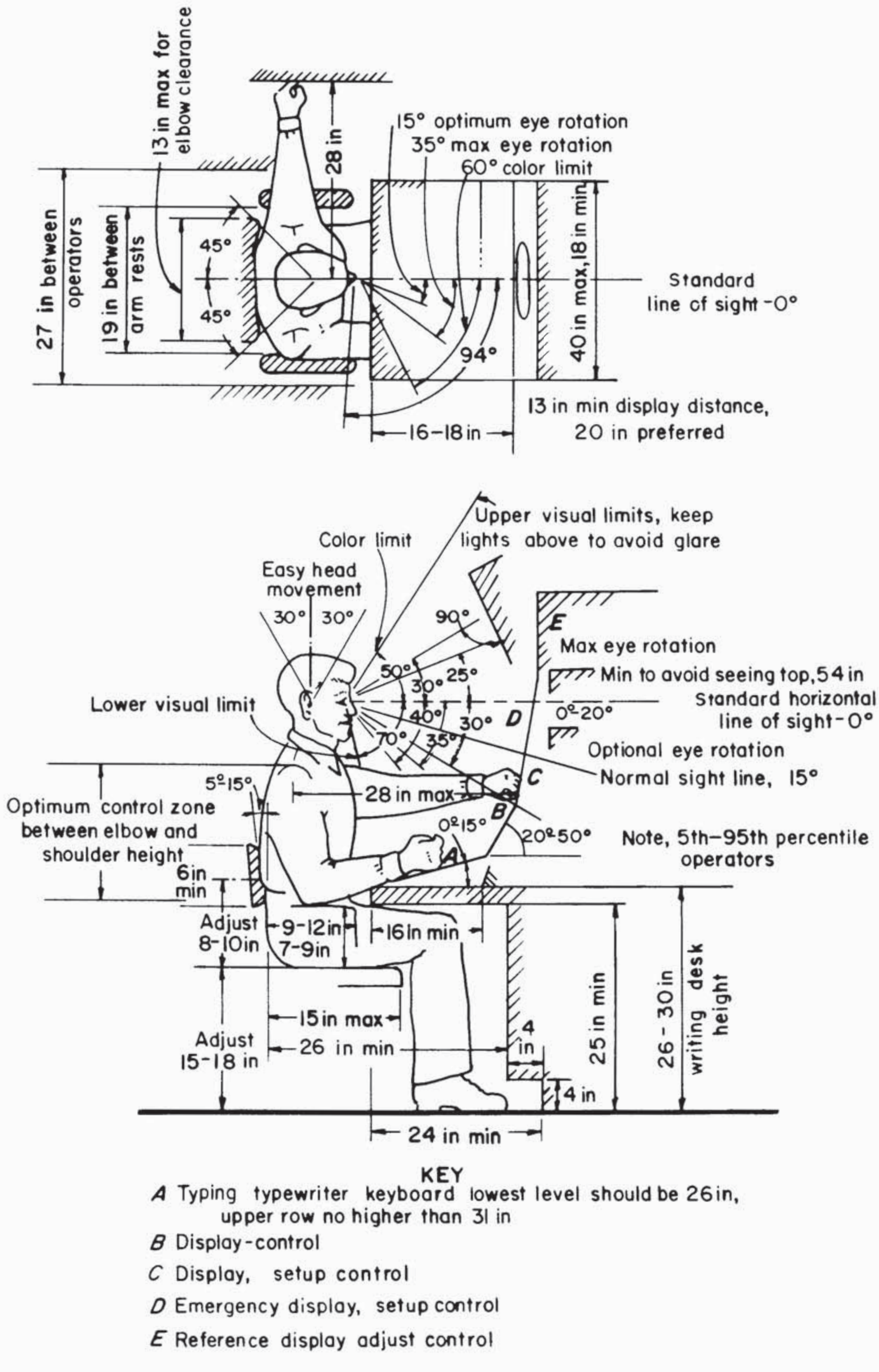


Figure 6-15.—Recommended dimensions and layout of seated operator workstations (32). (Copyright 1972 by John Wiley and Sons Ltd., and reprinted by permission.)

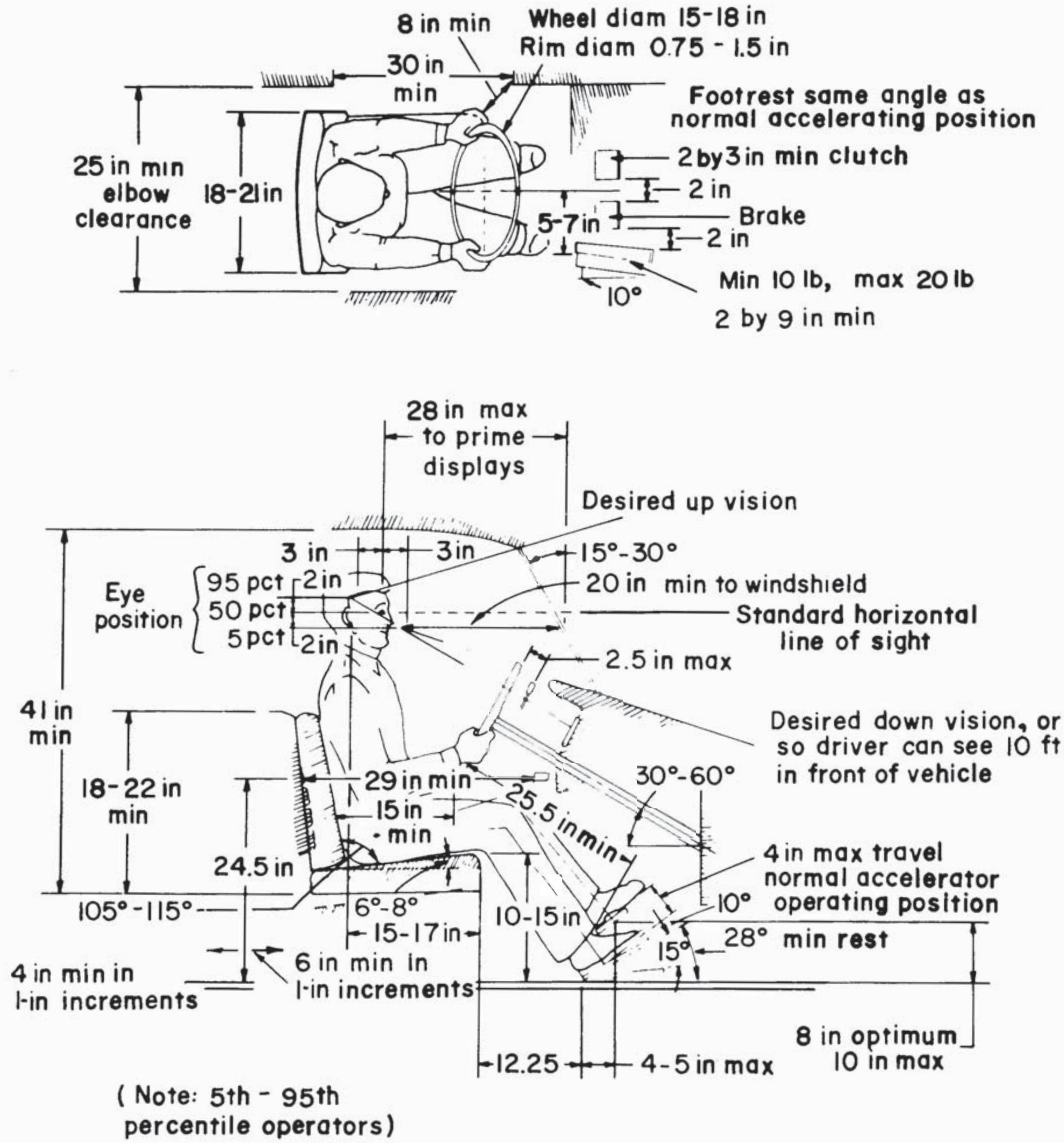


Figure 6-16.—Recommended configurations of a vehicle cab (*32*). (Copyright 1972 by John Wiley and Sons Ltd., and reprinted by permission)

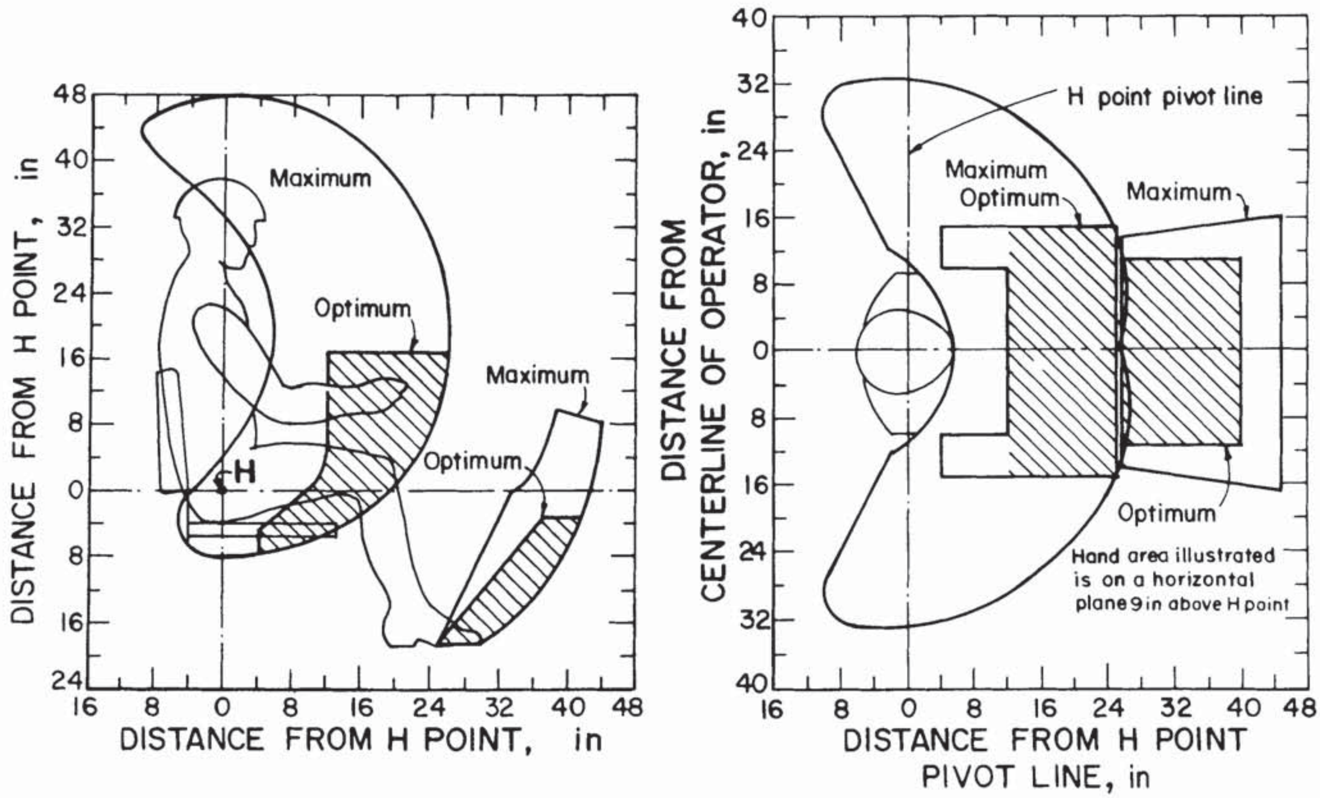


Figure 6-17.—SAE J898a recommended practice for control locations for construction and industrial equipment design (27). (Copyright 1974 by Society of Automotive Engineers Inc., and reprinted with permission)

With respect to standing workstations, figure 6-18 presents recommendations regarding placement of controls and displays.

One final consideration in the placement of controls is the distance between them; if they are too close together, the wrong control is more likely to be activated. This is especially true when operators are wearing gloves or workboots. If two controls must be operated simultaneously or in rapid succession, too great a distance would slow performance and even make it impossible to perform a task as intended. Figure 6-19, based on work by Chapanis (5), presents recommended control separations based on the type of control, whether one or two hands (or feet in the case of pedals) are being used, and whether the controls are operated in a random sequence, sequentially, or simultaneously. The empty cells indicate combinations for which no reliable data exist. Extra space should be added between controls when operators wear gloves or boots (in the case of pedals).

Special Problems in Equipment Design

Four special problems in equipment design, especially relevant to the mining industry, are discussed in the following sections. The problems are seating for low-seam coal equipment, operator field of vision, egress-ingress on equipment, and access for maintenance and service.

Seating for Low-Seam Coal Equipment Operators

Judeikis (17) reported that of 350 underground coal mine fatalities involving mobile face equipment, 24 (averaging three per year) involved inadequate compartment size, 20 (2.5 per year) involved an operator leaning out of the cab, 19 (2.4 per year) involved not having an operator compartment, and 13 (1.6 per year) involved poorly designed seats. This represents a total of 76 fatalities related to improperly designed operator compartments.

A major constraint in operator compartment design is the operating height of many coal mines in the United States. Many seams are less than 48 in high, and mine heights are usually no higher than the seam height. As pointed out by Aljoe (1), however, the practical working height of a coal mine is considerably less than the mine height because of overhead obstructions (e.g., a roof support timber) and undulating floor conditions. The upshot of this is that the height of an operator compartment may be as little as 22 in, thus requiring the operator to assume a reclined seating posture. Figure 6-20 shows three examples of typical seating accommodations in low-seam mining equipment.

Figure 6-21 shows diagrams of the 95th percentile male and 5th percentile female seating envelopes for two cab heights: 42 and 22 in (4). These diagrams dramatically illustrate the increased cab lengths, reduced reach envelope, and restricted fields of vision resulting from a reclined seating posture.

Figure 6-22 presents data on the interior cab length required for various interior cab heights to accommodate various sizes of operators. The data assume a 10° seat pitch and a 2-in helmet clearance space. As pointed out by Cooksey (7), the data in figure 6-22 do not take into consideration the space for a headrest or the additional cab length needed to depress foot pedals.

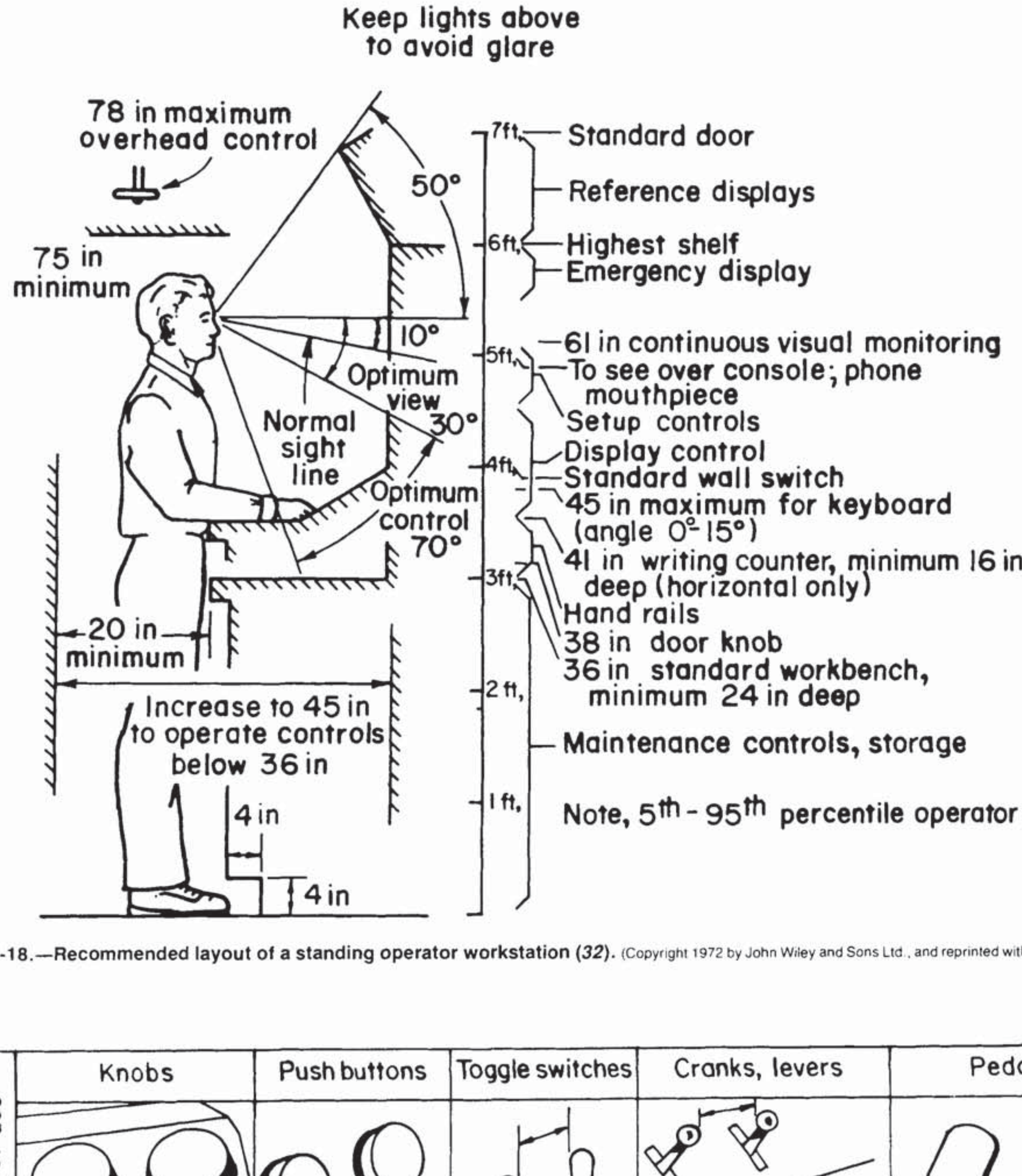
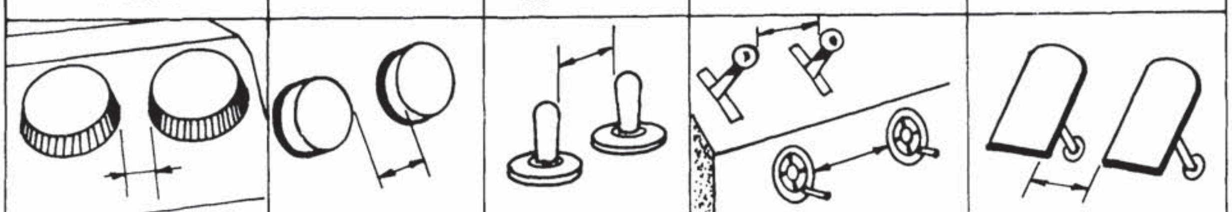


Figure 6-18.—Recommended layout of a standing operator workstation (*32*). (Copyright 1972 by John Wiley and Sons Ltd., and reprinted with permission)



Number of body members and type of use		Knobs	Push buttons	Toggle switches	Cranks, levers	Pedals
1, randomly	in	2(1)	2(1/2)	2(3/4)	4(2)	6(4)
1, sequentially	in		1 (1/4)	1(1/2)		4(2)
2, simultaneously	in	5(3)			5(3)	
2, randomly, sequentially	in		1/2(1/2)	3/4 (5/8)		

Figure 6-19.—Recommended separation between adjacent controls for one- and two-hand (or foot in the case of pedals) operation, randomly, sequentially, or simultaneously. Minimum separations are given in parentheses, alongside preferred separations.
(Adapted by McCormick and Sanders (20) from reference 5, courtesy of McGraw-Hill)

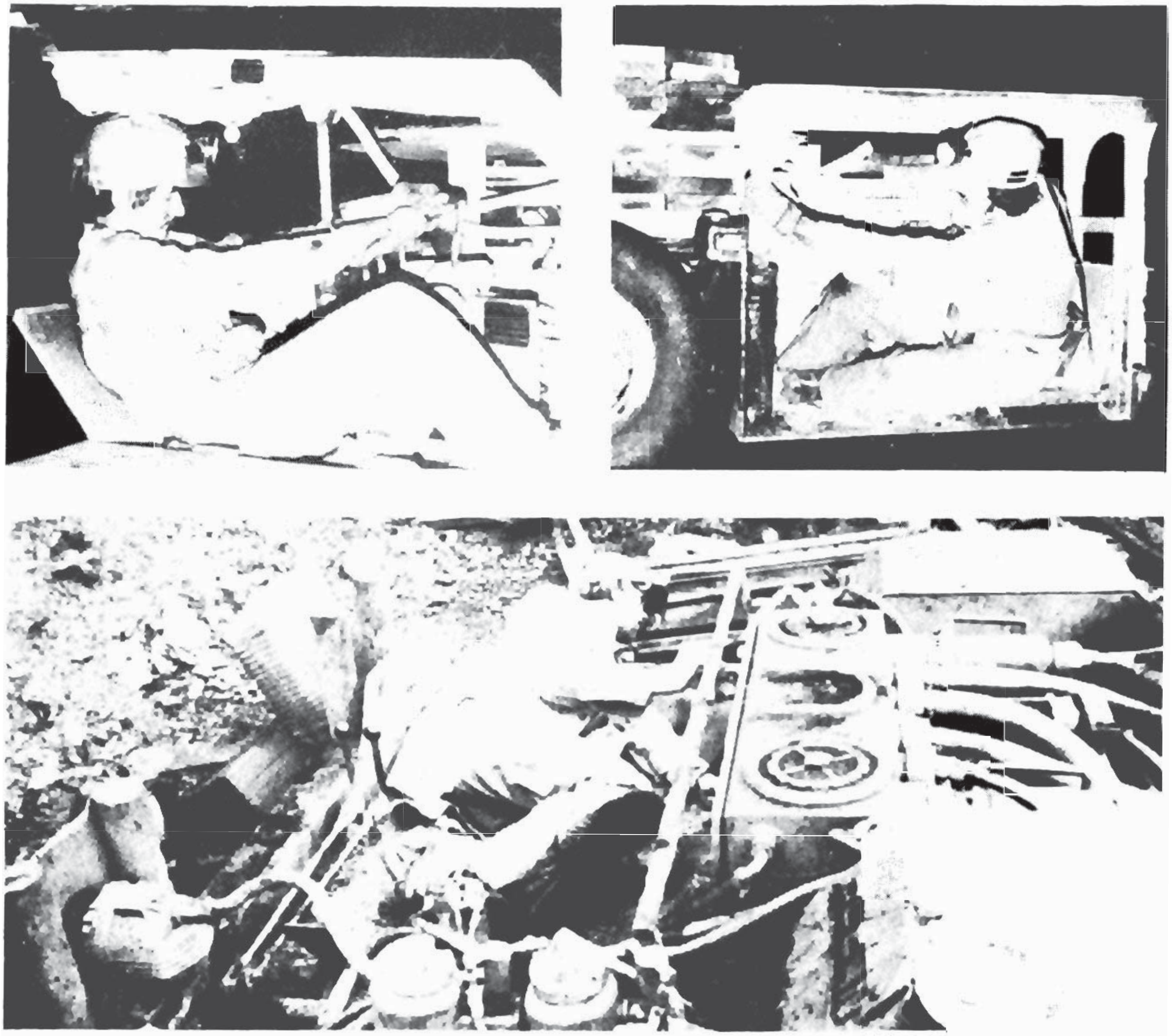
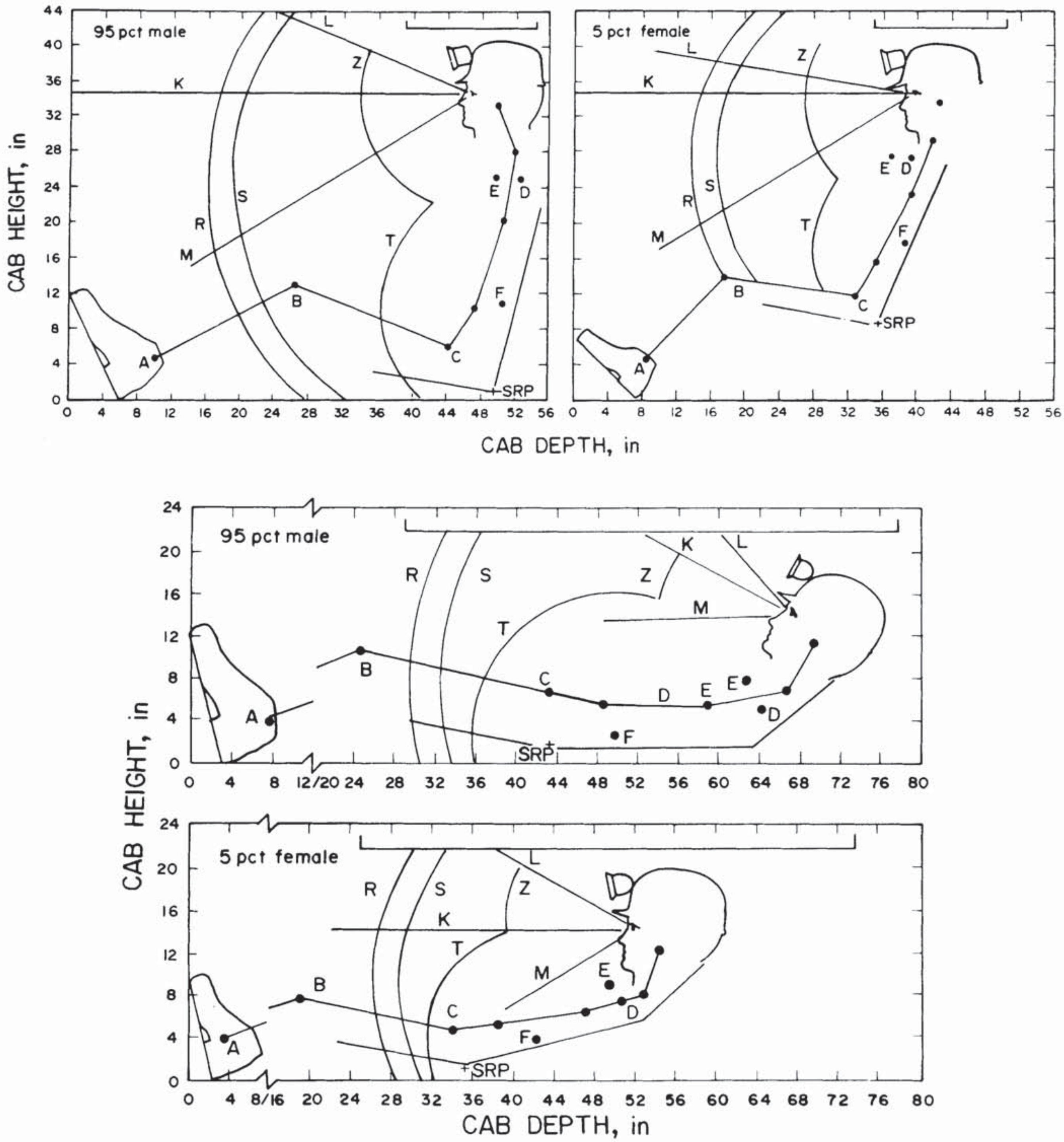


Figure 6-20.—Examples of typical seating postures in low-seam coal mining equipment.



A Ankle point
B Knee point
C Hip point
D Shoulder point
E Shoulder extended
F Elbow point

K Standard ling of sight
L Upper line of sight
M Lower line of sight
N Warning display vision
P Controls and display vision
Q Peripheral vision

R Maximum control reach
S Maximum control grip
T Maximum control grip
Z Minimum display distance
SRP Seat reference point

Figure 6-21.—Seating space envelopes for 95th percentile male and 5th percentile female operators in 42-in (top) and 22-in (bottom) cab heights (*4*). (Courtesy of Canyon Research Group Inc.)

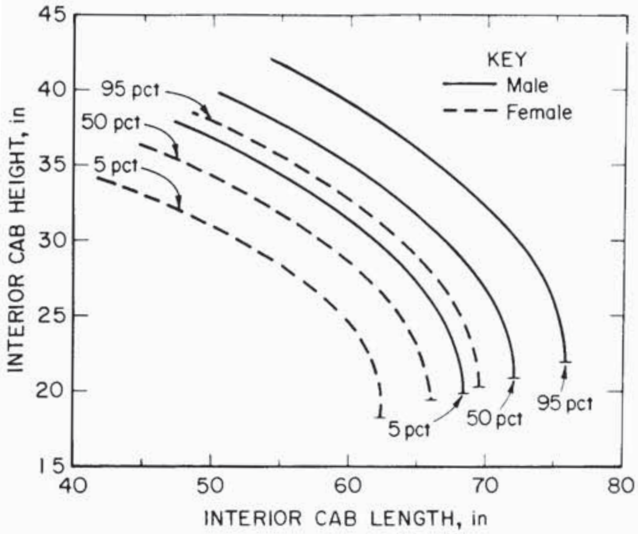


Figure 6-22.—Relationship between interior cab height and required interior cab length needed to accommodate various sized people. Assumes a 10° seam pitch and 2-in helmet clearance (*7*). (Courtesy of R. Cooksey, University of New England)

In an effort to reduce problems common to low-seam operator compartments, the Bureau sponsored a research project to develop a human-factored, state-of-the-art, low-seam seat (*13*). Although the aim was to develop a seat for the remote control of mining equipment, the design could conceivably be adopted to on-vehicle operator compartments as well. Figure 6-23 shows the seat and a schematic design. The seat is easily adjustable and fits a wide range of operator body sizes. The seat surface is made of strips of woven monofilament, open-mesh, polyester belting for strength, durability, and comfort. The headrest is constructed of a piece of standard seven-ply, neoprene conveyor belting looped so the bias provides maximum flexing resistance in the longitudinal direction.

Operator Field of Vision

Restricted field of vision from both surface and underground equipment is a common problem in mining. Conway and Sanders (*6*) pointed out that restricted vision from operators' compartments was a serious problem for haulage trucks, front-end loaders, and dozers in surface operations. A review of the literature, however, finds that almost all the research and development effort has been directed

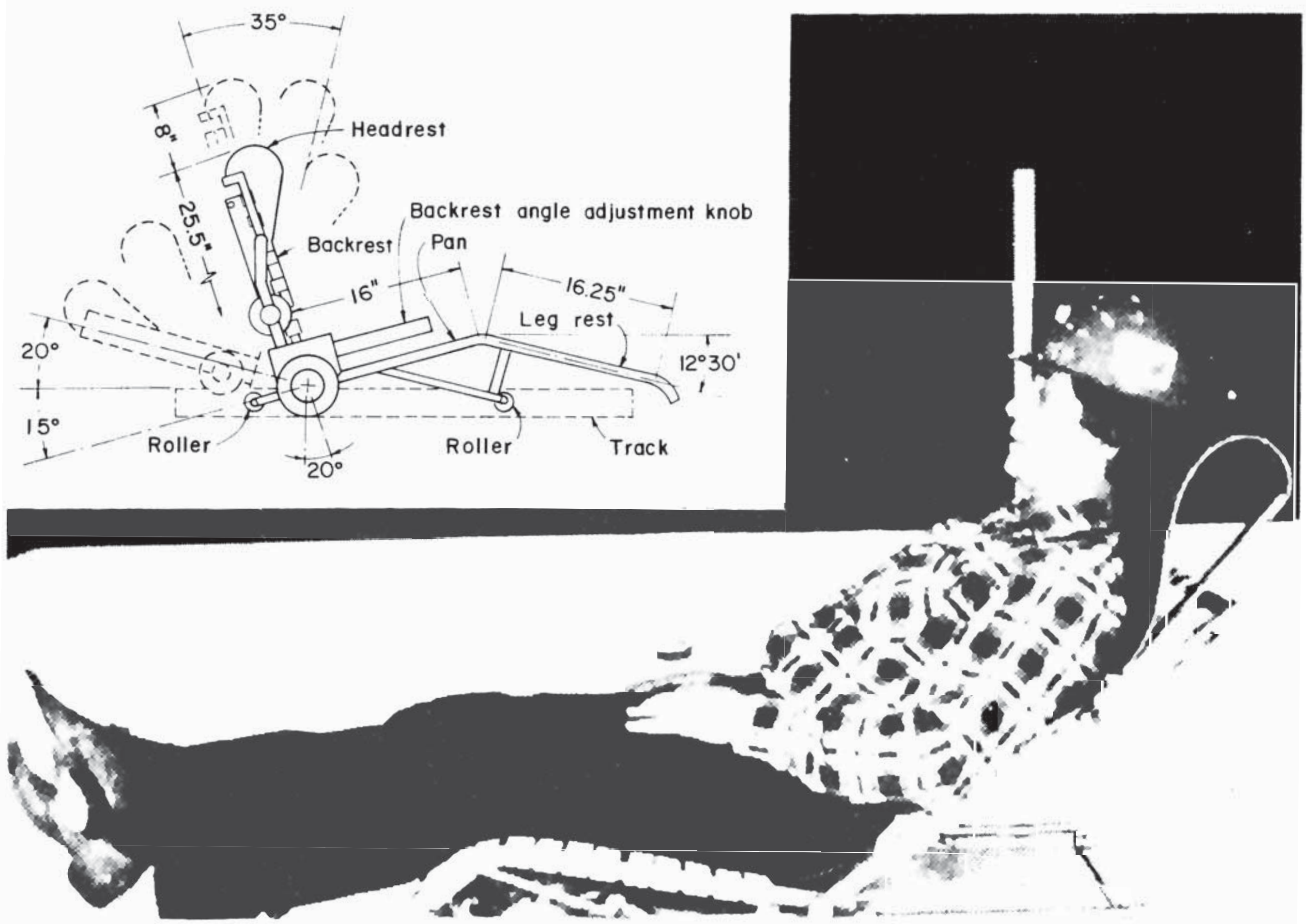


Figure 6-23.—Human-factored seat for low-seam mining equipment (*13*). (Copyright 1982 by the Human Factors Society Inc., and reproduced by permission)

toward haulage truck visibility problems. MSHA determined that lack of "visibility" was a contributing factor in approximately 20% of fatal and nonfatal truck haulage accidents during the years 1972 to 1975 (*21*). Poor or restricted field of vision greatly contributed to operators driving off haulage roads and over embankments, colliding with other equipment and fixed objects, and running or backing over individuals.

To illustrate the magnitude of the field of view problem for haulage truck operators, figure 6-24 shows front- and side-vision limitations for a 150-st-capacity rear-dump haulage truck. As can be seen, an operator cannot see a 6-ft person standing closer than 40 ft in front of the truck and can only see the ground beyond 62 ft in front of the truck. Figure 6-25 presents a plan view of the same truck and shows the blind spots and the distances required to see an 8-ft object and the ground around the operator's cab.

Visibility plots such as those presented in figures 6-24 and 6-25 are good for illustrating field of vision problems, but should not be considered as a totally accurate depiction of an operator's visual field. A single plot does not take into account different sized operators (and hence, eye heights); different seat adjustment positions and heights; and equipment modifications, such as new components on the right-side deck, shields over the engine, different tire sizes, etc. All of these factors will change the shape and size of blind spots. For example, a 3-in-diameter corner post in a cab located 33 in from an operator's eyes will block an object 5.5 ft wide at a distance of 60 ft.

The Bureau sponsored research to develop improved "visibility" systems for large haulage vehicles (*14*). The final system consisted of fresnel lens, blind area viewers; a quick-change left mirror; a rectangular convex right mirror; and a ruggedized, closed-circuit television system (*16*). Figure 6-26 shows a typical system on a haulage truck. The fresnel lens allows an operator to see objects as close as 5 ft to the truck, as shown in figure 6-27. Figure 6-28 shows the improved field of visibility using the new system of lenses, mirrors, and cameras. The improved system eliminated approximately 85% of the forward and right blind area, and about 95% of the rear blind area.

In the underground mining environment, MSHA attributed 25 fatalities involving mobile face equipment from 1972 through 1979 to inadequate "visibility" from the operator's cab (*17*). This represents an average of 4.6 fatalities per year as a result of restricted field of vision. A system for assessing the visibility requirements for operating continuous miners, shuttle cars, and scoops was developed by Sanders and Kelley (*25*). They also developed a methodology for measuring the adequacy of the actual fields of vision for underground equipment. This methodology involved a task analytic approach for identifying the important visual features needed to efficiently and safely

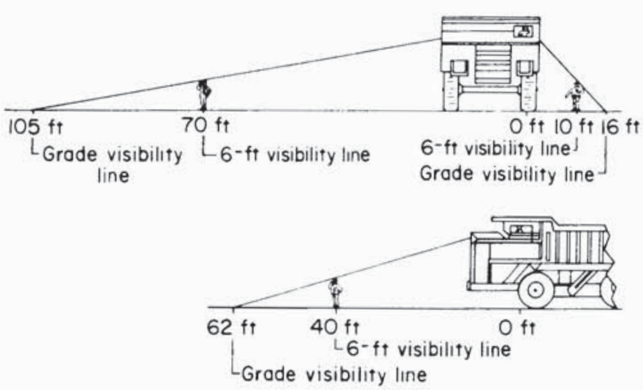


Figure 6-24.—Illustration of front and side visual limitations from the cab of a 150-st-capacity rear-dump haulage truck (*21*). (Courtesy of U.S. Mine Safety and Health Administration)

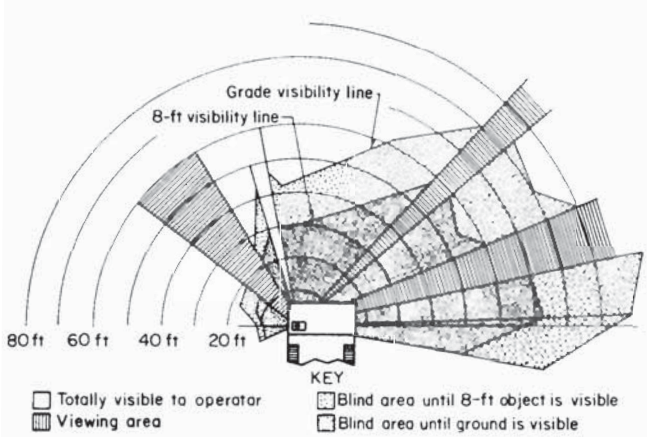


Figure 6-25.—Plan view illustrating front and side visual limitations and blind areas from the cab of a 150-st-capacity rear-dump haulage truck (*21*). (Courtesy of U.S. Mine Safety and Health Administration)

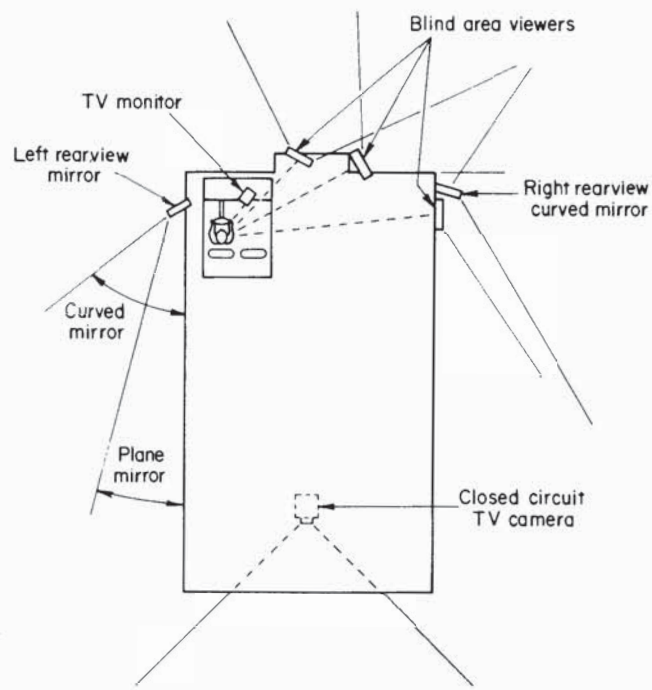


Figure 6-26.—Typical installation of an improved visibility system for large haulage trucks (*16*).

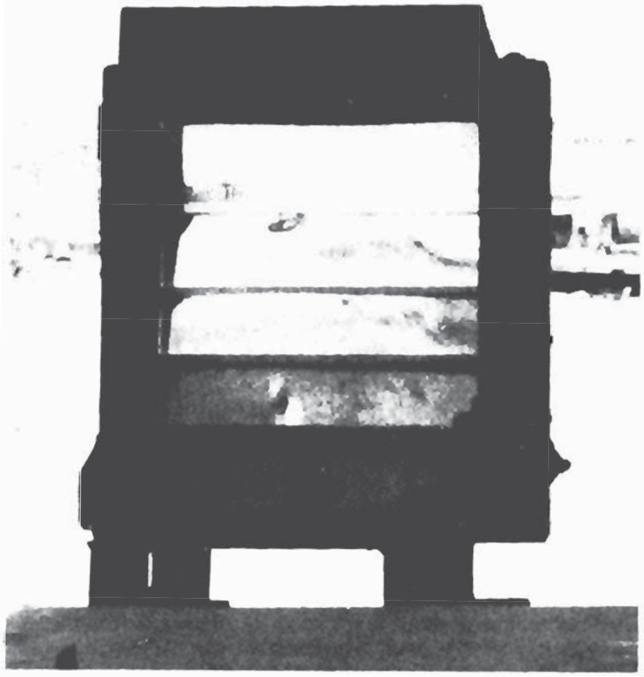


Figure 6-27.—Fresnel lens blind area viewer used to enhance visual field of haulage truck operators. A person standing a few feet from the truck can be seen through the lens.

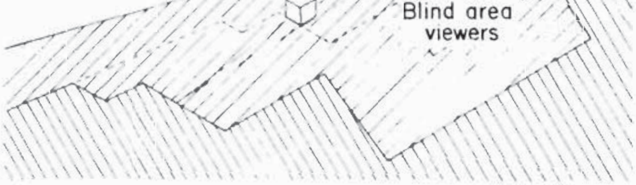


Figure 6-28.—Improved field of view resulting from installation of system shown in figure 6-27 (*16*).

operate the equipment. These visual features were translated into visual attention locations (VAL's) that should be visible from an operator's cab. Figure 6-29 shows a plot of the VAL's for continuous miner operations. (At each VAL, several heights above the floor should be visible.)

The method of assessing a field of vision involved the use of a human eye reference measurement instrument (HERMI) shown in figure 6-30. By placing the instrument in an operator's cab and taking pictures of the cab from each VAL, one can easily determine if a VAL is visible from the cab, and if not visible, what is obstructing the view.

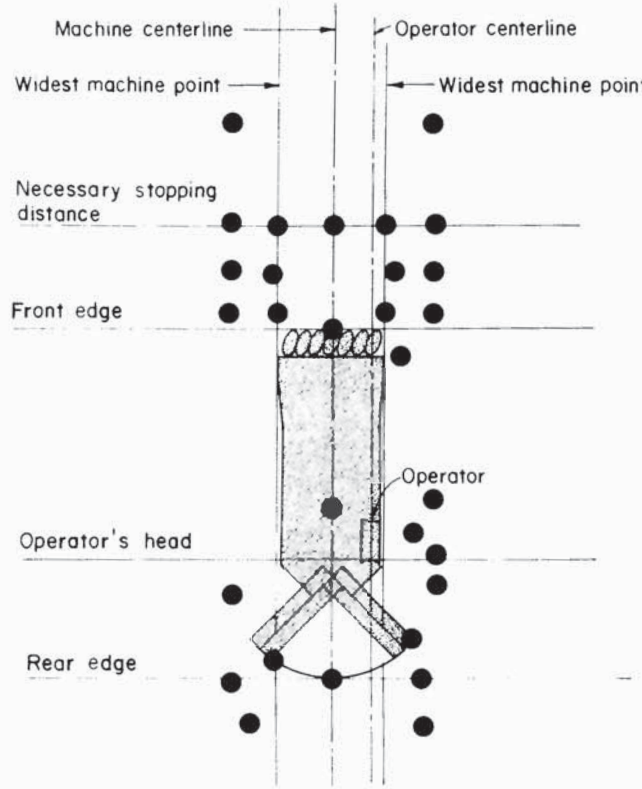


Figure 6-29.—Plan view of visual attention locations (VAL's) identified for continuous miner operators. Several vertical heights are represented at each VAL (*25*).

A sample of center- and end-driven shuttle cars for high- and low-seam height applications, with canopies in both high and low positions, was evaluated by Sanders and Krohn (*26*) using these techniques. It was found that with a canopy in the low position, the field of vision was increased by placing the cab in the front of the car as opposed to the center or rear of the car. It was also found that adding a canopy did not reduce the field per se, as long as it did not force operators to lower their eye position. The field of vision was degraded when the eye position was lowered, with or without a canopy in place.

Across all configurations and canopy positions, six VAL's were not visible from any machine tested. These VAL's were located at floor level, on the opposite side of the machine from the operator's cab, and from 2 ft to the necessary stopping distance in front of the machine's direction of travel. This area, then, represents a blind area on virtually all shuttle cars. It was recommended that mirror systems be developed and retrofitted on current shuttle cars to eliminate such blind spots.

Egress-Ingress on Surface Mining Equipment

Slips and falls while ascending and descending equipment account for over one-third of all surface mining lost-time accidents associated with the operation of haulage trucks, front-end loaders, track dozers, shovels, and draglines (*18*). A review of MSHA accident data by Gavan (*10*) revealed that almost 2,000 slip and fall accidents occurred on surface mine mobile equipment during 1978 and 1979 alone. These accidents averaged 15.3 lost days per incident.

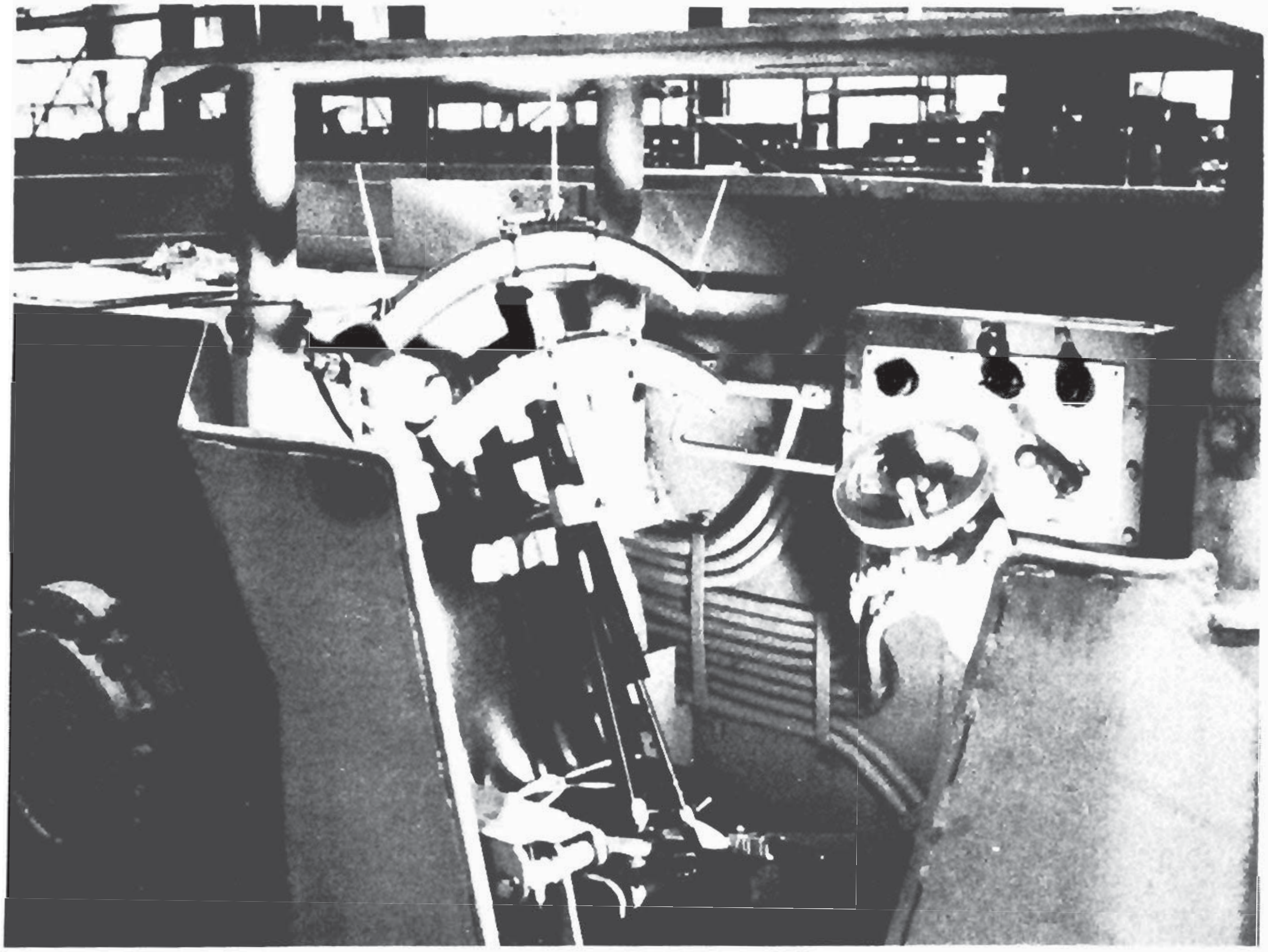


Figure 6-30.—Human eye reference measurement instrument (HERMI) used to assess fields of visibility from operators' cabs. The white arcs represent the 95th percentile male and 5th percentile female eye positions allowing reasonable head and trunk flexion (*26*).

Characteristic injuries are cuts, lacerations, contusions, fractures, sprains, and strains.

The types of generic design problems that contribute to the frequency of slip and fall accidents, according to Long (*18*), include

1. Excessively flexible lower section supports for lower steps or rungs on ladders (fig. 6-31).
2. Inappropriate distances from ground level to first step (fig. 6-32).
3. Use of access paths that are not intended for that purpose such as the tracks on dozers and shovels.

Added to these problems are the tendencies for mud, snow, ice, and oil to accumulate on the step surfaces, and the tendency of the operators to carry personal items with them, making it difficult for them to use both their hands to hold the rails when mounting or dismounting.

Figure 6-33 shows recommended design guidelines for stairs and ladders that are applicable to surface mining equipment egress-ingress systems. Figure 6-34 shows two innovative stair designs for haulage trucks. In both cases, stairs replaced conventional vertical ladders for easier and safer egress and ingress. The pulldown stair design (figure 6-34, top) also has the safety feature that when the stairs are down, the counterweight is clearly visible to the driver. This reduces the chance of moving a truck when someone is attempting to board.

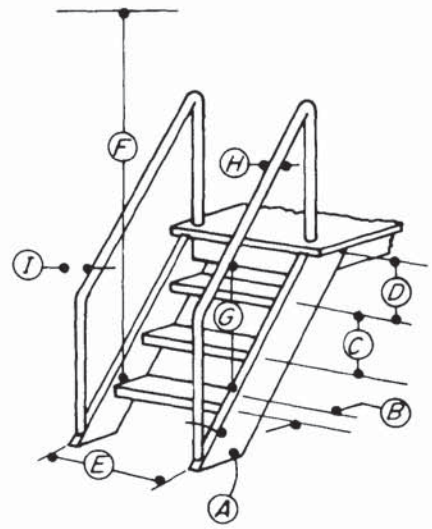
In addition to stair and ladder design, Bottoms (*3*) pointed out the need to consider the design and placement of the doorways for egress and ingress. Figure 6-35 shows a typical access path for entering a tractor. The door is aligned with the steering wheel, thus requiring the operator to maneuver around the wheel into the seat. Ideally, the gap between the seat and steering wheel should be opposite the doorway, as shown in figure 6-36. If this cannot be done, the effective platform width (W in figure 6-35) should be made as large as possible. Bottoms (*3*) also recommended door widths of 26 in at or above waist level, and 16 to 26 in at foot level. The minimum size recommended is 22 in at and above waist level, and 12 in at foot level.

The Bureau sponsored a research and development project to improve egress-ingress systems for surface mining equipment, as discussed by Long (*19*). Figure 6-37 shows the spring-supported lower step concept for large haulage trucks. This design consists of a lower first step that will flex and withstand collisions, as shown in figure 6-38, and still provide a semirigid mounting surface.

Figure 6-31.—Excessively flexible lower section support on haulage truck ladder, a common problem (*18*).

Figure 6-32.—Inappropriate height of first step on haulage truck ladder (*18*).

	In. Min	In. Max
A. Angle of rise:	50°	75°
B. Tread depth:		
For 50° rise:	6	10
For 75° rise:	3	6
C. Riser height:	7	12
D. Height, step to landing:	6	12
E. Width, handrail-handrail:	21	24
F. Min overhead clearance:	5.5ft	
G. Height of handrail:	34	37
H. Diam of handrail:	1.1	2
I Min hand clearance:	3	



	In. Min	In. Max
A. Angle of rise:	75°	90°
B. Rung or cleat diam:		
Wood:	1.1	1.6
Protected metal:	0.8	1.6
Metal that may rust:	1	1.6
C. Rung spacing:	9	
D. Height, rung to landing:	6	
E. Width between stringers:	12	
F. Climbing clearance width:	24	
G. Min clearance depth:		
In back of ladder:	6	
On climbing side.	36 for 75°	30 for 90°
H. Height of string above landing:	33	
I Max height of climb:		10ft

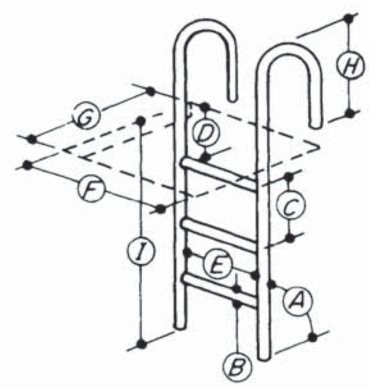
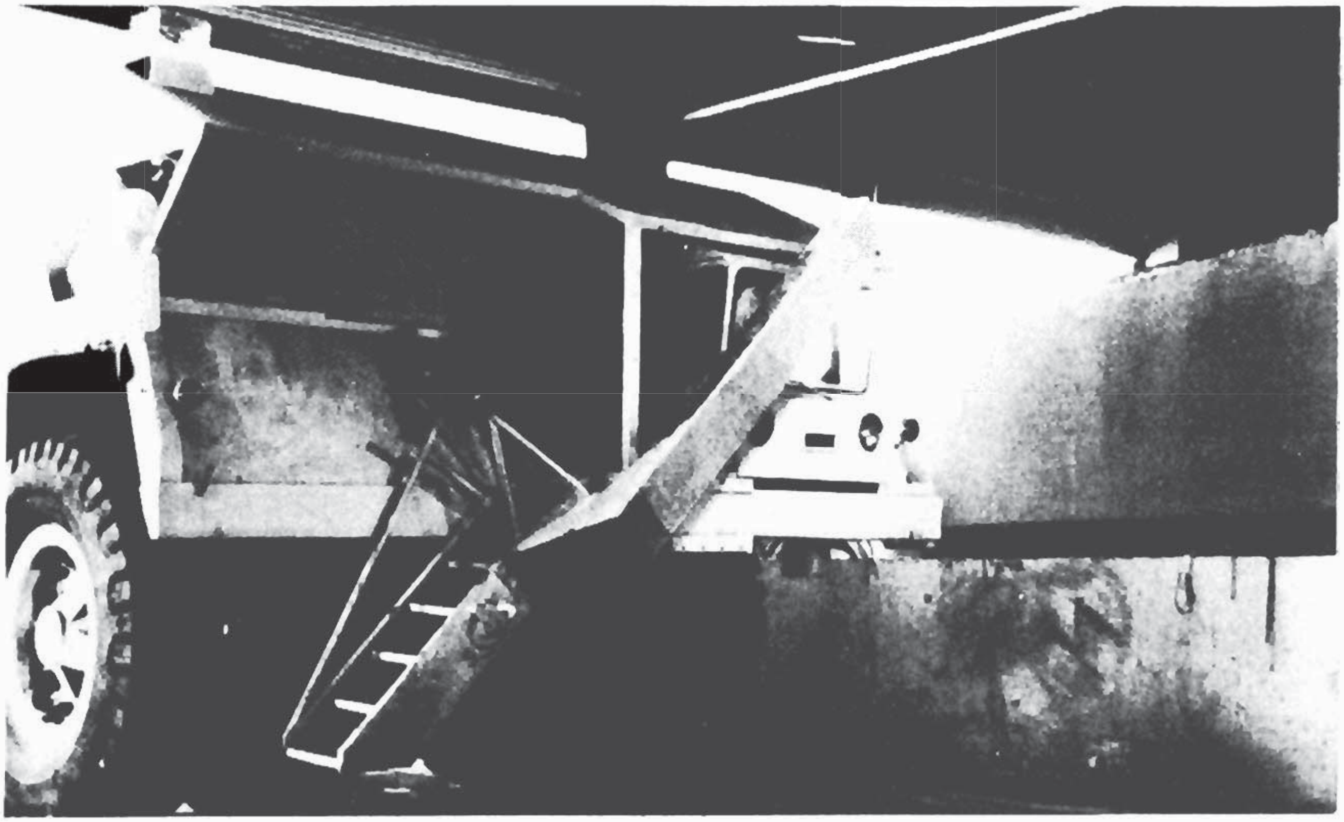


Figure 6-33.—Design recommendations for stairs and ladders, in inches (*30*). (Courtesy of U.S. Army Missile Command)



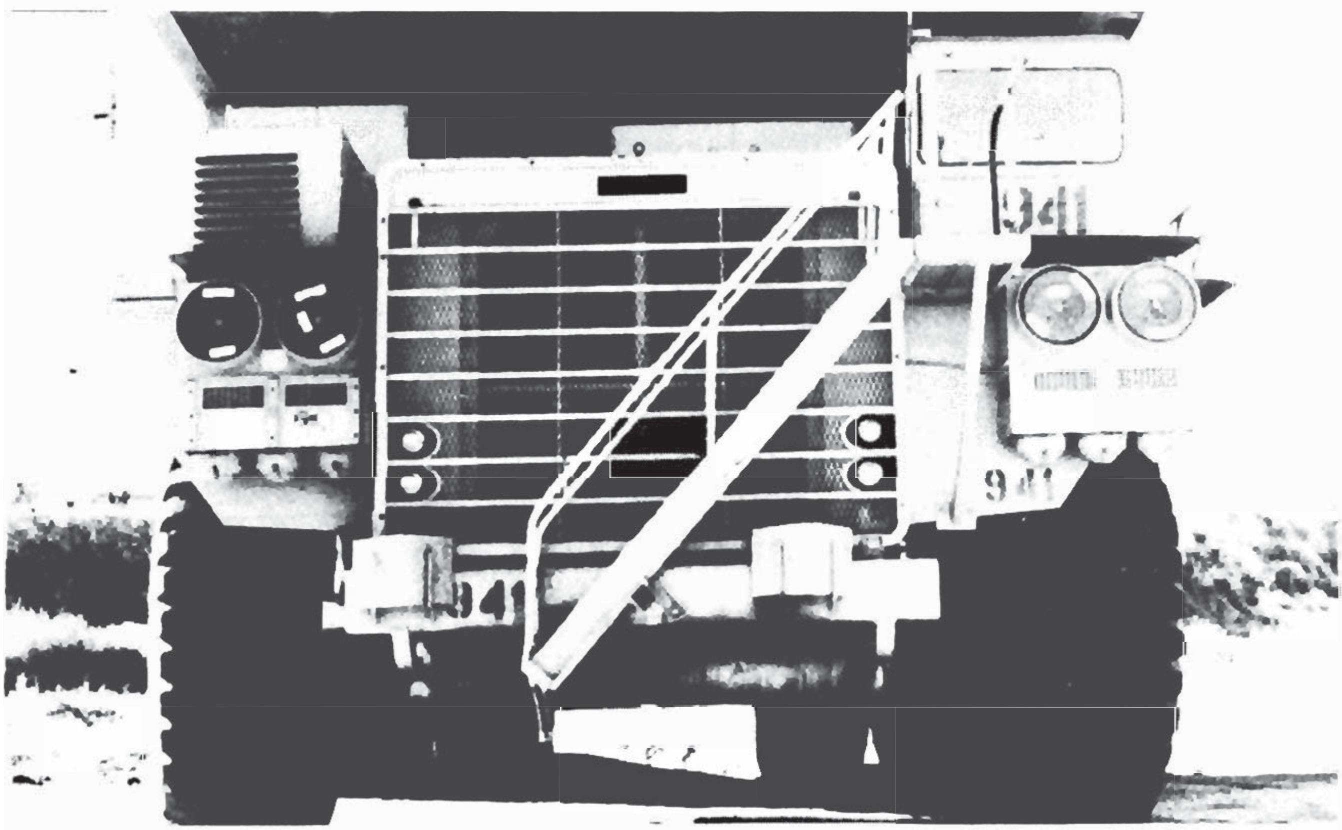


Figure 6-34.—Stairs used on haulage trucks instead of vertical ladders (*6*). Top, counterbalanced pulldown design; bottom, fixed immovable design.

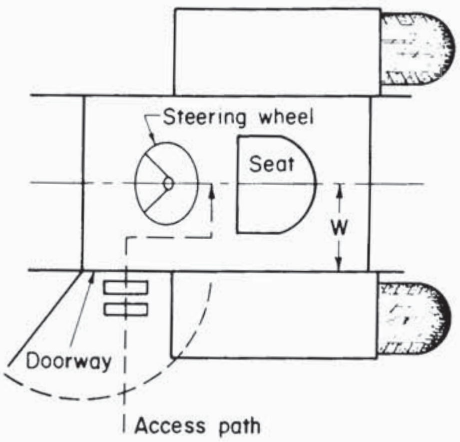


Figure 6-35.—Schematic diagram showing relationship of seat, steering wheel, and doorway on a typical tractor (W is effective platform width) (*3*). This design requires the driver to maneuver around the steering wheel. (Courtesy of Butterworth Scientific Ltd.)

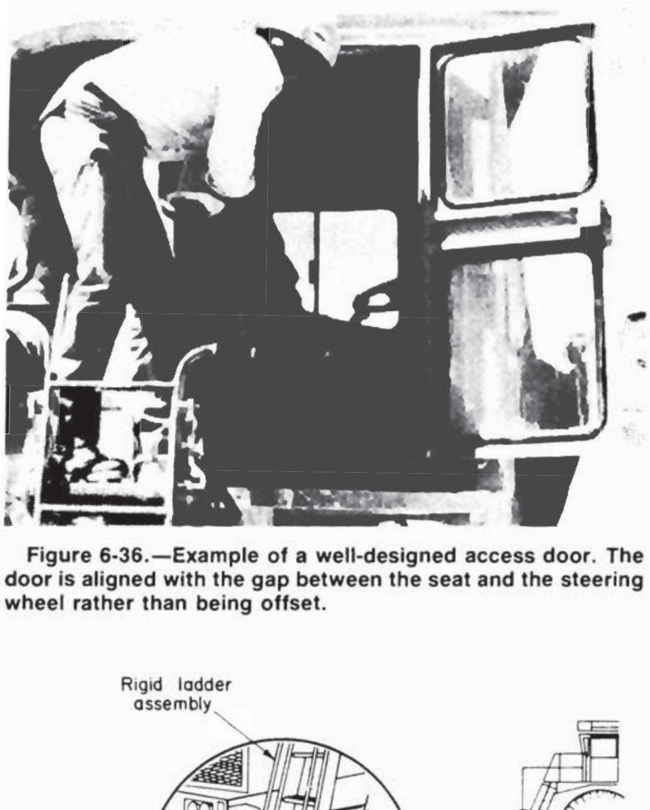


Figure 6-36.—Example of a well-designed access door. The door is aligned with the gap between the seat and the steering wheel rather than being offset.

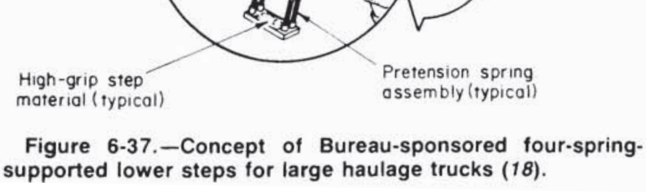


Figure 6-37.—Concept of Bureau-sponsored four-spring-supported lower steps for large haulage trucks (*18*).

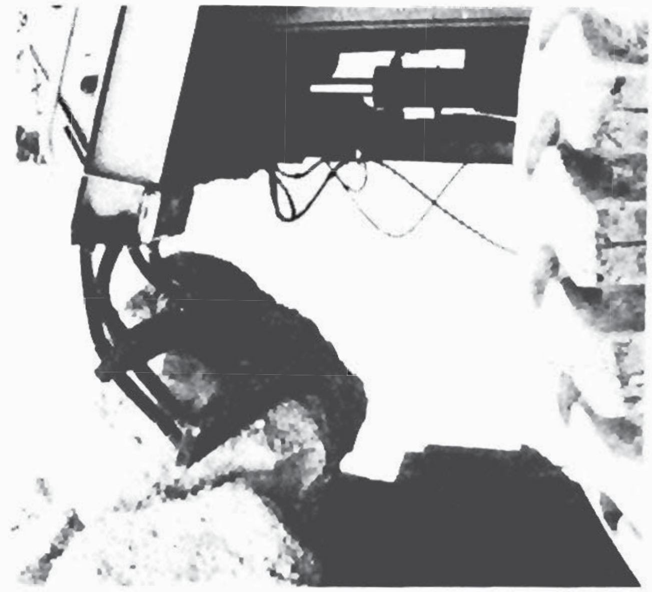


Figure 6-38.—Bureau-sponsored four-spring-supported lower steps colliding with a large rock (*18*).

The Bureau also supported a research and development project to build a hydraulic lift "power" step for access to an operator's cab. Its principal application is for track dozers and shovels. Figure 6-39 shows a man and some materials being transported via the power step. Both the spring-supported steps and the power step have been field tested with favorable results in terms of safety and reliability.

Designing for Maintainability

As mining equipment becomes larger and more complex, increased demands are placed on the maintenance function. Equipment must be routinely serviced to keep it in good working condition and to reduce downtime. When equipment fails, it must be fixed quickly and returned to service. Unfortunately, equipment is not often designed for serviceability or maintainability. Design problems with off-highway equipment were discussed by Puffer (*23*) and include poorly designed fluid level indicators that are so difficult to read that they are ignored, filters that are so difficult to reach and remove that they frequently are not serviced on schedule, and filler caps that are located where dust will accumulate and contaminate the system.

Complex maintenance procedures are required to fix simple problems. On one 120-st-capacity electric drive rear-dump truck, for example, to remove the wheel motor, it is necessary to remove the truck bed, the entire rear axle assembly, and the casing around the axle-wheel to expose the motor. In another truck, to change four belts or certain hoses, either the radiator or the engine block have to be removed (*18*). Long also listed the following design problems related to haulage truck maintenance. (These problems, however, are not restricted to trucks, but are found with most mining equipment.)

1. Poor access to machine parts or areas of the unit for routine or unscheduled maintenance tasks.
2. Inadequate access openings to permit a person to reach or climb in to repair or replace parts.
3. Need to remove or dismantle ancillary components in order to gain access to the failed unit.

Figure 6-39.—Bureau-sponsored hydraulic "power" step for egress and ingress from tractors, dozers, and shovels (*18*).

4. Inadequate or no provisions for the safe handling of heavy or large parts.
5. Inadequate tools to perform the required maintenance tasks.

Often, if maintenance tasks were thoroughly analyzed in the initial design stage, many of the problems would be obvious and correctable. Unfortunately, maintenance procedures are often not even developed until after the equipment is designed and fabricated.

This chaper does not cover the intricacies related to designing for maintainability, such as designing fasteners and connectors; covers, cases, and shields; or cables and hoses. However, because inadequate access for removal and replacement of parts and making periodic adjustments ranks as one of the most prevalent maintenance design problems, information is supplied on access space. Appendix E contains information regarding required work area clearances needed to accommodate various working postures, selected clearances for arms and hands, access spaces required to operate typical handtools, and access spaces required to grasp various sized objects with one or two hands (*30*).

HANDTOOL DESIGN

In 1983, MSHA accident data revealed 7% to 10% of all nonfatal, lost-days accidents in the mining industry were related to handtools (*31*). The problem can often be traced to using the wrong tool for the task at hand. This is not surprising when one considers the vast array of specialized tools available. For example, Williams (*34*) described 25 different types of wrenches for various tasks. One can hardly expect every maintenance person to carry a full complement of such wrenches in addition to all the various types of hammers, screwdrivers, etc., that are available. The result is that one wrench often serves multiple purposes, including acting as a hammer.

In the mining industry, as in most other industries, nonpowered handtools make up the bulk of handtool-related injuries, often 75% or more. The most commonly implicated tools are hammers, wrenches, and knives. There is a body of human factors literature related to the design of hand tools that provides guidance with respect to size and weight, handle design, and positioning of trigger switches. The interested reader is referred to references 8 and 9.

Principles of Handtool Design

This section discusses some general principles of handtool design as given by McCormick and Sanders (*20*). It also discusses the special problem posed by vibrating handtools such as rock drills, pneumatic chipping tools, and chain saws.

Maintain a Straight Wrist

The flexor tendons of the fingers pass through a tunnel in the wrist and attach to the muscles in the forearm. This tunnel is called the carpal tunnel because it is formed by the transverse carpal ligament. When the wrist is bent, the tendons bend and bunch up in the carpal tunnel. Repetitive wrist bending, or the exertion of forces by the hand with the wrist bent, can cause an inflammation of the tendon sheaths of the wrist (tenosynovitis). In addition, the median nerve also passes through the carpal tunnel and can be injured by the same kinds of actions that cause tenosynovitis. Injury to the median nerve is called carpal tunnel syndrome and sometimes requires surgery to correct the problem and relieve the pain. A common type of hand motion that can lead to tenosynovitis is that of "clothes wringing" (*28*), in which the wringing is done by a clockwise movement of the right hand and counterclockwise action of the left. This type of motion is involved when inserting screws in holes, and looping wire while using pliers. In general it is better to bend the tool than the wrist. Figure 6-40 shows examples of tools that have been redesigned to permit straight-wrist use.

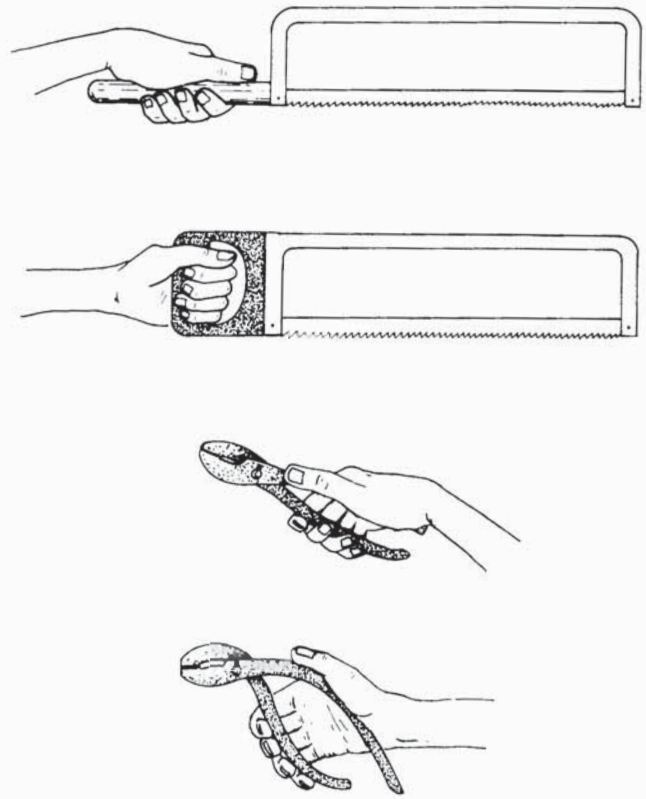


Figure 6-40.—Examples of common handtools designed to permit users to maintain straight wrists.

Avoid Tissue Compression Stress

Often in the operation of a handtool, considerable force is applied to the palm of the hand. Handles of pliers dig in to the palm area; the palm is used to exert force on the top of a screw driver; or the palm is used to pound a wrench. All of these actions can damage unprotected blood vessels and nerves in the hand.

Avoid Repetitive Finger Action

Excessive use of the index finger to operate triggers can result in "trigger finger," where the person can flex the finger but cannot extend it. In general, frequent use of the index finger should be avoided, and thumb-operated contacts should be used.

Design for Safe Operation

This includes the elimination of pinching hazards, sharp corners, and edges; installation of braking devices in power tools to stop the tool quickly when the trigger is released; and the proper placement of on-off switches to reduce accidental activation and permit quick response times to turn off the device.

Women and Left-Handers

The number of women in the mining industry workforce is increasing. The major problem women have with handtools is that their hands are too small to effectively operate some tools, such as wire strippers, crimping tools, pliers, and shears. The maximum grip strength can be applied when the handle opening of a tool is 2.5 to 3.5 in; this applies to both males and females. The maximum handle opening should not exceed 4.0 in in order to accommodate smaller female hands.

Left-handers make up about 8% to 10% of the population. Tools should be designed so that they can be used by either left- or right-handed operators. Trigger positions and stabilizing handles should be mounted to allow operation with either hand.

Although it is often not possible for companies to design and fabricate their own handtools, awareness of the basic human factors principles can be valuable in selecting the proper tools for a job and for training workers in the proper use of handtools.

Vibration-Induced White Finger

The National Institute for Occupational Safety and Health (NIOSH) estimated that over 100,000 workers in the mining industry are potentially exposed to hand-arm vibration from pneumatic and motor driven tools (*22*). It is now recognized that exposure to this sort of vibration can cause a condition known as vibration-induced white finger (VWF). Early stages of this syndrome are characterized by tingling or numbness in the fingers. As NIOSH points out, temporary tingling or numbness during or soon after use of a vibrating handtool is not considered VWF. The symptoms must be more persistent and occur without provocation. Other symptoms include blanching, pain, and flushing of the fingers. These symptoms usually appear suddenly, and are precipitated by exposure to cold. With continued exposure to vibration, the signs and symptoms become more severe and the pathology may become irreversible.

The recognition of VWF among miners dates back to the early 1900's when Hamilton (*12*) described spastic anemia of the hands among limestone quarry workers using pneumatic chipping hammers and drills. Studies by NIOSH (*22*) found an incidence of VWF symptoms as high as 83% in workers exposed to vibrating handtools in foundries.

Despite considerable research, little is known about the physiological basis of VWF or which specific vibration parameters are most necessary to control. It is certain, however, that progressive stages of VFW arise from the cumulative effect of trauma to the hands from regular, prolonged use of vibrating handtools.

Redesign of a rock drill and air leg unit, and reducing the level of vibration significantly, was reported by Rogers, Eglin, and Hart (*24*). They were not successful in their search for a glove material that would reduce the vibrations transmitted to the hand. Attempts by manufacturers to reduce vibration from chain saws has been very successful and has contributed to a reduction of VWF cases among chain-saw operators (*2*).

DISCUSSION

This chapter has briefly reviewed major human factors issues in the design of hardware and has presented some data, both in the chapter and in appendixes, that can be used to evaluate and enhance the design of mining equipment. More extensive data can be found in references 8, 30, 32, and 35.

The design of equipment is the culmination of a systematic approach that should detail the task requirements for the operator and maintainer, and incorporate considerations of human limitations into the final design. A well-designed piece of equipment will result in reduced training time, higher productivity, fewer accidents, and greater worker satisfaction and comfort.

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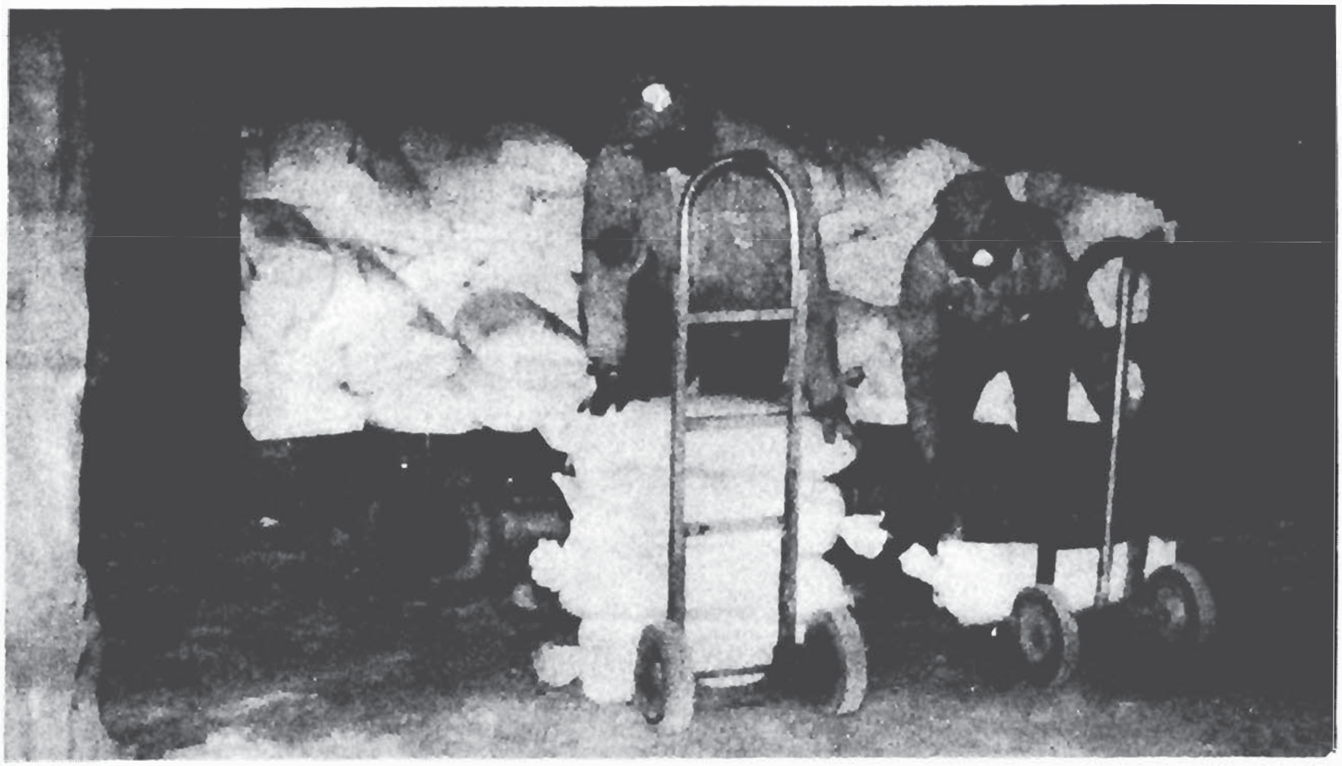
CHAPTER 7.—PHYSICAL WORK



Mining will always be a physically demanding occupation, but by proper design of the tasks and worksites and through employee training, the incidence and severity of injuries can be reduced.

Despite increased mechanization, mining remains one of the most physically demanding occupations in the world. For example, it was found by Van Rensburg *(37)*[1] that in South African gold mines with increased mechanization, more people were working in less strenuous jobs, but the physical demands of the tasks themselves were not reduced. The high physical demands inherent in mining take their toll in injury and productivity. Underground mining labor is especially susceptible because of the cramped working conditions and the presence of heavy objects that must be lifted and carried. Rock dust sacks can weigh 50 lb; a 75-ft roll of brattice, 60 lb; and a 6- by 10-in, 14-ft wood crossbar, over 200 lb. With such loads, it is not suprising that back injuries constitute the largest single type of lost-time accidents in the mining industry, accounting for approximately 25% of all lost-time injuries, 5,458 in 1981 alone *(30)*. Further, this type of injury accounts for more lost workdays than any other single type. In 1981, for example, Peay *(30)* noted that 40% of lost-time back injuries incurred by underground coal miners resulted in more than 4 weeks of lost time per individual.

In addition to the pain and suffering caused by injury, physically demanding tasks take their toll on productivity by fatiguing the worker. The more demanding the task, the more rest the worker needs.

[1] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

This chapter will review the basics of work physiology and manual materials handling, and the demands of common mining tasks. Recommended limits on physically demanding work will be discussed, as well as human factors methods for reducing the risks involved in such work.

WORK PHYSIOLOGY

Muscles

Muscles in our bodies allow us to move and to perform useful work. Approximately 40% of one's total body weight is composed of muscle. Each muscle consists of large numbers of muscle fibers ranging in length from 0.2 to 5.5 in. The diameter of an individual muscle fiber is about four ten-thousandths of an inch, and a muscle can have a million such fibers.

The most important characteristic of muscle is its ability to contract; that is, it can shrink to about two-thirds of its normal length. Each muscle fiber contracts with a certain force, and the strength of the whole muscle is the sum of the forces produced by these muscle fibers. Hence, the cross-sectional area of a muscle determines its strength. A muscle produces its greatest force at the beginning of its contraction when it is at its relaxed length. As a muscle shortens, its power declines.

Muscular contraction is initiated by an electrical impulse. This electrical activity can be detected and measured by a technique known as electromyography. Electrodes are attached (taped) to the surface of the skin over the muscle to be examined. The exact placement of the electrodes is important to insure reliable and valid data. Skin electrodes record the total electrical activity of the muscle. The readings appear as rapid pen movements on a strip chart recorder, much like those produced by a seismograph during an earthquake. These recordings can be calibrated to yield measurements of the force of the muscle contractions. Figure 7-1 shows electromyograms (EMG's) of a biceps muscle producing 15, 30, 45, and 60 ft-lb of static torque (*22*). As can be seen, the higher the torque being produced, the greater the electrical activity and the more "violent" the pen recordings.

EMG's are usually processed electronically to yield a simple integrated score. The use of this method, however, requires well-trained technicians and precisely calibrated equipment.

Energy Consumption

To perform work a muscle must expend energy. The detailed process by which a muscle obtains the energy needed to perform work is complex and beyond the scope of this report. The interested reader can consult Astrand and Rodahl (*3*) or Weiser (*38*). For the purposes of this report, a somewhat simplified presentation will suffice, as given by Grandjean (*17*).

Muscle work is accomplished by the transformation of chemical energy into mechanical energy. Energy is released in a complex series of chemical reactions. Figure 7-2 shows a very simplified diagram of the process. A muscle get its

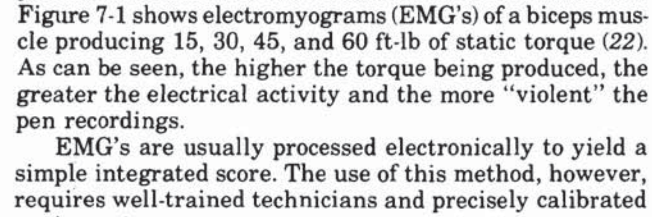


Figure 7-1.—Electromyogram recording of biceps muscle during static force application (*22*). (Copyright 1973 by the Human Factors Society Inc., and reproduced by permission)

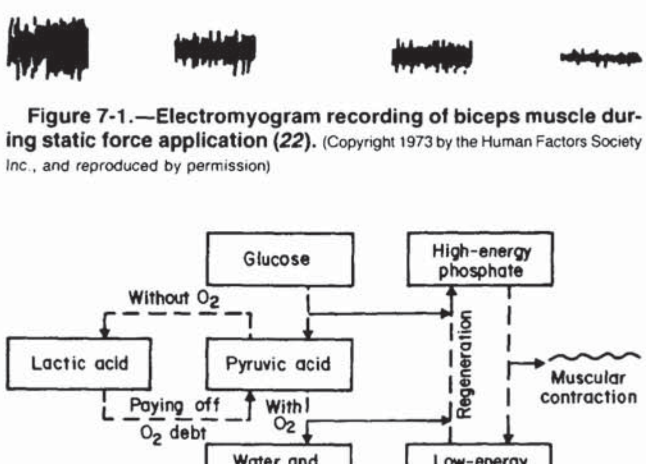


Figure 7-2.—Schematic representation of metabolic process that takes place during muscular work (*17*). (Courtesy of Taylor and Francis Ltd.)

energy from the breakdown of high-energy phosphate compounds into low-energy compounds; this process does not require oxygen. The problem is that there are not a lot of high-energy phosphate compounds available in a muscle, and they must be regenerated to provide additional energy for the muscle. This regeneration process requires energy from other chemical reactions.

The main energy source for the regeneration process during intense physical work is glucose, a sugar circulating in the blood. Glucose is converted into pyruvic acid, and this liberates energy for the regeneration process. The further breakdown of pyruvic acid depends on whether sufficient oxygen is present in the system. If pyruvic acid is being produced in small quantities, enough oxygen will be available to break down the acid into water and carbon dioxide (aerobic glycolysis). This breakdown is also a source of energy for the regeneration process.

If, however, insufficient oxygen is available to break down pyruvic acid, then the pyruvic acid is converted into lactic acid, a metabolic waste product (anaerobic glycolysis). This conversion releases a small amount of energy that can also be used for the regeneration process. The build up of lactic acid in a muscle, however, will cause it to cease contracting. To eliminate the lactic acid, oxygen is needed to first convert the lactic acid back to pyruvic acid and then to water and carbon dioxide, thus releasing more energy for regeneration of the high-energy phosphate compounds.

From this thumbnail sketch, it can be seen that at the outset of physical work, a muscle does not need oxygen to function. A sprinter, for example, can run a 100-yd dash without taking a breath (*14*). This is because energy is released from the breakdown of high-energy phosphate compounds and from the breakdown of glucose to pyruvic acid and pyruvic acid to lactic acid. At the completion of a run, however, the sprinter would be breathing heavily, and his or her heart would be pounding. The runner is said to be in oxygen debt. That is, the body must take in oxygen, after the muscular work has been completed, to convert the lactic acid back to pyruvic acid and ultimately to water and carbon dioxide. The energy released is used to regenerate the high-energy phosphate components depleted during the run.

The body does not respond immediately to the onset of heavy work; it takes a couple of minutes until the body mobilizes its forces to supply the working muscles with oxygen. Figure 7-3 shows the oxygen uptake, over time, in response to physical work. The initial lag creates an oxygen deficiency that is made up during recovery, when the oxygen debt is repaid.

Cardiac Output and Aerobic Capacity

The body mobilizes to supply increased quantities of oxygen and glucose to the working muscle. Just breathing deeper and faster, however, does little to increase the oxygen supply in the blood; this because blood leaves the lungs 97% saturated with oxygen under normal healthy conditions. The only way to increase the supply of oxygen to a muscle is to pump more blood through the muscle. This is done by increasing the heart rate (beats per minute) and increasing the volume of blood pumped with each beat (stroke volume). Combined, the overall cardiac output (liters of blood per minute) increases. At rest, the cardiac output is about 5 L/min. Coincidentally, the average adult body contains only about 5 L of blood. In severe work, a fourfold

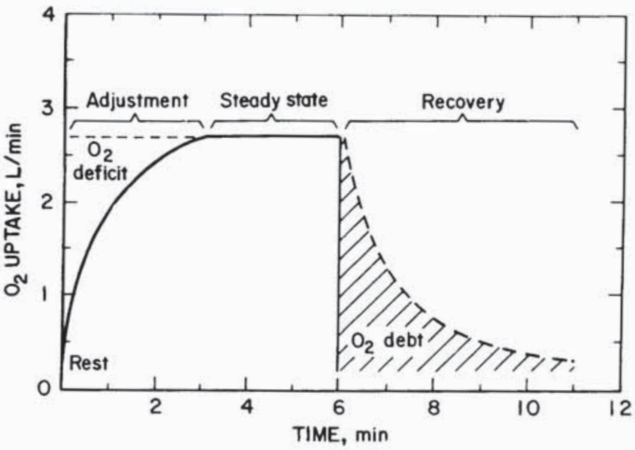


Figure 7-3.—Oxygen uptake during muscular work, showing oxygen deficiency at the outset of work and the repayment of the oxygen debt during recovery.

to fivefold increase in cardiac output, 20 to 25 L/min, can take place.

There is a limit to the capacity of the body to increase cardiac output and, hence, deliver oxygen to the muscles. This leads to an important concept: maximum aerobic capacity (VO_2 max). This is the maximum oxygen uptake (consumption) the body is capable of delivering. Individuals have different aerobic capacities because of such things as their degree of physical training, age, sex, and ability of their blood to carry oxygen. For discussion of how to determine an individual's maximum aerobic capacity, see reference 21. The concept of maximum aerobic capacity is important for determining safe levels of energy expenditure over the course of a workday, which will be discussed later in this chapter.

The aerobic work capacity of U.S. low-seam underground coal miners was measured by Ayoub (*4-5*). The results are shown in figure 7-4. Aerobic capacity declines with age (the exception in the over 50-yr group is probably due to the small sample of miners tested) and is lower for females. In comparing these results with American Health Association norms (*1*), the low-seam coal miners would be rated about average in terms of cardiovascular fitness. As shown in figure 7-4, the aerobic capacity of American low-seam coal miners is below the levels of physical work (aerobic) capacity of South African miners (*28*), and Norwegian and Romanian miners (*39*). American miners were also heavier than the other groups.

Ayoub (*4*) speculates that since low-seam coal miners engage in tasks that require short intervals of work with high energy expenditures, it is possible that these miners become specifically trained in the anaerobic (without oxygen) energy mode.

MEASUREMENT OF WORK

The basic unit of energy, heat, or work is the calorie. A kilocalorie is equal to 1,000 cal and is the basic unit of energy expenditure.[2] A kilocalorie is the amount of heat

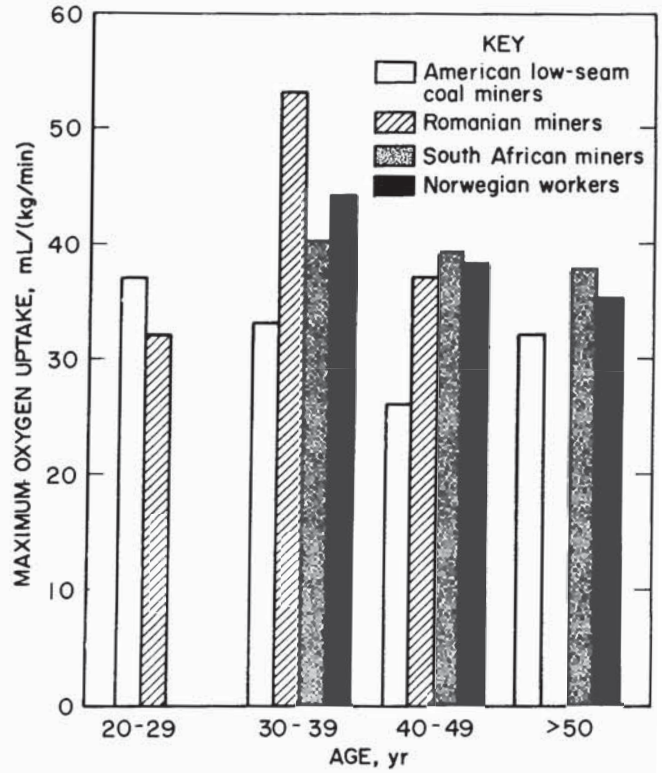


Figure 7-4.—Aerobic capacity of male miners by age group (*4, 28, 39*).

needed to raise 1 L (a little over a quart) of water, 1 °C (from 20° to 21 °C). In dietary circles, the term "Calorie" is equal to 1 kcal.

To determine the energy requirements of a given task, the amount of oxygen consumed by the person doing the task needs to be known. Based on the typical Western diet, it is known that for every liter of oxygen consumed, approximately 5 kcal of energy is expended. That energy is used by the muscles to perform work and is also given off as heat during the various chemical reactions discussed previously. Approximately 75% of the energy liberated by the body goes to heat; only about 25% is used for work. This level of efficiency is better than a steam engine, but not quite as good as an internal combustion engine.

Measuring oxygen consumption can be cumbersome, requiring the person performing the task to wear a mouthpiece, nose clip, and gas-measuring device on his or her back. Flexible hoses connect the mouthpiece to the measuring device. Fortunately, there is an easy way to estimate oxygen consumption without actually measuring it while performing the task. Heart rate and oxygen consumption are linearly related within the range from moderate to close-to-maximum work loads.

Once the specific linear equation relating heart rate to oxygen consumption for an individual is known, oxygen consumption can be estimated based on heart rate measured while performing the task. It should be pointed out, however, that factors such as heat, fatigue, and smoking can distort the relationship between heart rate and oxygen consumption.

Heart rate can be measured with a few wires attached to the subject and a tape recorder or telemetry device the

[2] The calorie is now obsolete and has been superseded by the joule (1 cal = 4.2 J). Since most of the literature still uses kilocalories (1 kcal = 4.2 kJ) it will be used in this chapter.

size of a cigarette package. The problem is that the equation relating heart rate to oxygen consumption is not the same for everyone. Physical fitness is a major factor determining individual differences. Figure 7-5 shows examples of heart rate-oxygen consumption relationships for various adult men; the steeper the slope of the line, the better the physical condition of the individual (*20*).

Therefore, to use heart rate to predict oxygen consumption, an individual must be calibrated. This is done by having the person perform a task at different levels of effort (e.g., walking on a treadmill at different speeds), while both heart rate and oxygen consumption are being measured. From such data, the relationship can be determined.

There are two types of muscular effort, dynamic (rhythmic or isotonic) and static (isometric). Dynamic effort is characterized by an alternation of contraction and relaxation of a muscle. During dynamic effort, the alternating contraction and relaxation squeezes blood through the muscle, thereby supplying the working muscle with glucose and oxygen.

Static effort, in contrast, is characterized by a prolonged state of contraction of the muscles. Examples of static effort are bending over at the waist and holding that posture while repairing a piece of equipment, or holding the arms out in front of the body while hanging brattice, as shown in figure 7-6. During static effort, the blood vessels are compressed by the muscle itself so that blood flow through the muscle is reduced or stopped. The flow of blood is constricted in proportion to the force exerted by the muscle. Grandjean (*17*) indicates that blood flow is almost completely interrupted if the effort is 60% of the maximum effort possible. At 15% to 20%, blood flow should be normal.

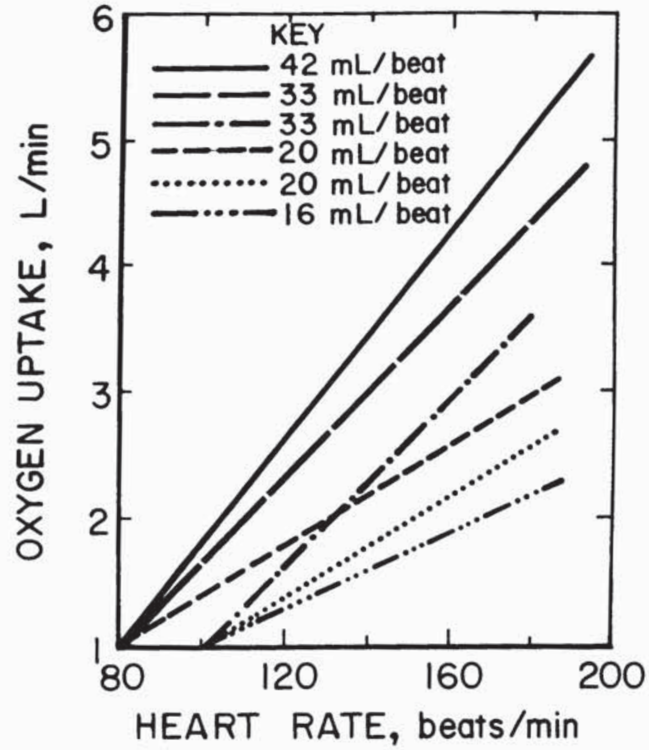


Figure 7-5.—Linear relationship between heart rate and oxygen uptake for six adult males (*20*). (Copyright 1973 by the Human Factors Society Inc., and reproduced by permission)

Figure 7-6.—Underground worker hanging brattice cloth with arms at full extension and static loading of shoulder muscle.

The impaired blood flow allows waste products (principally lactic acid) to build up in the muscle, leading to acute pain and muscle fatigue. The maximum duration of a contraction is related to the force exerted. Exerting a force of 50% of maximum can be endured, at most, for 1 min. Forces of 25% of maximum can be maintained for about 3 to 4 min, while forces of 20% or less can be endured for 10 min or more.

All tasks involve components of both static and dynamic effort. The static component, however, is by far the most fatiguing and should be reduced if possible. Static effort can be decreased by reducing the effort required, switching components of the task so that muscle groups can be alternately flexed and relaxed, and inserting numerous small rest breaks during the task.

ENERGY EXPENDITURE AT WORK

There are many factors that affect the energy expenditure involved in performing a task. With respect to lifting objects, the principal ones are the following:

1. *Body weight.*—A task that requires a person to move his or her body will require more energy the heavier the weight of the person's body. Tasks that involve carrying objects or picking up objects by squatting or bending at the waist are examples of those affected by body weight.

2. *Body posture.*—For example, a squat lift requires more energy than a stoop lift (straight leg, bent at the waist), because more of the body must be lifted in a squat lift.

3. *Weight of objects moved.*—The heavier the load to be moved, the greater the work performed, and hence the greater the energy expenditure. Figure 7-7, based on the work of Brown (*7*), for example, shows the combined effect of weight of load and lifting posture on energy expenditure.

4. *Work pace.*—Work pace is defined as the number of times an activity is performed per unit of time. In normal lifting, it is the number of lifts per minute. As shown in figure 7-8, it appears that the relationship between work pace and energy expenditure is essentially linear (*18*).

5. *Distance traveled.*—The distance a load is moved, or the distance over which a force is applied, is directly related to energy expenditure. In normal lifting, it is the vertical distance the load is lifted that is most important.

6. *Temperature and humidity.*—In general, the higher the temperature and humidity, the greater will be the energy expenditure for tasks performed in such environments. Part of this increase is due to a general increase in metabolic rate in hot environments.

One additional factor that impacts energy expenditure, and is especially important in normal lifting, is the vertical heights of the beginning and end points of the lift. Lifting the same distance, but starting at different heights, may require the lifter to assume different body postures and may involve differential movement of the body's center of gravity, as illustrated by the data in table 7-1. Although the same overall mechanical work is being performed, the energy expenditure is greater for the task that starts out at a lower height (task B), despite the fact that the work pace is less.

Figure 7-9 shows the energy efficiency (energy per unit mechanical work) for lifting various weights 20 in from various starting positions (*12*). The most energy efficient lifting occurs when the starting position is between 39 and 59 in above floor level. When the starting position is below 39 in the efficiency is greater the heavier the load. This is true because the energy required to lift the body is constant, no matter what the load.

Grades of Physical Work

Table 7-2 defines seven grades of work, including rest, based on energy expenditure. Also included are associated average heart rates and oxygen consumption values. The data presented apply to reasonably fit adult males.

Energy Expenditures for Common Mining Tasks

In a survey of low-seam coal mining tasks, Ayoub (*4*) identified the following jobs as most physically demanding: roof bolter, bolter helper, miner helper, and timberman. Table 7-3 shows the energy expenditure on these jobs and for the task of shoveling; the grade of work to which each corresponds is also shown. The energy expenditure for shoveling is unusually high because this task is performed at a rapid work pace at the coal face. In addition, it was reported by Morrisey (*24*) that the energy cost of shoveling increases as a worker is forced to assume a more stooped posture, common in low-seam mines. At 60% of a normally

Table 7-1.—Effect of vertical starting position on energy expenditure (*27*)

(Courtesy of National Institute for Occupational Health)

	Task	
	A	B
Load . . . lb	10	10
Work pace . . . lifts/min	25	21
Vertical starting position . . . in	36	[1]0
Vertical ending position . . . in	66	36
Mechanical work performed . . . kg-m	86.6	86.0
Energy expenditure . . . kcal/min	3.56	6.77

[1] Floor.

Table 7-2.—Grade of physical work based on energy expenditure level[1] (*2*)

(Reprinted with permission by American Industrial Hygiene Assoc.)

Grade of work	Energy expenditure, kcal		Heart rate, beats/min	Oxygen consumption, L/min
	Per min	Per 8-h day		
Rest (sitting)	1.5	720	60- 70	0.3
Very light work	1.6- 2.5	768-1,200	65- 75	0.32- .5
Light work	2.5- 5.0	1,200-2,400	75-100	.5 -1.0
Moderate work	5.0- 7.5	2,400-3,600	100-125	1.0 -1.5
Heavy work	7.5-10.0	3,600-4,800	125-150	1.5 -2.0
Very heavy work	10.0-12.5	4,800-6,000	150-180	2.0 -2.5
Unduly heavy work	>12.5	>6,000	>180	>2.5

[1] Assumes a reasonably fit adult male.

Table 7-3.—Energy expenditures for four low-seam tasks (*4*), kilocalories per minute

Task and grade of work	*Expenditure*
Shoveling, heavy work	9.3
Helping,[1] moderate work	7.2
Timbering, moderate work	6.0
Roof bolting, light work	4.9

[1] Includes both continuous miner and roof bolter helpers.

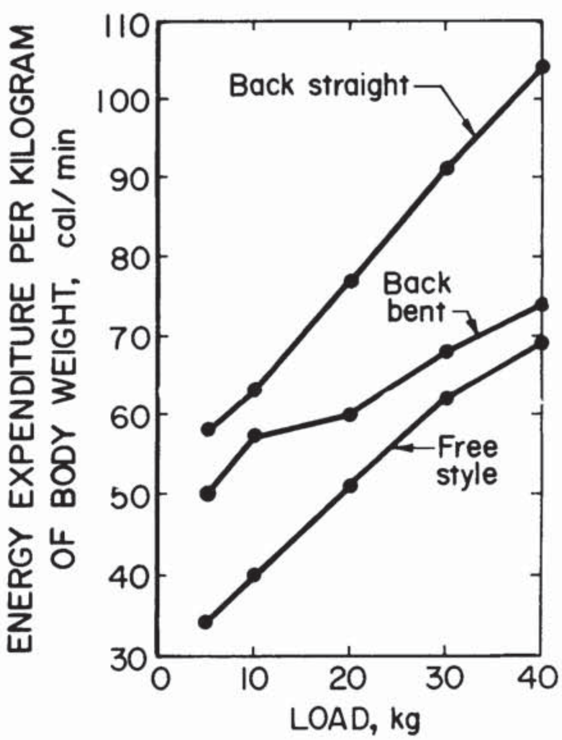


Figure 7.7—Effect of weight of objects being lifted and lift posture on energy expenditure (27). (Courtesy of National Institute for Occupational Safety and Health)

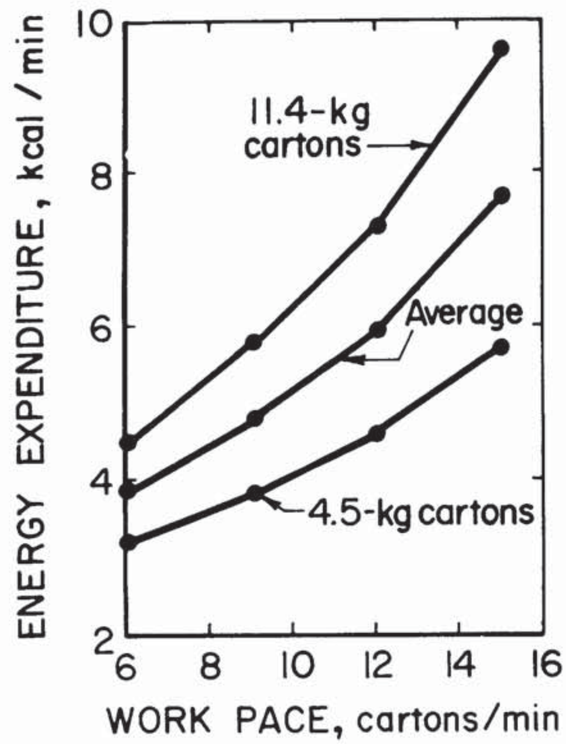


Figure 7-8.—Effect of work pace on energy expenditure for a lifting task (18). (Copyright 1969 by the American Institute of Industrial Engineers, and reprinted by permission)

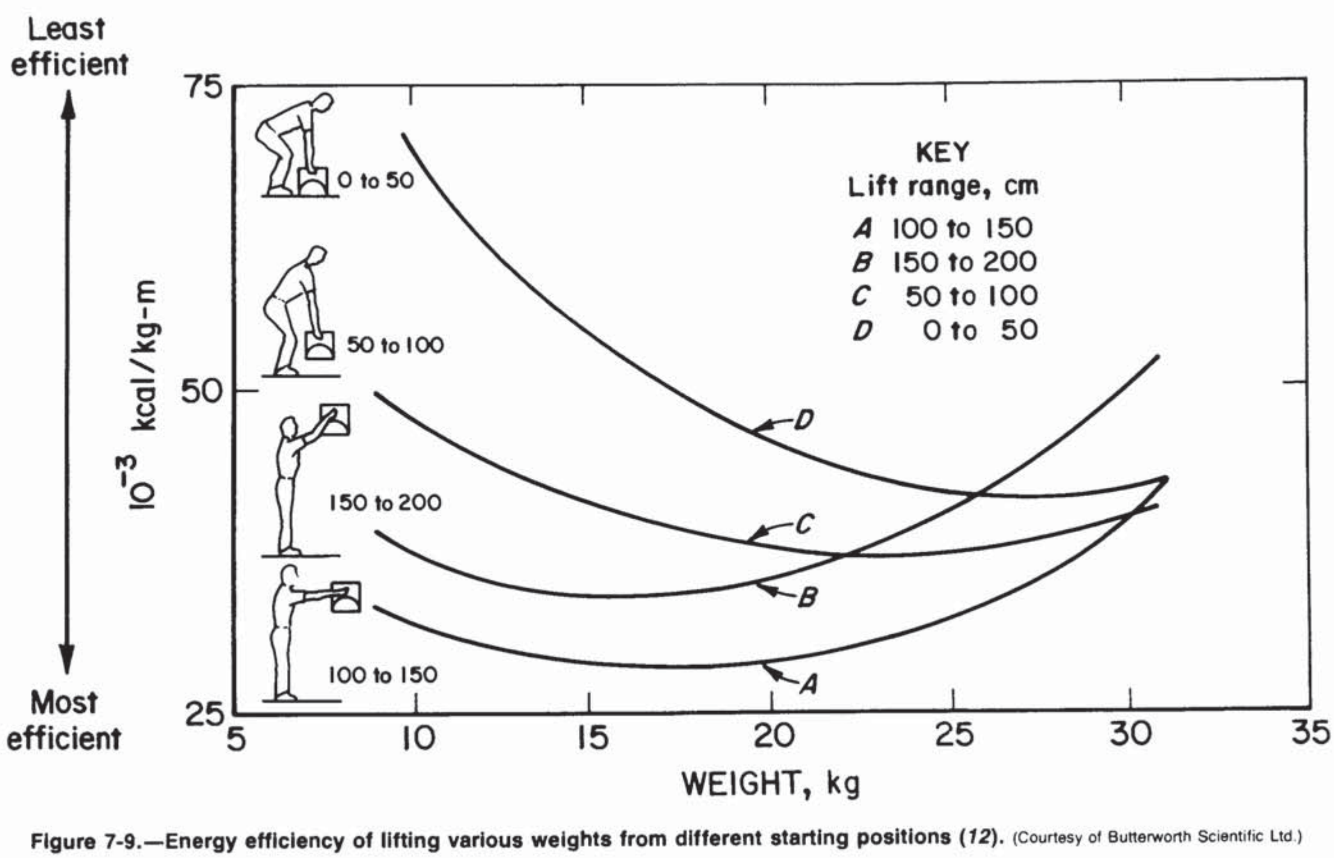


Figure 7-9.—Energy efficiency of lifting various weights from different starting positions (12). (Courtesy of Butterworth Scientific Ltd.)

erect posture, for example, energy expenditure was 13% higher than in a fully erect posture. Table 7-4 presents energy expenditure data collected in South African gold mines on additional tasks. In handling rock dust bags (50-55 lb each) or arch sections (12 legs, 180 lb each; 6 crowns, 170 lb each), it was found by Sims (*33*) that the energy expenditure was approximately the same, 6.0 kcal/min (moderate work).

Table 7-4.—Average energy expenditures for mining tasks in South African gold mines (*37*), kilocalories per minute

(Reprinted with permission by Chamber of Mines South Africa)

Task and grade of work	*Expenditure*
Transport of explosives (25 lb), moderate work	6.85
Shoveling, moderate work	5.85
Mechanical loader operators, moderate work	5.20
Barring down, light work	4.75
Equipping: Pipes and tracks, light work	4.65
Tip operator, light work	4.43
Timbering, light work	4.40
Sweeping, light work	3.95
Pneumatic drill operator, light work	3.95
Stonewall building, light work	3.90
Pneumatic drill assistant, light work	3.15
Locomotive driver, light work	2.60
Winch driving, light work	2.55

When these values are reviewed, it must be remembered that changes in the work pace or the method of carrying out the task can significantly affect the energy expenditure levels. Further, the energy expenditure during performance of a task varies widely depending on the specific cycle of activity. Figure 7-10, for example, presents the energy expenditure levels during a work cycle for a low-seam roof bolter helper. As can be seen, energy levels peak at approximately 11 kcal/min (very heavy work), but dip as low as 5.0 kcal/min (light work) elsewhere during the cycle.

Ayoub (*4*) calculated the total energy expenditure over a 7.5-h shift (8 h minus 0.5 h for lunch) including idle time, travel, and other activities for the workers they analyzed. The results were as follows: Helpers (moderate work), 2,789-kcal expenditure for 7.5-h shift (average of 6.1 kcal/min); roof bolters (light work), 2,102-kcal expenditure for 7.5-h shift (average of 4.7 kcal/min).

Although several tasks in mining require high levels of energy expenditure over short time periods, the level of work is generally in the light to moderate class. This, of course, is because the workers intersperse rest breaks in the work cycle or alternate between heavy and light activities. With the exception, perhaps, of shoveling, it appears that high levels of cardiovascular fitness, although desirable, are not necessary to perform the majority of mining tasks. Thus, females who generally have lower aerobic capacities than men should be able to function well in overall mining operations. As Ayoub (*4*) points out, however, females and small males may be limited because of strength, as opposed to aerobic, capacity in their ability to perform mining tasks as such tasks are performed today.

RECOMMENDED ENERGY EXPENDITURE LEVELS

The National Institute for Occupational Safety and Health (NIOSH) recommends that short-term energy expenditure levels (for 1 h or less) should not exceed 9 kcal/min for physically fit males or 6.5 kcal/min for physically fit females (*27*). The difference between the male and female recommendations is due to the generally lower aerobic capacity of females.

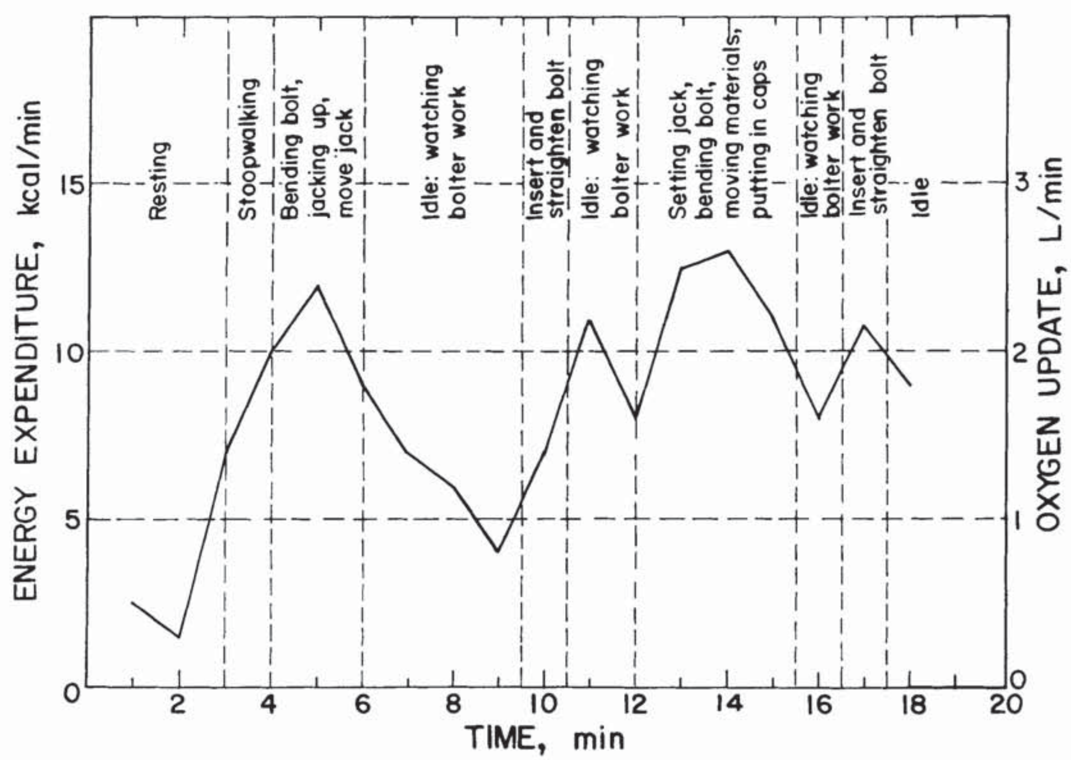


Figure 7-10.—Energy expenditure and activity profile for roof bolter helper (*4*).

Long-term energy expenditure levels (averaged over a workday) should not exceed 5.0 kcal/min for males and 3.5 kcal/min for females. These values correspond to approximately 33% of the average aerobic capacity of males and females. NIOSH points out, however, that these guidelines do not reflect the increased metabolic costs associated with overweight or poorly conditioned individuals.

Based on the aerobic capacity of males and females, and these NIOSH recommendations, the recommended maximum working time for tasks requiring various levels of energy expenditure can be computed. Figure 7-11, for example, shows recommended maximum working times for males and females performing various low-seam mining tasks. This figure gives maximum times for the 5th, 50th, and 95th percentile males and females. The 5th percentile represents the bottom 5% of the population in terms of aerobic capacity and recommended work time. The 50th percentile is the average, and the 95th percentile is what can be expected by someone who is 5% from the top of the population

Several authors have attempted to develop formulas to predict the amount of rest required, or the amount of work permitted before rest is required. Unfortunately, the formulas do not always produce the same results.

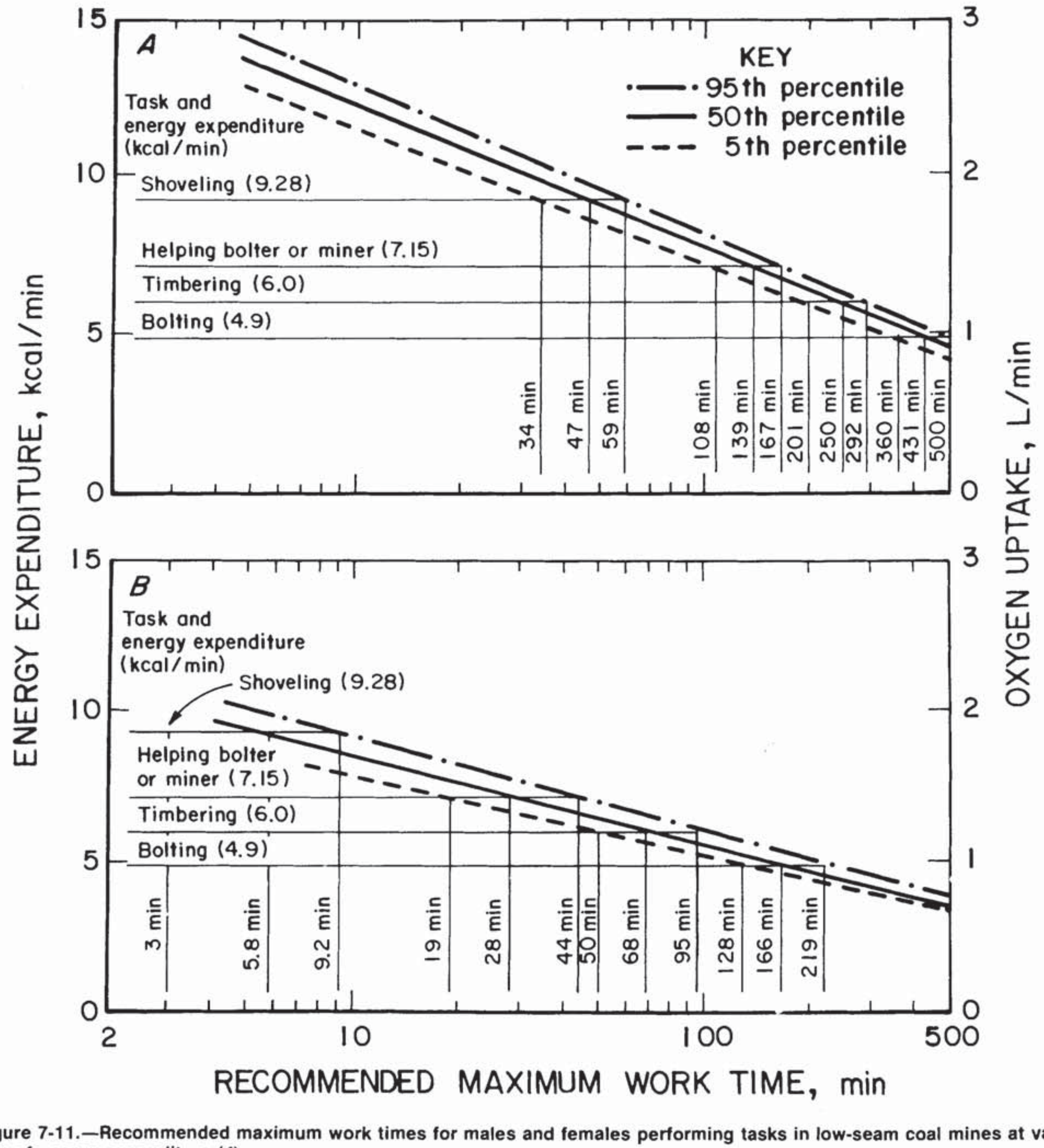


Figure 7-11.—Recommended maximum work times for males and females performing tasks in low-seam coal mines at various levels of energy expenditure (*4*).

One formula embraced by the American Industrial Hygiene Association (AIHA) (*2*) is based on the assumption that over an 8-h shift, average energy expenditures should not exceed 5.5 kcal/min. Because at-rest energy expenditure is 1.5 kcal/min, the 5.5 kcal/min figure really represents an actual work expenditure of 4.0 kcal/min. The following formula computes the needed rest allowance expressed in terms of percentage of time working:

$$RT\% = \frac{W - 1.5}{4.0} - 1 \times 100,$$

where RT% = rest allowance
and W = energy expenditure during work, kcal/min.

Murrell (*26*) presented another formula similar to the AIHA formula, but which computes directly the number of minutes of rest required. The formula assumes a maximum average energy expenditure of 5 kcal/min. Murrell's formula is as follows:

$$RT = \frac{T\ (W - 5)}{(W - 1.5)},$$

where RT = rest time, min,
T = work time, min,
and W = energy expenditure during work, kcal/min.

Application of these formulas to a male shoveling coal in a low-seam mine (9.3 kcal/min) for 10 min yields the following calculations:

$$\text{AIHA formula—RT\%} = \frac{9.3 - 1.5}{4.0} - 1 \times 100 = 95\%, \text{ or}$$

95% of 10 min work = 9.5 min rest, and

$$\text{Murrell formula—RT} = \frac{10\ (9.3 - 5.0)}{(9.3 - 1.5)} = 5.5 \text{ min rest}$$

Of equal or even greater importance than the amount of rest is the arrangement of the rest periods. In general, the greater the energy cost of a task, the more frequently rest pauses should take place. There is less cumulative fatigue and less demand on the heart and lungs with many short rests (every 0.5 to 2 min) than with the same amount of total rest time taken in fewer, but longer breaks. In addition, hot environments make extra demands on the circulatory system, and hence the rest requirements are greater than in cool environments.

Muller (*25*) presented a formula that attempts to predict when to take a rest. Muller assumed that people have a 25-kcal energy reserve that is only tapped when work exceeds 5 kcal/min. His formula is based on taking a rest when the 25-kcal reserve is used up. He further assumed that at rest, the reserve is rebuilt at the rate of 3.5 kcal/min (5 kcal/min − 1.5 kcal basal metabolic rate). Hence, all rests are 7 min long (i.e., 25/3.5). The formula is as follows:

$$WT = \frac{25}{(W - 5)},$$

where WT = work time, before rest is required,
and W = energy expenditure during work, kcal/min.

Application of this formula to a 9.3-kcal shoveling task yields

$$WT = \frac{25}{(9.3 - 5)} = 5.8 \text{ min.}$$

That is, after 5.8 min of work, a shoveler should rest for 7 min. For 10 min of work, he or she would require 1.7 rests (10/5.8) of 7 min each for a rest total of 12 min. This can be compared to the 9.5-min and 5.5-min values obtained by applying the AIHA and Murrell's formulas, respectively.

Unfortunately, there are no objective data available to determine which formula should be used to determine the amount of rest required. The fact that most mining tasks are self-paced, compensates in part for the heavy work loads. However, workers cannot always be depended upon to take rest breaks at the best times. Work-rest cycles can be empirically determined by testing various combinations and monitoring heart rate and oxygen consumption during the work and rest phases. A good work-rest schedule should result in significant recovery of heart rate during the rest period and little increase in oxygen consumption during successive work periods. One known fact is that people are poor judges of when they require rest. Usually, by the time a person feels tired, an inordinately long rest will be required for recovery. A rest break should be taken before the need for one is felt.

MANUAL MATERIALS HANDLING

Materials handling involves the lifting, pushing, pulling, or shoveling of materials or components used during equipment or mine maintenance activities. Generally speaking, there is more manual handling of materials in underground mining than in surface mining. This is due to several factors, including a greater variety of supplies used and the difficulty of using mechanical handling devices underground. Unger and Connelly (*35*) cataloged materials handling activities in underground mining into five functions:

1. *Production supply.*—Handling materials from the surface yard to locations near the working face. Examples would include transporting rock dust bags, roof bolts, and timbers.
2. *Production end use.*—Handling items during their end use at the working face. Such work activities would include erecting temporary curtains for ventilation, rock dusting, roof bolting, and erecting cribbings.
3. *Section move.*—Handling materials from the surface yard to the section being moved, including the handling during the process of moving a mining section. Examples include moving haulage belts, transporting cables, moving air lines, and moving longwall roof support.
4. *Equipment maintenance.*—Handling materials used during maintenance of mine equipment. Examples include extracting motors from continuous miners, replenishing hydraulic oil, and splicing cables.
5. *Mine maintenance.*—Handling materials used in mine maintenance. Examples of activities include maintenance of roof, ventilation, rail track, and roadways.

Table 7-5 lists some common underground mine materials and representative weights to give an idea of the kinds of loads that are often manually lifted, pushed, and pulled.

Table 7-5.—Common mine materials and their weights (*15, 35*), pounds

Roof support supplies:		Trailing cable, 2- to 3-in diam, 10 ft long	50-100
Roof bolts, 5/8 in by 6 ft, bundle of 10	55	Concrete supplies:	
Sheets, box of 25	25	Cement, 1 bag	80- 90
Plates, 6 by 6 by 1/4 in, bundle of 10	27	Concrete block, 8 by 8 by 16 in	62
Roof jack, 6 by 6 in by 5 to 8 ft, closed	50- 70	Rebar, 3/4 in by 6 ft, bundle of 10	90
Wood crossbars, 6 by 8 in by 10 to 14 ft	160-225	Rail supplies:	
Round wood post, 6 in by 5 to 8 ft	48- 76	Rail:	
Metal "H" beam, 6 by 6 in by 16 ft	320	30-lb, 30 ft	300
Rock dust, 1 bag	50	60-lb, 30 ft	600
Oil container, 5-gal (full)	40	Rail tie, 8 by 6 by 72 in	90-100
Brattice roll, 75-ft	60	Belt supplies:	
		Belt roller, 6 by 42 in	50
		Belt chain, 8 by 9 by 52 in	20- 25

Materials Handling Accidents

Annually, materials handling is the leading accident classification in coal, metal, nonmetal, stone, and sand and gravel underground and surface mining and in all processing and preparation plants. Table 7-6 shows the number of materials handling nonfatal-days-lost injuries occurring in the industry in 1983, as determined by MSHA (*36*). Overall, materials handling accounted for 33.7% of all nonfatal-days-lost accidents in the mining industry that year.

Table 7-6.—Materials handling nonfatal-days-lost (NFDL) injuries in the mining industry, 1983 (*36*)

(Courtesy of U.S. Mine Safety and Health Administration)

	NFDL injuries	Share of all injuries, %
Coal:		
Underground	2,432	35.1
Surface	439	28.8
Preparation plants	236	36.8
Metal:		
Underground	162	24.0
Surface	103	31.6
Mills	175	35.6
Nonmetal:		
Underground	82	33.7
Surface	50	33.3
Preparation plants	236	41.2
Stone:		
Underground	16	21.9
Surface	254	32.2
Mills	376	36.3
Sand and gravel surface	164	29.9
Overall	4,725	33.7

Materials handling injury reports covering a 3-yr period showed that 40% involved injury to the back (*11*). Finger injuries while handling materials were the next most prevalent (18%). It was also found that over half of the injuries (52%) involved overexertion; of these, 60% occurred while lifting objects. Table 7-7, for example, lists the type of objects underground coal miners were attempting to move when they incurred back injuries because of overexertion. (*31*).

Table 7-7.—Objects involved in overexertion back injuries suffered by underground coal miners during 1981 (*31*)

	Injuries	%
Electric cables	233	11.9
Broken rock and coal	211	11.8
Timbers and posts	198	10.1
Metal objects[1]	156	8.0
Belt conveyor systems	99	5.1
Wood objects[2]	82	4.2
Steel rails	82	4.2
Bagged materials	82	4.2
Jacks	61	3.1
Mining machines	49	2.5
Roof bolts	49	2.5
Oil containers	48	2.5
Cement blocks	47	2.4
Buckets and cans	46	2.3
Metal covers and guards	43	2.1
Pry bars	33	1.7
Motors	33	1.7
Wheels	32	1.6
Boxes	30	1.5
Other	324	16.6
Total	1,958	100.0

[1] Does not include metal objects such as rails, roof bolts, jacks, motors, etc., which are listed separately.
[2] Does not include timbers, posts, caps, and headers.

Materials handling accidents at 27 underground coal mines during 1973 were analyzed (*16*). As shown in figure 7-12, the majority of injuries occurred in production supply activities. This high number is probably due to several factors, including (1) materials are often handled several times from the yard to locations near the face, thus increasing exposure to injury; (2) many shipments of materials are made on a daily basis, again increasing injury exposure; and (3) materials are often banded or tied together in large, heavy packages, thus increasing the risk of injury.

Biomechanics of Lifting

Because a majority of materials handling injuries result in back injury from overexertion, and most of these occur during lifting activities, a review of the basic dynamics of lifting and back injury is in order. Biomechanics is the science that, among other things, considers the actions of the human body in bringing about controlled movements and applying forces, torques, energy, and power to external objects (*32*).

The basic principle of lifting involves the physics of levers. When a load is held in the hands, the load as well as the person's body mass creates rotational movements or torques at the various joints of the body. The skeletal muscles are positioned to exert forces at these joints to counteract the movements due to the load and body weight. The problem is that the muscles are positioned so that they act through relatively small moment arms. Consider the example depicted in figure 7-13 where a 10-kg (22-lb) weight is held in the hand with the elbow at a 90° angle. For the arm to maintain its position, the bicep muscle must exert a force sufficient to overcome the weight of the load and the weight of the forearm and hand. Based on anthropometric data for an average male, the forearm weighs approximately 4.4 lb. For the average male, the biceps muscle is attached 2 in. from the point of rotation of the elbow, the length of the forearm is approximately 14 in, and the center of gravity of the forearm and hand is approximately 6.7 in. from the elbow. This is shown in simplified form in the lower half of figure 7-13.

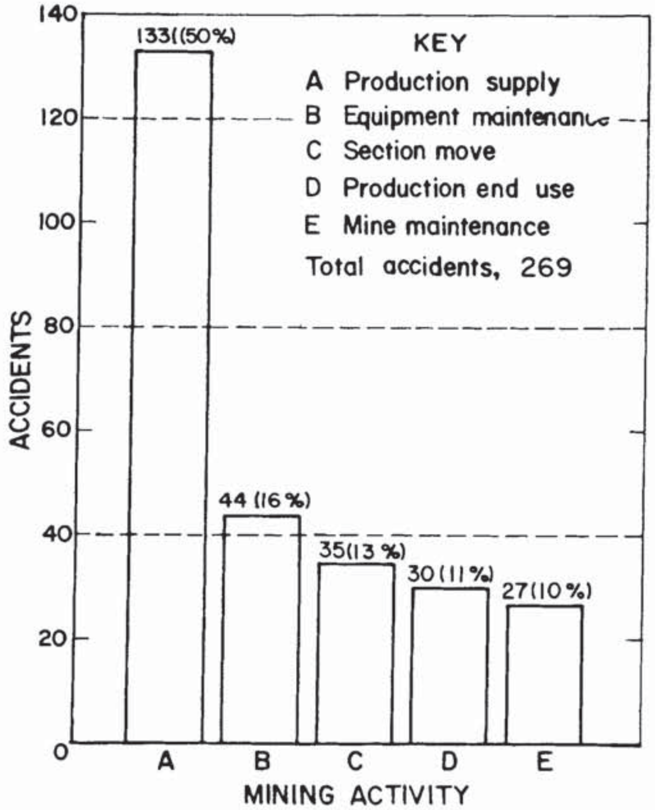


Figure 7-12.—Materials handling accidents by major activity or function. Data are from 27 coal mines during 1973.

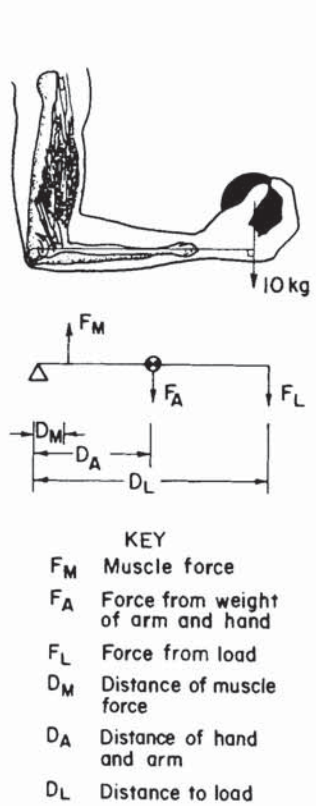


Figure 7-13.—Illustration of basic muscle biomechanics and lever analog (*27*). (Courtesy of National Institute for Occupational Safety and Health)

The moment or torque created by each load is the product of its force (a weight) and the distance from its center of gravity to the rotation or pivot point. As with a teeter-totter, to balance a light and heavy person, the light person should sit at the end of the teeter-totter arm and the heavy person nearer the pivot point. The light weight and long distance compensate for the heavy weight and short distance.

The force the biceps muscle in figure 7-13 must exert to hold the 22-lb weight can be calculated using the following formula:

$$(F_M \times D_M) = (F_L \times D_L) + (F_A \times D_A),$$

where: F = force, lb,
D = distance from the force to the pivot point, in,
M = muscle,
L = load being held,
and A = arm.

The solution is

$$(F_M \times 2) = (22 \times 14) + (4.4 \times 6.7) \text{ or } F_M = 169 \text{ lb}.$$

Therefore, even in this simple situation, the biceps must exert a force more than seven times the weight of the object being held. In addition, when a muscle pulls across an extended joint, it compresses the joint with about the same magnitude of force. This is an important concept when considering low-back biomechanics.

The spine is made up of a series of bony vertebras stacked up with flexible fibrous pads, called disks, between each one. As shown in figure 7-14, the spinal column is divided into five sections, and the vertebras in each section are numbered for easy reference (*19*).

Most back injuries occur in the lower lumbar spine, and the L_5-S_1 disk (sacrovertebral joint) has been used to represent the spinal stresses of lifting. Biomechanical models have shown that during the lifting of a weight, the bending moment at the L_5-S_1 joint can become quite large due, in part, to the weight of the upper body. For example, lifting a 110-lb weight from the floor can produce a bending moment of approximately 1,732 lb-in at the L_5-S_1 joint, according to NIOSH (*27*). To counteract this moment, the muscles of the lower back region (i.e., the erector spinae group) must exert large forces because they operate on very small moment arms (approximately 2 in). Thus, to produce 1,732 lb-in, the muscles must exert a force of 880 lb. The large forces generated by the lower back muscles are the primary sources of compression forces on the L_5-S_1 disk. The only force that acts to diminish the compression forces of the spine is intra-abdominal pressure.

Figure 7-15 shows the results of an analysis of the back muscle force and compression forces resulting from lifting a 100-lb timber in the posture depicted. The resulting muscular force on the back in this situation was 1,148.5 lb and the compression force on the L_5-S_1 disk was 1,219.6 lb.

The amount of compressive force that the vertebras can tolerate before experiencing microfractures is a function of, among other things, age, sex, and prior compressive stresses experienced. Data from cadavers of males under 40 yr of age show a mean of about 1,485 lb of compression required before microfractures occur. The value drops to approximately 880 lb for males 50 to 60 yr old. There is, however, considerable individual differences in compression tolerance within any age group. It has been estimated by Sonoda (*34*)

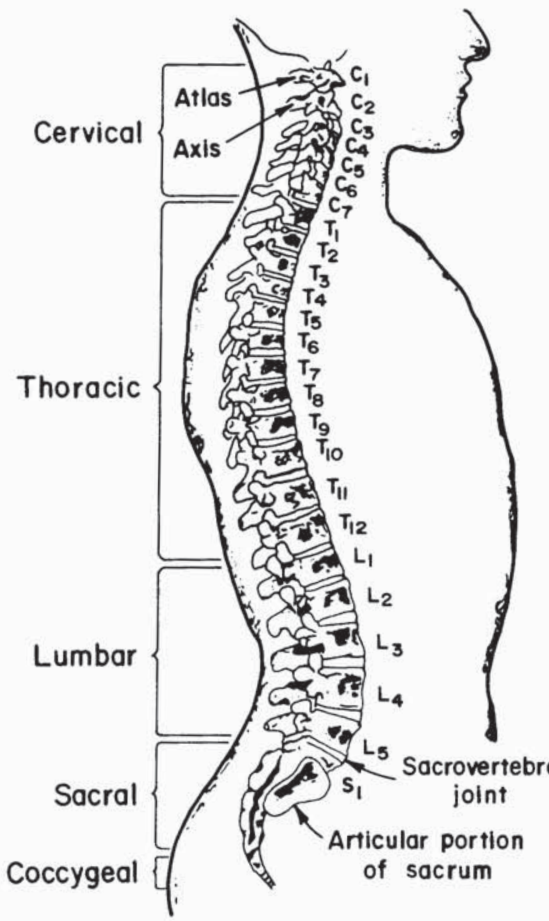


Figure 7-14.—Diagram of spinal column showing division and naming convention of vertebras (*19*). (Courtesy of W.B. Saunders Co.)

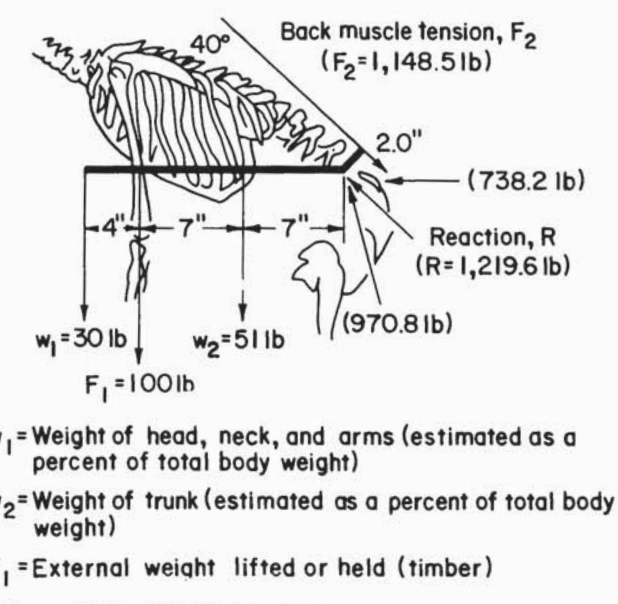


Figure 7-15.—Calculated lower-back muscle force and compressive (reactive) forces acting on L_5-S_1 disk resulting from lifting a timber post (*6*). (Copyright 1983 by the Human Factors Society Inc., and reproduced by permission)

that the female spinal compression tolerance is about 17% less than that of males due, in part, to the smaller force-bearing area of their vertebras.

According to NIOSH (*27*), the following is the current view on the genesis of a ruptured disk. Repeated compressive stresses, especially from lifting, are sufficient to cause microfractures in the cartilage end plates and subchondral bone of the vertebras, which it is believed alters the metabolism and fluid transfer to the disk. If this occurs, the disk begins to degenerate, and its capacity to withstand further compression loads decreases. The result is that the disk squeezes out from between the vertebras and presses on the spinal nerve root as shown in figure 7-16. This is commonly called a slipped or ruptured disk.

If this scenario is correct, then assigning cause for lower back pain to the immediate circumstance at the time when the pain first developed may be overly simplistic. In fact, most low-back injuries do not suddenly start with a jabbing pain, although such cases are easily remembered. Most often, the symptoms are slow to develop, with stiffness, dull aching pain, and finally incapacitating discomfort that can occur hours or days later.

Effects of Lifting Posture

The most important rule in lifting is to bring the torso (really the L_5-S_1 joint) as close as possible to the center of gravity of the load before lifting. The closer the L_5-S_1 joint is to the load, the shorter the moment arm and the lesser the force applied to the back. A second and subordinate principle, is that the back should be kept straight and vertical during a lift. In that posture, the compressive forces on the spine are more or less evenly distributed over the load-bearing surface of the vertebras. When the trunk is allowed to bend forward, the forces are concentrated on the front edges of the vertebras and tend to squeeze the disk toward the rear of the vertebral column.

The best posture for lifting depends partially on the size of the load being lifted. Small loads that can fit between the knees when in a squat posture are best lifted with the classical bent knee–straight back technique. With the load between the knees, the torso is very close to the load center of gravity, and the strain on the back is reduced. In addition, the back is kept vertical. Although this is often the

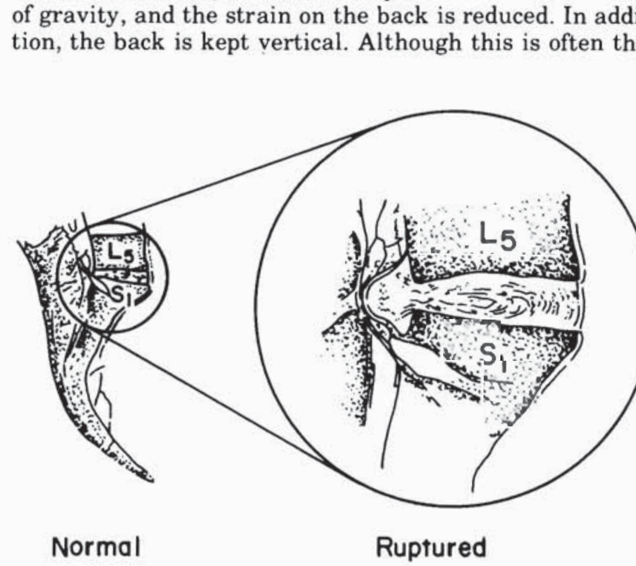


Figure 7-16.—Cutaway view of ruptured L_5-S_1 disk pressing the spinal nerve (*8*).

recommended lifting method, it may be easier said than done. Often, people do not have the upper leg strength needed to lift the load and the weight of the body. Because the body must be lifted in this technique, it is one of the most costly in terms of energy expenditure, and it quickly induces fatigue if adequate rest periods are not taken. In addition, this squat-lift technique requires flexibility and ranges of motion in the hips, knees, and ankles that many people do not possess. A systematic exercising and stretching program may be required to build the strength and flexibility needed to use this type of lift. Finally, it is often not possible to get close to the load being lifted to perform a bent-knee lift because of obstructions.

When an object to be lifted is large (not necessarily heavy), then the squat lift may be more dangerous than the stoop-back lift technique, where knees are only slightly flexed, and the person bends over at the waist to lift the object. If a squat lift is attempted on a large object, the knees will not fit around it, and the object will have to be lifted in front of the knees. This places the load further from the L_5-S_1 joint and increases the compressive forces on the disk. Figure 7-17 shows a comparison of the two techniques while lifting a wide box (*29*). The stoop-back lift results in about two-thirds as much compression force as the squat lift. Actually, the difference would be greater if the person moved in over the load even more than pictured in figure 7-17.

Thus, the best lifting technique, from a biomechanical point of view, depends on the strength and mobility of the lifter and the dimensional size of the object to be lifted. The main idea is to keep the load close to the L_5-S_1 joint.

Another technique of lifting, called asymmetric lifting, is one to avoid. In this technique, the person brings the load up along the side of the body with one hand. This not only causes lateral (side-to-side) bending of the lumbar column, but because of the natural arc of the lower back, also produces a rotation of each vertebra on its adjacent vertebra. This is especially hard on the disks between the vertebras and concentrates stress on the muscles used to stabilize the spinal column.

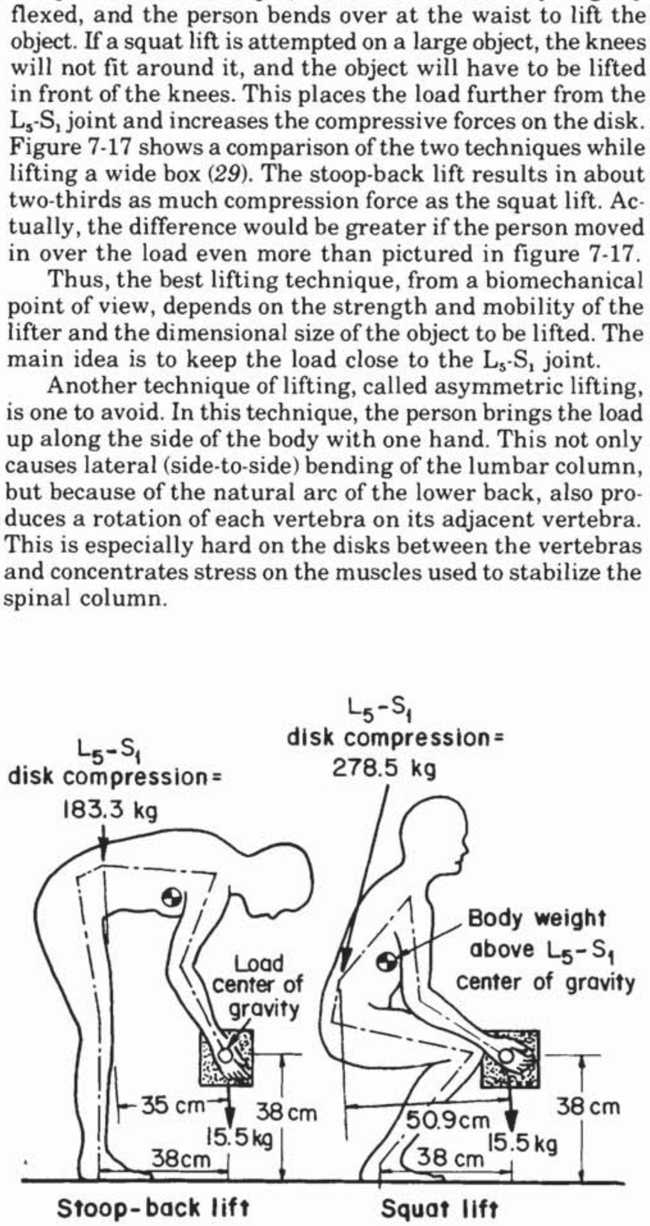


Figure 7-17.—Comparison of lower-back compression forces associated with stoop-back and squat methods of lifting a wide object (*29*). (Copyright 1974 by the American Institute of Industrial Engineers, and reprinted by permission)

NIOSH Recommended Lifting Load Limits

NIOSH formulated a method for determining maximum load limit recommendations for lifting tasks (*27*). A lifting task is defined as "the act of manually grasping and raising an object of definable size without mechanical aids." A lifting task, under this definition, takes normally less than 2 s to complete. This is in contrast to a holding or carrying task that requires sustained exertion.

The recommendations are intended to apply only for–

1. Smooth lifting;
2. Two-handed, symmetric lifting directly in front of the body with no twisting during the lift;
3. Moderate width objects, e.g., 30 in or less;
4. Unrestricted lifting posture;
5. Good couplings (handles, shoes, floor surface); and
6. Favorable environments.

In addition, the recommendations do not include safety factors to assure that unpredicted conditions are accommodated.

Given the nature of the mining environment, many of the characteristics of the lifting tasks listed are often not present, especially in the underground environment. Posture is often restricted, floors are often slippery, environments are often hostile, and load widths are often larger than 30 in. It is important, therefore, to consider the NIOSH recommendations as best case limits. Any prudent mine superintendent or supervisor should reduce the recommended limits to compensate for unfavorable lifting situations.

The NIOSH recommendations take into account five parameters of the lifting task to determine the load limits. Two limits are defined: the maximum permissible limit and the action limit, which is one-third the maximum permissible limit. Situations that are above the maximum permissible limit are considered unacceptable and require redesign of the task. Situations below the action limit are considered acceptable for most of the workforce. Situations that fall above the action limit, but below the maximum permissible limit are considered unacceptable, unless the task is redesigned or a selection and training program is used to upgrade the capabilities of the workforce.

The NIOSH (*27*) formula for determining the action limits for a given lifting situation and the determination follow. The maximum permissible limit is taken as three times the action limit. Table 7-8 shows the maximum lift frequency based on the average vertical location at the origin of the lift and the period of time for which the lift is performed. Horizontal location (H) = 6/H; vertical location (V) = $1 - (0.01 \times |V-30|)$; vertical distance traveled (D) = $0.7 + (3/D)$; frequency of lift = $1 - (F/F_{max})$; and constant = 90.

$$AL = 90 \times H \times V \times D \times F,$$

where AL = action limit, lb,
90 = constant,
H = horizontal location forward of midpoint between ankles at origin of lift, 6 to 32 in,
V = vertical location at origin of lift, 0 to 70 in,
D = vertical travel distance between origin and destination of lift, 10-in minimum,
F = average frequency of lift, lifts/min, considering maximum lift frequency, F_{max} (from table 7-8),
and F_{max} = maximum lift frequency that can be sustained (from table 7-8), lifts/min.

Table 7-8.—Maximum lift frequency based on average vertical location and period of performance, lifts per minute

Av vertical location . . . in . .	>30	<30
1 h or less	18	15
More or less continuous during shift	15	12

The maximum permissible lift is three times the action limit. An example of determining the action limit and maximum permissible lift follows.

Situation.—A worker lifts 36- by 18- by 8-in rock dust bags (50 lb each) from a scoop shovel on the ground and stacks them three high on a bin pallet. The first tier is 6 in off the ground, the second is 14 in off the ground, and the third tier is 22 in off the ground. The task is performed for less than 1 h at a rate of five bags lifted per minute.

Analysis.—Although the vertical location, V, at the origin of the lift is the same throughout the task, the vertical travel distance, D, varies from 6 to 22 in, depending on the tier. One approach would be to perform the analysis on each tier separately as if it were a separate task. Another approach, used here, is to determine an average travel distance (i.e., 6 + 14 + 22 = 42, 42/3 = 14) and apply the action limit formula to the average task. The horizontal location, H, is estimated to be 6 in plus half the width of the object (i.e., 6 + 18/2 = 15).

Calculations.—Constant is 90; horizontal location factor, H, is 6/15 or 0.40; vertical location factor, V, is 1 − (0.01 × 30) or 0.70; vertical travel distance factor, D, is 0.7 + (3/14) or 0.91; maximum frequency, F_{max}, from table 7-8, is 15; and frequency of lift factor, F, is 1 − (5/15) or 0.67. Using the action limit formula, AL is determined as follows: AL = 90 × 0.40 × 0.70 × 0.91 × 0.67, which yields 15.4 lb. The maximum permissible lift (3 × AL) is 46 lb.

Conclusion:—Since the rock dust bags weigh 50 lb, the AL is 15.4 lb, and the maximum permissible lift is 46 lb, this task would be unacceptable under the best of circumstances and the task should be redesigned.

REDUCING THE RISK

The risks inherent in a manual materials handling task can be reduced by redesigning the task, redesigning the workspace, selecting physically capable people to do the task, training workers involved in normal materials handling tasks, or a combination of these methods.

The following are methods for reducing the physical stresses involved in manual materials handling tasks, the fundamental concept being that active awareness of the problem and a conscious effort to reduce the physical stresses involved in the task can accomplish significant results without incurring significant costs.

Redesign the task:

1. Use lifting aids (e.g., hoists, cranes, rollers, jacks, conveyors).
2. Reduce weight of object.
3. Reduce frequency of lifting (lifts per minute).
4. Reduce duration of task (hours per shift).
5. Reduce the size of the object being handled.
6. Supply properly designed handles on the objects being handled.
7. Maintain a predictable center of gravity in the load being lifted.

Redesign the workspace:

1. Remove obstructions that prevent worker from getting close to the object being lifted.
2. Provide ample space to maneuver and assume most advantageous lift posture.
3. Begin lifts at about elbow height.
4. Reduce vertical travel requirements for lift.
5. Provide slip-resistant soles and floors.
6. Provide good lighting.
7. Maintain comfortable temperature, humidity, and airflow.

Select workers:

1. Strength testing.
2. Aerobic capacity testing.
3. Clinical examination.

Train workers:

1. Hazard awareness.
2. Biomechanics of manual materials handling.
3. Reducing hazards.
4. Physical fitness.

Redesign the Task

The use of lifting aids is an obvious way to reduce the physical strain on the job. Often, a little forethought can make the use of such devices easier and safer to use. For example, if materials are transferred at the cage or skip, the area should be designed to accommodate lift trucks and cranes. If components must be removed for maintenance in a processing plant, fixtures should be installed so that temporary winches can be attached. Floors should be smooth so that rollers and dollies can be easily used.

Reducing the weight of the load is an obvious solution to the problem, yet is often overlooked. The 50-lb rock dust bags might be purchased in 25-lb bags. In addition, the smaller bags would be more compact and hence permit the worker to get closer to the load to lift it. To illustrate this effect, if the width of the rock dust bags described in the action limit determination were reduced from 18 to 12 in, the action limit would increase from 15.4 to 19.2 lb. In addition to the overall weight, the center of gravity of the load should be predictable and nonshifting. A box, half filled with supplies that shift when lifted, places asymmetric loads on the back and increases the probability of falls. The use of baffles, dividers, or packing to stabilize the center of gravity is recommended.

The proper placement and design of handles can reduce biomechanical strain and reduce the chances of dropping the load. In general, handles should be placed above the center of gravity, unless the height of the load would interfere with the legs during walking. Many handles in use today are unsatisfactory because of insufficient hand clearance, sharp edges that can cut into a worker's hand, and handle diameters that are too small.

Handle width should be at least 4.5 in with a 2-in clearance all around the handle. If gloves are worn during lifting, clearance should be at least 3 in, and the handle should be 5.5 in. Handle diameter should be between 1 and 1.5 in.

Redesign the Workspace

Often, a simple rearrangement of the workspace will permit a worker to get closer to an object when lifting and releasing it. The use of platforms on which to stack materials can bring the lifting task to elbow height and require little or no vertical movements. In the action limit determination, if the scoop shovel were lifted to the same height as the stacked rock dust bags, and if the bags were stacked on a pallet 22 in high (instead of 6 in), then the action limit would be increased from 15.4 to 24.1 lb, and the maximum permissible limit would be 72 lb. Thus, the task would be acceptable.

Good lighting and slip-resistant soles and floors, of course, reduce trip and slip-and-fall accidents. Comfortable temperature, humidity, and airflow are especially important for continuous physical activity since heat adds a considerable burden to the circulatory system, and when added to the strain from the physical task, can be dangerous.

Selection of Workers

Any methods for selecting workers for physically demanding tasks should meet the following criteria:

1. Be safe (if a physical test of abilities is used).
2. Produce reliable results.
3. Be related to the specific demands of the task.
4. Be practical to administer.
5. Predict risk of future injury or illness.

Most of these are obvious; however, the methods used to select workers must be related to the specific demands of the job in order to eliminate accusations of bias in selection methods. Further, the job must be designed to reduce the physical demands to the lowest practical level, and the selection methods should be built around the redesigned job. Failure to redesign a job, consequently excluding females, might well be considered an act of discrimination.

Methods for selecting workers for physically demanding tasks have centered around clinical examinations, strength testing, and aerobic capacity testing. A clinical examination is a must for selecting workers for physically demanding tasks. The purpose is to uncover any abnormalities that might restrict the physical activity of a worker, and to identify those with prior episodes of back pain. It was reported by Dillane (*3*) that the probability of an episode of back pain increases by a factor of 3 to 4 after the first reported attack.

Some clinicians promote the use of lower-back X-rays as a means of evaluating the risk potential to an individual engaged in a lifting task. Current thinking, however, is that such X-rays are of little practical value in predicting future disability. Several studies, such as by NIOSH (*27*), report no significant differences in the incidence of radiologically identified abnormalities between workers with known histories of back pain and those without. Such X-rays, however, can be useful in conjunction with prior clinical examinations to corroborate a suspected diagnosis.

Considerable attention has been given to the use of strength testing as a means of selecting workers for demanding lifting tasks. For continuous, high-energy tasks, the measurement of aerobic capacity appears to be a valuable selection device. Specific methods for measuring strength for preemployment testing are discussed by Chaffin (*8*) and Kroemer (*23*).

Ayoub (*6*) reported the use of a job severity index (JSI) as a measure to match an individual with the demands of a lifting task. The JSI is the ratio of a measure of job demand to a measure of the capacity of the person performing the job under the job conditions. The measure of lifting capacity is determined from formulas that predict the maximum weight an individual feels he or she can lift repeatedly without undue stress or overtiring. The formulas take into consideration the following factors: sex, weight, age, arm strength, back strengh, dynamic endurance, shoulder height, and abdominal depth.

In a study of 101 jobs involving 385 males and 68 females, Ayoub (*6*) found that as the JSI increased, the incidence and severity (days lost per incidence) of lower-back injuries increased (fig. 7-18). JSI values below 1.0 indicate that the worker's capability exceeds the demands of the job. JSI values greater than 1.0 indicate that the job demands exceed the capabilities of the worker. As can be seen in figure 7-18, the number of incidents dramatically increases with JSI values greater than 1.5, and the severity of incidence dramatically increases with values greater than 2.25.

Training Workers

Although training for manual materials handling has been practiced in some European countries since World War II, there appears to have been few, if any, controlled studies showing a drop in injury rates following training. Probably what has kept up the interest is that employers feel a legal or moral obligation to provide such training. The following is the NIOSH recommended (*27*) content for a training program on manual materials handling.

1. Risks to health of unskilled manual materials handling (including accident experience of the organization).
2. Basic physics of manual materials handling.
3. Effects of manual materials handling on the body (including anatomy of spine and muscles and joints).
4. Individual awareness of the body's strengths and weaknesses (including how much can be handled safely and comfortably).
5. How to avoid accidents (including task design variables, workspace layout, sizing up the load, planning the activity).

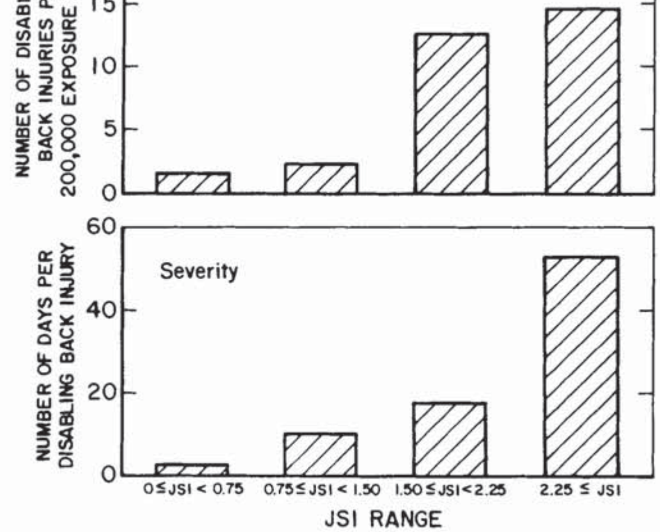


Figure 7-18.—Incidence and severity of back injury as a function of the job severity index (JSI). JSI values greater than 1.0 indicate job demands exceed worker capabilities; values less than 1.0 reflect worker capacities exceed job demands (*6*).
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6. Handling skill (including actually lifting, carrying, pushing, pulling materials handled on the job; the best way to perform each task; and the principles involved).

7. Handling aids (including when to use them, how to use them, how to improvise).

Examples of training materials for the mining industry based on the components listed above were developed by Connelly (*10*).

NIOSH (*27*) also pointed out that an adequate training program must do more than just demonstrate the principles using slides or films; participants must be actively involved in the program. Teaching must extend beyond the classroom back to the worksites to be effective.

Physical fitness training is another aspect of manual materials handling training, although it is not listed in the recommended course content by NIOSH. A 12-week program in which sessions were held twice per week was reported on by Chenoweth (*9*). The results showed small, but reliable improvements in heart rate, blood pressure, body weight, percentage of body fat, and flexibility.

DISCUSSION

Although manual materials handling injuries continue to be the major category of lost-time injuries in mining, an active awareness of the problem and an understanding of the principles and dynamics involved can go a long way toward reducing the hazards. Mining will continue to be a physically demanding occupation, but by proper design of the tasks and worksites and proper employee training and selection, the incidence and severity of injuries can be reduced. Proper task design will also contribute to a higher level of productivity by reducing the level of fatigue experienced by a worker. Much has been done to improve the work environment, and much still remains to be done.

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CHAPTER 8.—ENVIRONMENTAL FACTORS

In addition to the obvious environmental factor of temperature, illumination and noise factors, as well as others, affect the performance, health, comfort, and safety of miners.

Humans live and work in a wide range of environments, each with its own set of particular characteristics that can affect performance, health, comfort, and safety. Because the list of such environmental factors is extensive, including odors, dust, chemical fumes, radiation, and even insects, this chapter will only concentrate on four factors that are traditionally covered in the human factors literature: illumination, noise, whole-body vibration, and climate (heat and cold stress). For each of these factors, a brief discussion is presented covering the measurement of the factor, conditions found in mining, effects of the factor on humans, standards that exist, and methods for reducing the negative effects of the factor on workers.

ILLUMINATION

The topic of illumination is especially important in the mining environment. Underground mines are completely dependent on artificial sources of illumination, as are night operations in surface mines. Because humans receive the bulk of their information visually, the quantity and quality of illumination is critical to the safe and efficient performance of our jobs.

Measurement of Light

Two major systems of units are currently used for the quantification of light: English system and International

System of Units (SI). The primary difference between the English and SI systems is that the English system uses U.S. standard measures for linear dimensions in the unit definitions, while the SI system uses metric measures. Current U.S. coal mine lighting regulations customarily use English units; therefore, these will be used primarily in this section.

All standard systems of light units employ the following basic concepts:

1. *Luminous Flux* (ϕ, unit—lumens, lm).—The time rate flow of light energy.
2. *Illuminance* (E, unit—footcandle, fc, or lux, lx).—A measure of the density of luminous flux striking a surface.
3. *Luminous Intensity* (I, unit—candle, c).—A concept used to describe how a light source distributes the total luminous flux, or lumens, it emits into various portions of the space surrounding the source.
4. *Luminance* (L, unit—candle per square inch, c/in^2, or candle per square meter, c/m^2).—In physical terms, luminance is a concept used to quantify the density of luminous flux emitted by an area of a light source in a particular direction toward a light receiver, such as an eye.
5. *Reflectance* (ϱ).—The ratio of reflected to incident light energy, which may be defined as lumens emitted per unit area divided by lumens incident per unit area.
6. *Contrast.*—The concept that the greater the luminous and color contrasts of an object with its background, the greater the object visibility.

Luminous Flux

Flux is a power quantity in the same manner as horsepower or Btu per hour. The unit of luminous flux, the lumen, is most frequently used to describe the total lighting power of light sources.

Illuminance

Imagine a light source placed inside, at the center of a sphere. The amount of light striking any point on the inside of the sphere is called illuminance. It is measured in terms of luminous flux (per steradian)[1] per unit surface. One lumen per square foot is equal to 1 fc, and 1 fc is equal to 10.76 lx. An accepted practice for some purposes is to consider 1 fc equal to 10 lx, ignoring the fraction (*23*).[2]

The amount of illuminance striking a surface from a light source follows the inverse square law, $E = I/D^2$, where D is the distance from the source. At 2 ft, a 1-c source would produce 1/4 fc; and at 3 ft, it would produce 1/9 fc.

Luminous Intensity and Luminance

Some light striking a surface is reflected. The amount of light (luminous intensity) per unit area leaving a surface is called luminance. Luminance is defined in terms of lumens (luminous flux per steradian) per square foot, or footlambert.

Reflectance

The ratio of reflected luminous flux to the total incident luminous flux is reflectance. Some surfaces reflect, while others absorb almost all the luminous flux that strikes them. Generally, dark-colored surfaces absorb more luminous flux than do light-colored surfaces.

In actuality, no surface is a uniform diffusing surface. The reflectance of 34 wet and dry rock and mineral samples from underground metal and nonmetal mines was measured by Crooks (*11*). Table 8-1 presents some representative data from that survey. Notice that wet samples show lower average reflectance than dry samples. Over three-fourths of all worksites measured by Crooks (*11*) had reflectances of less than 30%. To illustrate the consequences of different reflectivity on the amount of illumination needed, Crooks and Peay (*12*) indicated that the lighting adequate for development activities in dry dolomite would have to be increased approximately 400% to achieve the same luminance levels in wet sphalerite.

Table 8-1.—Examples of average reflectances of rocks and minerals from underground metal and nonmetal mines (*11*), percent

Sample description	Dry	Wet
Light brownish gray trona	59	28
Brownish gray trona	38	19
Feldspar with olivine, chalky surface	61	38
Feldspar with pyrite, medium gray color	39	24
Dolomite	59	44
Almost pure sphalerite	16	9
Whitewashed shale (haulageway wall)	82	61
Quartzite	17	11
Chalcopyrite	14	8

Contrast

Although contrast is not a light measure per se, it is a critical concept for determining visibility. If an object has no contrast with its background, it will not be seen, regardless of how much illuminance is supplied. Luminous contrast is measured by the following formula:

$$\text{Contrast} = \frac{\text{Object luminance} - \text{Background luminance}}{\text{Background luminance}}.$$

With more light, the eye can see detail better and, hence, less contrast is needed. For example, an object with luminance of 43.8 fL on a background having a luminance of 14.6 fL will be easier to see than an object with luminance of 4.5 fL on a background having a luminance of 1.5 fL, even though both have contrasts equal to 2.0. Experiments have shown that a 1% loss of contrast requires a 10% to 15% increase in illuminance to maintain the same visual performance (*15*).

In addition to luminous contrast, color contrast also enhances visibility, even if the luminous contrast is zero. For example, a yellow target shows up against a blue background, even if the luminance of the two colors is the same.

Illumination and Performance

At the turn of the century, coal miners commonly suffered from an eye disease called nystagmus. The symptoms were uncontrollable oscillations of the eyeballs, headaches, and dizziness. One of the main contributing factors was the effect of working under very low levels of light for long

[1] The steradian is a measure of the unit solid angle at the center of a sphere. There are 4 π or 12.57 sr in a sphere.

[2] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

periods of time. With the advent of electric caplamps, the disease virtually disappeared.

The literature on mine lighting with respect to accidents, production, and health was reviewed by Trotter (*44*). With respect to accidents, several European studies were cited that showed accident rates decreasing as much as 60% when the overall level of illumination was increased. Studies in industries other than mining supported the general conclusions that increased levels of illumination have a positive effect on accidents.

With respect to the effects of lighting on productivity, numerous studies have been done using simple tasks, such as threading needles, to show that increasing illumination up to about 100 fc results in increased productivity and decreased errors. Trotter (*44*) cited two studies relating lighting to productivity in the mining environment. Adding general area illumination resulted in an increase of 17% to 26% in productivity, compared to similar sections of the mine where only caplamps were used.

In the underground environment, caplamp illumination results in notoriously poor peripheral vision, because the beam is usually focused to a narrow spot. The addition of general lighting in such situations greatly enhances peripheral vision and allows workers to see objects more quickly and at greater distances. For example, the effect additional background luminance had on the detection time of various targets, such as simulated rock cracks, tripping hazards, and rock movements was measured by Merritt (*28*). In all cases, the provision of additional background luminance decreased detection time and errors. As an example, figure 8-1 shows the average response time to detect holes in the floor at a distance of 10 ft. With caplamp illumination only (0.055 fL), response time was 15 s. The provision of additional background luminance with general area lighting decreased the response time to 1 s.

Thus, it appears that improved lighting can improve safety, productivity, and the time needed to respond to hazards. Recognition of these facts has prompted government agencies to specify illumination requirements, which are discussed in the following section.

Illumination Requirements

The setting of illumination requirements involves many tradeoffs, including weighing the cost of increased illumination against the improvement in visual performance, and balancing increased levels of illumination against the increase in glare. Trotter (*44*) reviewed standards set by various countries for underground coal mining. The minimum light levels specified vary considerably from country to country, as shown in table 8-2. The data in table 8-2 are given in terms of illuminance (i.e., the amount of light striking a surface). The United States and the Commission Inter-

Table 8-2.—Samples of illumination standards set by various countries for underground coal mining (*44*), lux

	Shaft	Loading	Around machines	Haulageways
Belgium	20- 50	20	25	10
British Columbia, Canada	53	21	53	21
Czechoslovakia	15- 40	20	20	5 -10
Germany, Federal Rep. of	30- 40	40	80	15
Hungary	40-100	40-60	20-50	2 -10
Poland	15- 50	15-30	NA	.5- 2
United Kingdom	70	30	NA	2.5

NA Not available.

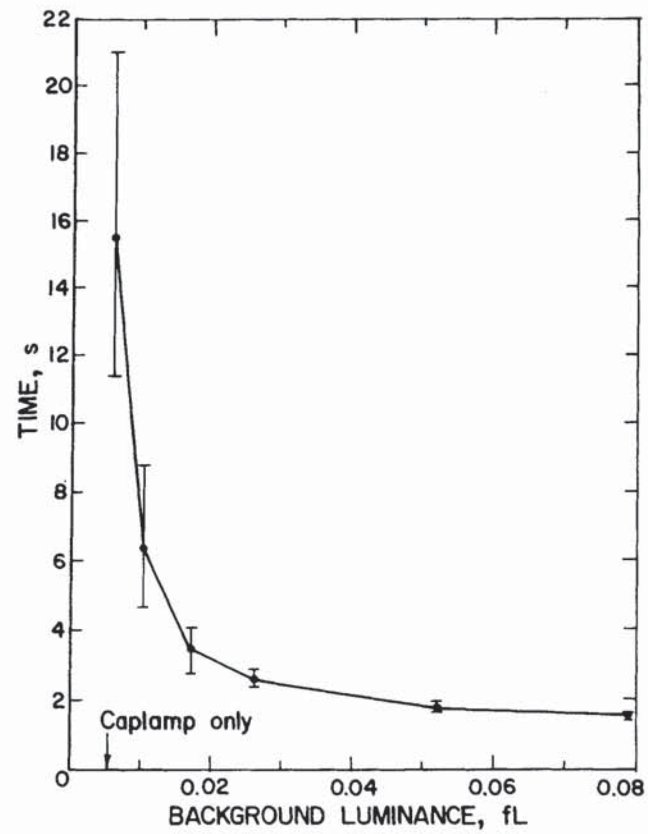


Figure 8-1.—Effect of adding additional background luminance (area lighting) on speed of detecting holes in a floor at a distance of 10 ft (*28*).

nationale de l'Eclairage (CIE), by contrast, specify minimum levels in terms of luminance (i.e., reflected light). It is more appropriate to state requirements in terms of luminance, because it is reflected light that allows us to see objects; and, depending on the reflectance of the surface, the same amount of incident light can result in very different levels of reflected light. Whitewashing an area, for example, can greatly increase luminance without increasing the number or intensity of light sources.

The United States requires 0.06 fL of luminance in work areas and around equipment in underground coal mines. Specific details of the requirements for underground coal mines are contained in reference 45. The usual practice is to plan illumination systems based on an assumed reflectance of 0.04 in coal mines. A luminance requirement of 0.06 fL, with a reflectance of 0.04, yields an illuminance requirement (light striking the surface) of 1.5 fc. The Mine Safety and Health Administration (MSHA) requirements recognize the problem of glare, especially in low-seam mines (under 48 in), and have reduced the size of the area around machines that must be illuminated to the minimum required luminance.

With respect to surface mining, MSHA proposed that all exterior areas related to draglines, shovels, and wheel excavators, where people regularly work and travel, be illuminated to 5.0 fc. This area extends out 20 ft in all directions from the machines. Areas beneath the boom, from 20 ft out from the main frame to the furthest point the equipment can excavate or discharge material, must be illuminated to 1 fc.

Merritt (*28*) performed extensive research to determine illumination requirements for underground metal and nonmetal mines. The recommendations are somewhat more complex than the requirements for coal mines. For example, he recommends 0.1284 fL at 8-ft viewing distance, 12° off axis; and 0.05 fL at 6-ft viewing distance, 22.5° off axis. It was believed that a more powerful caplamp could supply the needed luminance. Recommendations for illumination of mobile equipment operations include 0.10 fL on the floor, 20 ft in front of the machine.

In order to determine if an illumination system will supply the proper amount and distribution of light, it is necessary to simulate the situation and equipment, install the lights, and take the required measurements. The Bureau, however, has developed a computer model that uses representations of mining machinery and data on luminance output characteristics of various lights to compute the level and distribution of illumination in the work area (*19-20*). The system is interactive so that different types of lights and light positions can be tested quickly and easily.

Glare

Illumination engineers distinguish two types of glare: disability glare and discomfort glare. Disability glare interferes with visibility and reduces visual performance. Disability glare operates in two ways. In the first, a glare source reduces the contrast of a visual scene by causing a scattering of light in the fluid of the eyeball. This scattering creates a veiling brightness on the retina that in turn reduces contrast. The second mechanism by which a glare source reduces visual performance is due to transient adaptation. The source causes a shift in the eye's adaptation or sensitivity to light. The glare source causes the eye to become adapted to a higher level of illumination and hence less sensitive, which makes it harder to see low-contrast or dimly lit objects. The effect is similar to going into a dark movie theater on a sunny day.

The disability glare factor (DGF) of various lighting arrangements on underground coal mining equipment was reported on by Whitehead (*49*). The DGF indicates the percentage of visibility still left, given the effect of glare. The higher the number, the less the disability glare effect. For a continuous miner operator, DGF values in four work positions varied from 1.8% to 100% using various light sources. The average DGF across all positions and light sources was 51%, a reduction of almost 50% in visibility due to disability glare. An even poorer situation was reported for a roof bolter operator, where the average DGF was only 30%, i.e., a 70% reduction in visibility.

Discomfort glare increases eye fatigue and pain, and causes distraction. The exact mechanism by which discomfort glare causes pain is not known, but probably has something to do with the muscles that constrict the pupil when faced with a bright light. Actually, the absolute intensity of the glare source is not important, but rather the difference in contrast between the source and the general adaptation level of the eye. A 200-W lightbulb would not cause discomfort glare, outside, on a sunny day; but it would on a dark moonless night.

Because discomfort glare is a subjective experience, some people are more tolerant of discomfort glare, while others are more sensitive. For example, Whitehead (*49*) reported on sensitivity to discomfort glare among underground coal miners. The results showed that the miners were no more sensitive to discomfort glare than nonmining populations.

Trotter (*44*) listed the following ways to reduce glare in the mining industry:

1. *Avoid small sources of high luminance.* The use of frosted tungsten-filament bulbs rather than clear bulbs, for example, increases the surface area of the source and thus reduces glare.
2. *Use large sources of low luminance.* Fluorescent tubes provide larger, low-luminance sources. The veiling brightness effects of disability glare are the same whether the glare source is small and of high luminance, or large and of low luminance, provided that the illuminance at the eye is the same. The large, low-luminance source, however, will produce less discomfort.
3. *Move luminance sources out of the field of view.* A source of light above the line of sight is less distracting than one that lies to the side or below it. As a rule of thumb, the angle between the horizontal line of sight and a line from the eye to the light source should be greater than 30°.
4. *Shield sources from direct view.* As miners approach a shielded light source, they cannot see the source directly. When they are under the source, it no longer is in the field of view.
5. *Use prismatic lenses, filters, or cross polarizers.* These devices diffuse the light from the source, effectively increasing its size and reducing its apparent brightness.
6. *Keep differences in luminance small between visible source and background.* Use low-luminance sources in large surrounds or direct some of the light to illuminate the area beyond the source.
7. *Keep background and surround luminances high.* The ratio of luminances of the task, the background, and the environment should not exceed 10:3:1, with a 10:5:2 ratio being very good. Generally, providing peripheral lighting yields acceptable ratios.
8. *Position work and lighting properly.* A change in the angle of a light source or the position of the task relative to the position of the worker can reduce reflected glare.
9. *Avoid specular surfaces.* This relates to reflected glare from shiny surfaces; use matte or rough surfaces instead.
10. *Use light of the right quality.* Color of illumination, as for example the yellow of pressure sodium lamps, is believed to penetrate dust and fog better than white, green, or blue light.

NOISE

Since the advent of mechanized mining, noise has become an integral part of the mining environment. As equipment becomes more powerful, noise levels generally increase. Noise as an environmental factor has important implications for the worker population. The obvious implication is, of course, the potential for noise-induced hearing loss. In addition, noise produces other health effects, influences work performance, and makes communications more difficult. Noise is probably the most prevalent environmental stressor in the mining industry, considering both surface and underground operations.

Measurement of Noise

Noise, and sound in general, originates as vibrations. The two primary characteristics of sound are frequency and intensity.

Frequency

Sound waves are really alternating increases and decreases in air pressure caused by a vibrating source. Figure 8-2 shows the waveform of a simple sound source. The wave is called a sinusoidal or sine wave. The height of the wave above the midline, at any point in time, represents the amount of above-normal air pressure at that point. Points below the line represent the below-normal air pressure. One complete cycle is shown in figure 8-2. The number of cycles generated per second is the frequency of the sound and is measured in hertz, which is equivalent to cycles per second. Complex sounds can be decomposed into an additive set of sine waves of various frequencies.

Intensity

The intensity of sound pressure level (SPL) of a sound is defined using a logarithmic measure called the decibel. It is really based on the ratio of two sounds, one of which is an arbitrary standard set to represent 0 dB. The formula of SPL is as follows:

$$\text{SPL (dB)} = 20 \log P_i/P_r,$$

where P_i = the sound pressure (usually measured in $\mu N/m^2$) of the sound being measured
and P_r = 0-dB reference level (usually 20 $\mu N/m^2$).

Notice that the 0-dB reference level cannot itself be zero because the P_i–P_r ratio would be infinity. The reference level is set at an SPL roughly equivalent to the lowest intensity, 1,000 Hz pure tone, that a healthy adult can just barely hear under ideal conditions. Therefore, when the sound pressure of the sound being measured equals the reference level, the P_i–P_r ratio equals 1.0, and the log of 1.0 equals zero, hence 0 dB.

There are several implications of using the decibel scale: (1) sounds can have intensities less than 0 dB; (2) a doubling of the power of a sound will increase the SPL by only 3 dB; and (3) signal-to-noise ratios are really just the difference between the SPL for noise and the SPL for signal.

Indexes of Noise Intensity

As discussed in chapter 3, the ear is not equally sensitive to all frequencies of sound; it is more sensitive to frequencies in the 2,000- to 6,000-Hz range, and less sensitive to lower frequencies. To account for this differential frequency sensitivity, sound pressure meters contain frequency-response weighting networks that electronically attenuate sounds of certain frequencies, and produce a weighted total sound pressure level. The networks are designated A, B, and C; and their relative responses, as given by Jensen (*26*), are shown in figure 8-3, along with the response characteristics of the ear at threshold. Of the three scales, the A scale comes closest to approximating the response characteristics of the ear. This scale is used by MSHA to set environmental noise criteria.

Noise often varies in intensity over time. To account for this, a time-weighted average of the noise exposure can be computed. The Environmental Protection Agency recommends the equivalent sound level (L_{eq}) as the best measure of the cumulative effects of noise. The equivalent sound level is defined as the sound pressure level (usually measured in decibels, A weighted) of a constant noise that, over the time period being measured, transmits to the receiver the same amount of acoustic energy as the actual time-varying sound. For example, if a person is exposed to 100 dBA for 1 h and quiet for the next 4 h, the L_{eq} for the total 5-h period would be 94 dBA. That is, 5 h of 94-dBA noise is equivalent in acoustic energy to 1 h of 100 dBA and 4 h of quiet (less than 80 dBA). Sound pressure meters have been developed that give direct readouts of L_{eq} values.

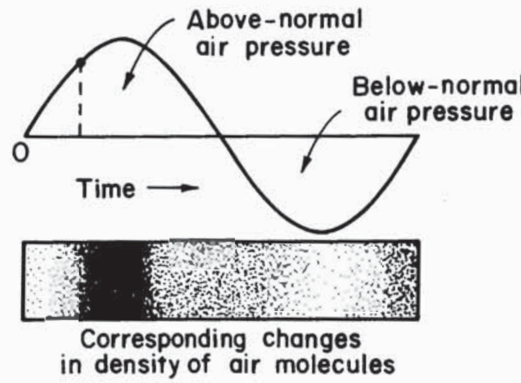


Figure 8-2.—Sine wave sound pressure wave showing one cycle with corresponding changes in air pressure.

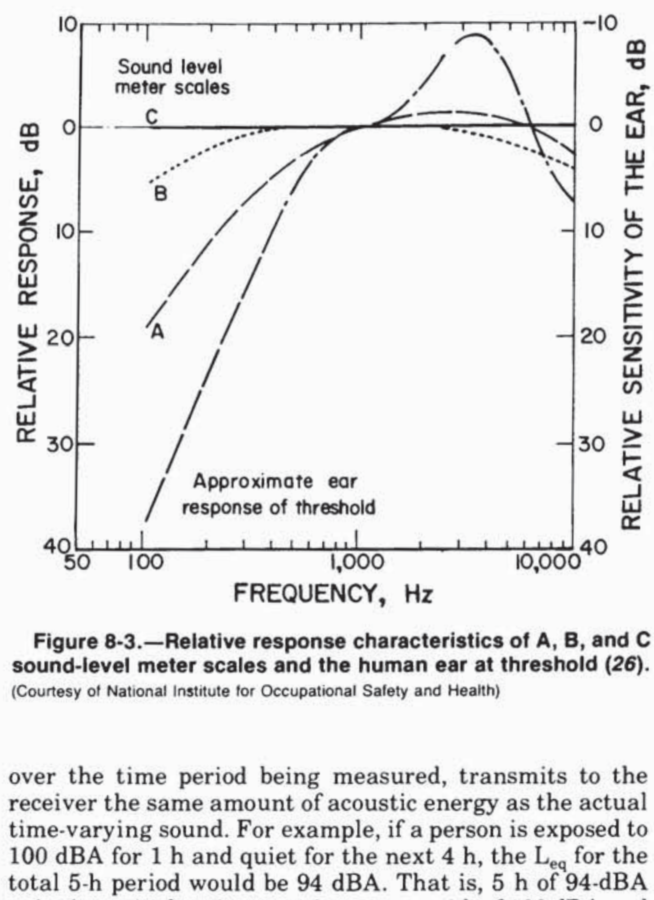


Figure 8-3.—Relative response characteristics of A, B, and C sound-level meter scales and the human ear at threshold (*26*).
(Courtesy of National Institute for Occupational Safety and Health)

Conditions in Mining

Figure 8-4 presents an overview of the noise levels typically experienced in underground and surface mining by operators of various types of equipment (*18*). As can be seen, all the levels listed exceed 90 dBA. With the exception of longwalls, underground shuttle cars, and surface trucks, all exceed 100 dBA.

Standards for Noise Exposure in Mining

In the United States, the Walsh-Healy criteria for noise exposure, shown in table 8-3, are the standards set for underground and surface mining. Comparing these standards against the typical levels reported in figure 8-4 makes it very likely that operators are exceeding recommended noise exposure criteria. For example, the noise exposure of over 700 underground coal miners was studied by Bobick and Giardino (*8*). They found that 20% of the miners were overexposed according to the Walsh-Healy criteria.

Table 8-3.—Walsh-Healy noise criteria for underground and surface mining

Max noise level, dBA	*Max exposure time, h*
90	8
92	6
95	4
97	3
100	2
102	1.5
105	1
110	.5
115	.25

Hearing Loss

As would be expected, daily exposure to high levels of noise results in permanent hearing loss. The National Institute for Occupational Safety and Health (*31*) conducted a hearing survey of 1,500 underground coal miners who had no history of significant nonoccupational noise exposure, severe head trauma, or chronic ear infections, and had been out of the working environment for at least 14 h. Figure 8-5 presents the results, showing the percentage of miners, by age, who suffered hearing loss of 25 and 40 dB for the frequencies of 1,000, 2,000, and 3,000 Hz (these are important frequencies for speech perception). By age 50, approximately half of the miners had a hearing loss in excess of 25 dB, and about 30% had a loss exceeding 40 dB. These statistics were measurably worse than the national average.

Other Physiological Effects of Noise

Noise acts as a nonspecific physiological stressor. The onset of a loud, unexpected noise will cause a startled response. This usually involves flexion of the arms, arching of the torso, and blinking. Although not harmful, it may cause a person to be injured, or to injure others. Much of the literature dealing with the physiological effects of noise was reviewed by Antecaglia and Cohen (*3*). They reported the following noise effects noted by various researchers:

1. Undue excitability and nervousness.
2. Reduced speed of eye movements to focus clearly on objects.
3. Narrowing of the visual field.
4. Modification of the perception of color (partial deficiency for perceiving red).
5. Increased secretions of corticosteroids (an indicator of general stress).
6. Constriction of blood vessels, fluctuations in blood pressure, and cardiovascular irregularities.
7. Increased gastric secretions.

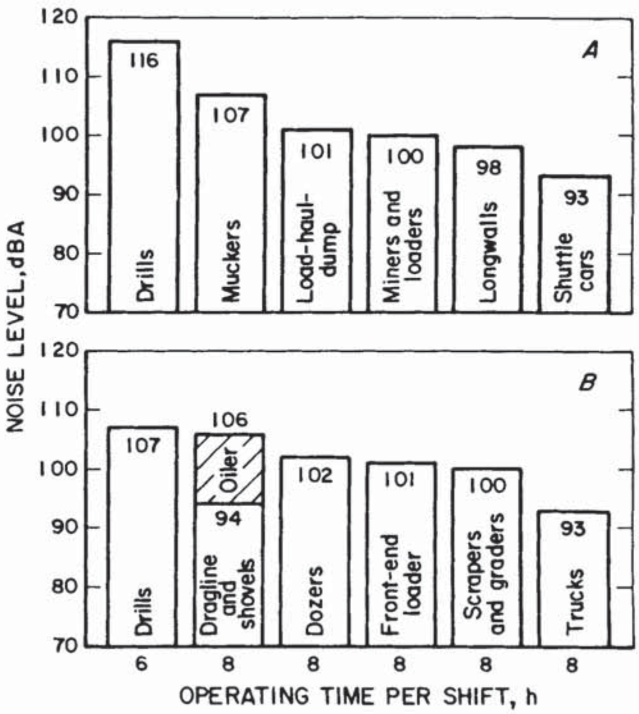


Figure 8-4.—Typical noise levels of machinery in underground (*A*) and surface (*B*) mining (*18*). (Courtesy of U.S. Mine Safety and Health Administration)

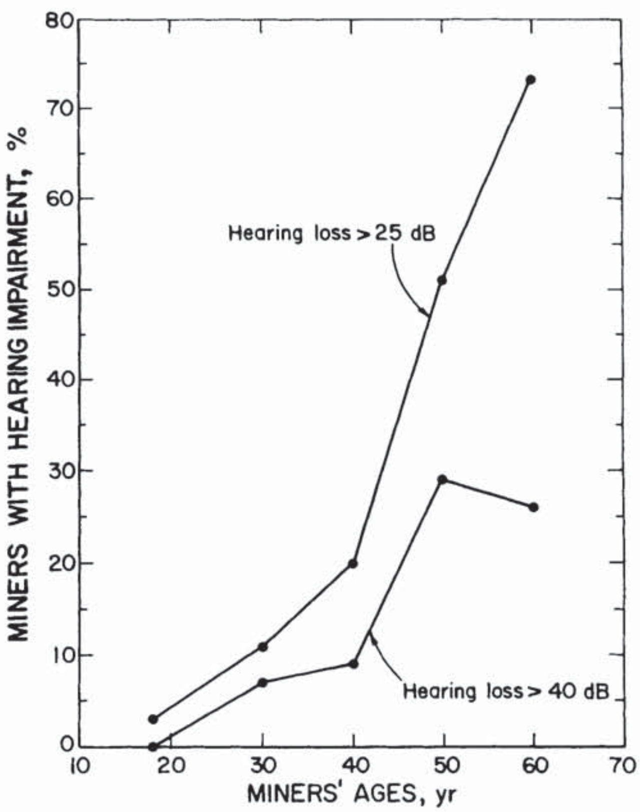


Figure 8-5.—Hearing loss among underground coal miners, by age (*18*). (Courtesy of U.S. Mine Safety and Health Administration)

It must be emphasized that these changes are, for the most part, small. The long-range effect of continual noise exposure has not really been addressed outside the realm of hearing loss. There is some evidence of potential stress-related problems, but the reports are few and sketchy at best.

Effects of Noise on Performance

The effects of noise on performance depend heavily on the task being performed. The more cognitively demanding a task, the more likely it is that noise will adversely affect performance. Performance of simple, routine tasks shows little or no effect from noise, and in some cases even shows a facilitative effect. One effect of high noise is that people tend to funnel attention on a task, focusing on the most important aspects and ignoring peripheral aspects. This may be fine for simple tasks, but where information may be coming from many sources and directions, funneling increases the probability of missing important information.

One important detrimental effect of noise, of course, is that is masks auditory cues. If workers depend on sound cues or voice communications to perform their jobs efficiently and safely, noise robs them of that valuable information, and safety and performance will suffer.

Controlling the Noise Problem

Noise can be controlled at the source, along the path from the source to the receiver (i.e., operator), and at the receiver's ear. In the mining industry, most efforts at noise control have been directed at reducing noise at the source and at the receiver. Little effort has been directed toward reducing noise along its path by using enclosures and barriers. Some processing plants have used sound absorption and acoustic enclosures to reduce ambient noise, but such approaches are less feasible when the sound source is mobile, such as a truck or drill (although treating the inside of a truck cab with absorbent material is often used).

Because sound is essentially caused by vibrating objects, the aim of noise reduction programs has been to reduce the vibrations of the machine or component generating the noise. The discussion of sound-reduction techniques is beyond the scope of this report. However, a few general principles of noise control are discussed and the results of a few noise-reduction programs in the mining industry are presented in this chapter.

Low-frequency noise, the predominant type of noise in many mining situations, is attenuated less than high-frequency noise as it travels in air. In addition, low frequencies are much harder to contain using barriers and enclosures than are high frequencies because low frequencies travel over and around obstacles and through small holes. High frequencies, on the other hand, are more easily deflected. Although harder to contain, low frequencies are less harmful than high frequencies.

When an object vibrates at its natural frequency related to its mass, it resonates. Resonance actually increases the amplitude of the vibration and, hence, the noise. This is dramatically demonstrated by wetting your finger and gently rubbing around the rim of a stemmed glass, causing the glass to vibrate. By changing the speed and pressure of the rubbing action, the resonant frequency can be found, and the glass will emit a very loud tone. Be careful, however; the resonance can increase the vibration to the point of shattering the glass.

In the context of noise control, a piece of equipment vibrating at its resonance frequency will emit loud noises. The noise can be reduced by changing the natural frequency of the equipment. For example, adding or removing mass (e.g., bolting a plate to the machine), drilling large diameter holes in very flat plates, or tightening loose bolts can reduce resonance.

Because vibration causes noise, isolating the vibrating machine from surrounding structures also can reduce noise. Using vibration-isolation springs, pads, etc., for example, often drastically reduces noise. Such isolation materials, however, must be selected carefully because they could change the natural frequency of a machine and cause the equipment to resonate, thus actually enhancing the noise output of the source.

Noise from fluids flowing through pipes is usually caused by turbulences in the flow. Such turbulences can be caused by abrupt pressure changes, such as opening and closing a valve quickly, or by sharp bends or partial obstructions in the pipes that set turbulences in motion. Using fewer or softer (less than 90°) bends and not placing bends close together will often reduce flow-generated noise.

Noise generated by fans can be reduced by changing the pitch and/or number of blades in the fan or by supplying an uninterrupted, nonturbulent flow of air to the fan. Positioning a fan so that the intake side is close to corners or baffles will cause a turbulent flow of air to enter the fan and will increase noise. The purchase of a commercially available silencer from the fan manufacturer is probably the most cost-effective solution.

The Bureau has published a handbook of noise control(*5*) that details specific noise control procedures for various types of surface, underground, and preparation plant equipment. Included are the noise characteristics of particular mining machines, noise-control treatments, anticipated reductions in noise level, cost, and commercially available sources for noise reducing kits, components, etc., references, and case history reports. As an example, figure 8-6 presents a page from this handbook for diesel-powered rotary drills used in surface mining.

A project to reduce noise exposure to operators of diesel-powered track dozers was discussed by Daniel (*13*). One dozer had no operator cab and only a rollover protective structure (ROPS). The noise level at the operator's ear was 105.5 dBA. Through the series of modifications listed in table 8-4, the overall noise level was reduced 11.5 dBA, to

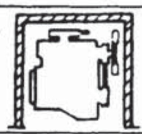
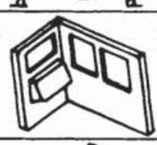
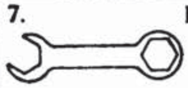
Table 8-4.—Effects of noise control treatments installed on a diesel track dozer equipped with ROPS only (*13*), decibels (A-weighted)

Treatment	Sound level	Reduction from baseline
None (baseline)	105.5	NAp
Windshield	101.5	4
Absorption under ROPS	102.5	3
Exhaust muffler	104.0	1.5
Windshield and absorption	100.0	5.5
Windshield, absorption, and muffler	99.5	6
Windshield, absorption, muffler, and dash seals and isolation	96.5	9
Windshield, absorption, muffler, dash seals and isolation, and floor seals	95.5	10
Windshield, absorption, muffler, dash seals and isolation, floor seals, and seat seals	95.0	10.5
Windshield, absorption, muffler, dash seals and isolation, floor seals, seat seals, tank seal, and hydraulic valve cover	94.0	11.5

NAp Not applicable.

DIESEL-POWERED ROTARY DRILLS

Typical noise level
85-100 dBA

Treatment		Quieted noise level, dBA	Cost and labor	Status	Reference
1. 	Add mufflers(s) to engine exhaust	85-95	$100-$450 2 h	Commercially available for all models.	A1 C2
2. 	Modify existing cab.	75-90	$500-$900 20-80 h	Local design and fabrication required.	A4 B1 B2
3. 	Add acoustic cab.	70-85	$10,000-$15,000 80-140 h	Commercially available for some models.	A2 A4 B2
4. 	Add enclosure for engine with mufflers.	75-90	$1,500-$8,000 140-280 h	Local design and fabrication required.	B2 B4
5. 	Add partial barrier at operator with mufflers.	80-95	$500-$2,000 20-120 h	Local design and fabrication required.	A4 B1 B2
6. 	Modify cooling fan with mufflers for models with noisy fans.	85-95	$500-$2,000 20-120 h	Local design and fabrication required.	B3
7. 	Install item 5 along with covers for hydraulic valves, dust collector for blow air, and isolated centralizer or drill pipe snubber.	80-90	$5,000-$10,000 200-250 h	Local design and fabrication required.	A3 A4 B1 B2 B3

Recommendations

Reduce engine noise using a muffler, cab, or barrier as appropriate.

Acoustically treated noise level

75-90 dBA

Figure 8-6.—Example of type of information contained in *Mining Machinery Noise Control Guidelines* (*5*).

94 dBA. This represents a one-sixteenth reduction in sound power, and a one-half reduction in loudness. About 6 dBA of reduction was obtained by providing a windshield, muffler, and sound-absorption material under the ROPS canopy. The remaining 5.5-dBA reduction resulted from carefully sealing openings and isolating the dash from engine vibrations.

As a final example, a Bureau project to reduce noise levels in low-seam, underground coal mine, mantrip trolley cars was reported on by Galaitsis and Bobick (*17*). Noise levels were typically 90 to 100 dBA in such vehicles at normal operating speeds. The major noise sources were the wheel-rail interface system and the drive motor and train. The noise-reduction treatments included metal panel damping, soft spring seats, soft suspension arm bushings, suspension arm guideplate isolators, motor enclosures, motor mounts, and helical gears. Figure 8-7 shows the results of the treatment for the passenger and operator compartments, with average reductions of 5 to 10 dBA obtained. (Note that a decrease of 3 dB represents a reduction of sound power by one-half.)

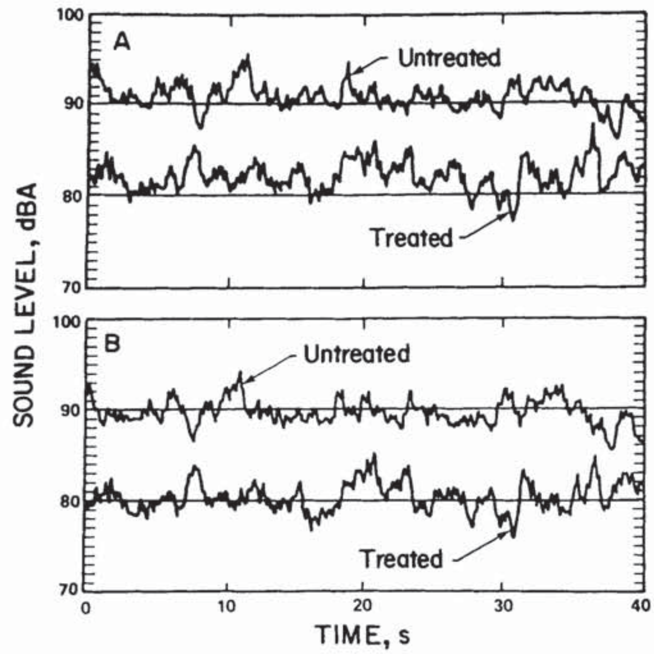


Figure 8-7.—Typical noise-time histories in passenger and operator compartments of an untreated and noise-reduction-treated mantrip (*17*).

Hearing Protection

If noise cannot be reduced at the source or in its path, then hearing protection should be worn by the exposed worker to reduce the noise level reaching the vulnerable structures of the inner ear. There are a wide variety of hearing protectors available: earplugs, muffs, custom ear molds, etc. The two most common types are insert-type and muff-type protectors. Table 8-5 presents the advantages and disadvantages of each (*37*).

Table 8-5.—Advantages and disadvantages of insert-type and muff-type hearing protection devices (*37*)

Courtesy of Charles C. Thomas, Publisher, Springfield, IL

MUFF	
Advantages	More attenuation and less variable. Single size. Easily monitored for wearing compliance. Usually more comfortable. Persons with infected ears can wear them. Harder to lose.
Disadvantages	Uncomfortable in heat. Harder to store or carry. Suspension forces may decrease with bending, and attenuation may vary. Large size. Expensive.
INSERT	
Advantages	Small size. Easily worn with other headgear. Comfortable in hot environments. Inexpensive.
Disadvantages	More fitting time required. Less attenuation and more variable. Dirt may be inserted into the ear canal with the plug. Hard to monitor for wearing compliance. Only persons with healthy ears can wear them.

Each type and make of hearing protection has slightly different attenuation properties. Some give better attenuation at lower frequencies, some at higher frequencies. It is important, therefore, to select hearing protection that matches the environmental noise characteristics for which protection is sought. It must be pointed out, however, that the attenuation curves published by manufacturers are usually generated under more or less ideal laboratory conditions. These data do not take into account wearing habits, fit, interference with safety glasses or hair, and other on-the-job factors. For example, tests conducted with muff-style protectors in the underground environment were reported on by Nguyen (*32*). Whereas the manufacturer claimed attenuation of 25 to 30 dBA, actual measurements showed values of 10 to 16 dBA. In other tests, it was found that suspension fatigue and cushion deterioration had only a minor effect on attenuation, but leakage caused by safety glass temples resulted in up to a 5-dBA loss in attenuation. Insert-type protectors, if properly inserted, are not affected by interference of eyeglass temples and hair, as are muff-type protectors.

An objection often given by workers to wearing protection devices is that such devices reduce speech intelligibility and make it more difficult to hear warnings and other auditory signals. The evidence, however, indicates that wearing hearing protection does not necessarily reduce speech intelligibility. In high noise level conditions, above 80 dBA, wearing hearing protectors reduces both noise and speech, and brings them into a range where they can be more easily discriminated, hence, increasing intelligibility. The problem is that when people wear hearing protectors, they tend to speak more softly than when not wearing them. Personnel have learned to change their voice levels to compensate for a noisy environment, and the quieting effect of hearing protectors cause the wearers to think it is quieter than it really is. The upshot is that people must be instructed to speak loudly, slowly, and distinctly in noisy environments and to be cognizant of the effect of hearing protectors on their speech intensity. Thus, hearing protection per se does not decrease intelligibility for a listener, but it may reduce the speaker's intensity.

There is some evidence that wearing hearing protection can reduce the ability to localize sounds. Approximately 50% more errors in sound localization were found by

Atherley and Noble (*4*) when subjects were wearing protection. There was also a marked increase in left-right errors, where the subjects reported a sound on the right as coming from the left, or vice versa.

Hearing protection should not be considered a permanent solution to a noise problem, but rather only a temporary fix while efforts are being made to reduce the noise level at the source or along its path.

WHOLE-BODY VIBRATION

Whole-body vibration is prevalent in both surface and underground mining environments. In surface mining, mobile equipment operators are exposed to vibration and buffeting as they drive their vehicles over bumpy roads. In underground mining, shuttle car and scoop operators, as well as miners being transported by mantrip, are also exposed to vibration and buffeting. Vibration was discussed in chapter 6 in the context of handtools. Although handtool-induced vibration, as any jackleg drill operator will confirm, can shake your entire body, it is necessary to distinguish that sort of vibration from the lower frequency, higher amplitude vibration transmitted to the whole body by mobile equipment. The physiological and performance effects of the two types of vibration are somewhat different.

Vibration Terminology

Vibration is primarily of two types, sinusoidal and random. As was discussed in relation to noise, sinusoidal motion is regular and repeats itself at set intervals. Most studies of the effects of vibration on humans use sinusoidal wave patterns. Random vibration, as would be expected, is irregular and unpredictable; most real-world vibration is random.

Vibration occurs in different directional planes (up-down, forward-backward, left-right), with the predominant vibratory forces experienced in the mining environment in the up-down plane.

As in the case of noise, whole-body vibration is discussed in terms of frequency and intensity. In the case of sinusoidal vibration, frequency is defined in hertz, and intensity is defined in several ways: amplitude (measured in inches or feet); displacement (inches or feet); velocity (inches or feet per second); or acceleration (inches or feet per square second). Sometimes acceleration is expressed in terms of number of gravity (g) where $1\ g = 386\ in/s^2$ or $32.17\ ft/s^2$.

The situation becomes more complex with random vibration, because the frequency spectrum varies randomly. Frequency is usually displayed in a power spectral-density plot, showing the power density (gravity squared per hertz) in each frequency band. Intensity is often expressed as root-mean-square acceleration (e.g., RMS G) and is a measure of the total energy across the frequency range.

Vibration transmitted to the body can be amplified or attenuated as a consequence of body posture (e.g., standing, sitting), muscle activity (e.g., relaxed or rigid), type of seating, and the frequency of the vibration. Every object has a resonant frequency related to its mass. When an object is vibrated at its resonant frequency, the object will vibrate at maximum amplitude, greater than the amplitude of the original vibration. This is called resonance. Different parts of the body have different resonant frequencies. The following is a partial list of frequencies, in hertz: Vertebras of neck and lumbar region, 2.5 to 5; trunk, shoulder, and neck, 4 to 6; head and shoulders, 20 to 30; and eyeballs, 60 to 90.

It is generally agreed that frequencies between 4 and 8 Hz are most likely to cause damage to the back and spine because of resonance of these body parts.

Effects of Vibration on Humans

The effects of vibration on humans can be divided into two classes, health effects and performance effects.

Health Effects

Several studies have been conducted on individuals exposed to whole-body vibration on the job: tractor drivers, truck drivers, bus drivers, and heavy equipment operators. All the studies suggest that low-frequency vehicle vibrations are associated with increased incidence of lower-back pain, disk and vertebra degeneration, gastrointestinal disorders, and hemorrhoids. The problem is that not all of these ailments can be attributed to vibrations alone; it is likely that other factors, such as maintaining a fixed-seated posture, irregular and poor eating habits, and physical lifting associated with the job, may have contributed to some of these disorders. It was reported by Cain and Pettry (*10*) that at one coal company in 1983, 33% of back injuries occurred to persons employed in jobs where they were regularly exposed to whole-body vibration, yet only 20% of the workforce were in such jobs.

Performance Effects

The primary performance effects of vibration are on visual and manual tasks. Decrements in visual acuity occur most prominently with vibrations in the 10- to 30-Hz region. Vibration does not seem to have much of an effect on cognitive performance or speed-of-reaction time. Vibration leads to fatigue, partly because it causes muscles to tense in order to steady the body or attenuate the vibration. This general fatigue can, of course, lead to reduced cognitive-processing capability. It was reported by Grandjean (*21*) that vibration impairs driving efficiency and increases errors, which may result in accidents.

Vibration Exposure Standards

Researchers have for years been trying to develop a standard for human exposure to whole-body vibration. In 1974, the International Organization for Standardization published a recommended exposure standard for vertical and lateral vibration (*24*). Three criteria were established: fatigue-decreased proficiency boundary (FDP), beyond which working efficiency was postulated to decrease; health exposure limit, which is equal to two times the FDP; and the reduced comfort boundary (RCB), equal to FDP/3.15. Figure 8-8 shows the FDP criteria for vertical vibration. Curves are shown for 8-h, 1-h, and 1- to 4-min exposures. The criteria, although widely accepted, can only be considered approximate. Evidence has accumulated that challenges the validity of the criteria (*48*), and that indicates that fatigue effects occur at lower levels and for shorter durations than the criteria suggest.

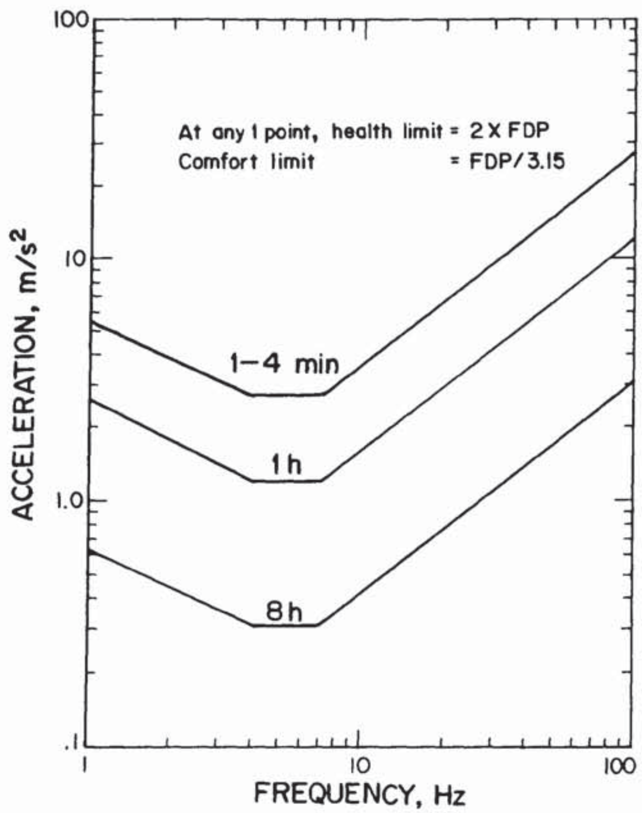


Figure 8-8.—Vertical vibration exposure limits for preservation of performance (fatigue-decreased proficiency, FDP) (*24*). (Copyright 1974 by the American National Standards Institute Inc., and reprinted with permission)

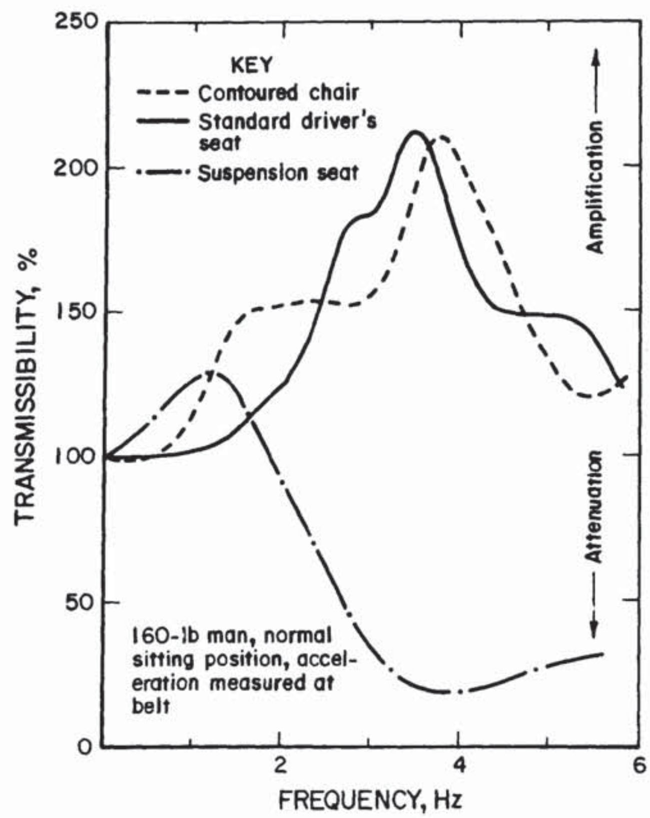


Figure 8-9.—Mechanical response of a person's body to vibrations when sitting in different seats (*39*).

Vibration Exposure of Surface Coal Miners

The vibration exposure of surface coal miners operating equipment such as track dozers, scrapers, haulers, blasthole drills, motor graders, and shovels was measured by Remington (*36*). This work indicated that about half of all surface machine operators are exposed to vibration exceeding the FDP criteria; only about 15% experience vibration exceeding the health exposure limit. The machines in which operators were most likely to exceed the FDP criteria (probability = 0.87-0.90) were scrapers, dozers, and loaders. Truck drivers were next most likely (probability = 0.56-0.58), followed by grader operators (probability = 0.32). The operators of blasthole drills, shovels, and draglines were exposed to very little vibration. Remington concluded that although one would not expect to see many mine machine operators with vibration-induced health effects, one would expect to find significant numbers with impaired ability to operate their machines safely and efficiently because of vibration exposure.

Controlling Vibration

Vibration can be reduced at the source through engineering modifications to the equipment, including better suspension systems and component isolation. In addition, shock-resistant seats can be installed to reduce the intensity of the vibration reaching the operator's body. Figure 8-9 shows the transmission of vibration to a seated person in three types of seats (*39*). As can be seen, the suspension seat reduced the level of vibration considerably. The amplitude of vibration was actually increased when the person sat in the contoured and standard seats. The cost of a good pneumatic seat can accrue dividends in increased worker health, comfort, and efficiency.

HEAT STRESS

Thermal conditions in mining run the gamut from bitter cold, experienced by surface miners in the winter, to hot humid conditions, experienced in deep underground mines. Heat stress is probably more prevalent, and certainly more dangerous, than cold stress. The body can tolerate cold stress much better than heat stress, and the performance effects of cold stress seem to be more restricted than is the case with heat stress.

Physiological Response to Heat Stress

As discussed in chapter 7, the body oxidizes glucose to release energy and heat. The more physically demanding an activity, the greater the amount of heat generated. This is the process of metabolism, and it can increase heat production 10 to 20 times greater than at rest. The body also gains and loses heat from and to the environment. Heat is gained or lost due to convection (the mixing of cool and warm air and the transfer of heat by molecular contact of the air molecules), conduction (direct contact with another object—usually so negligible that it is combined with convection), and radiation (the transfer of heat by electromagnetic radiation—as is done by the sun or hot object not in direct contact with the body). The body loses heat through evaporation (the conversion of water to water vapor). Evaporation is the principal avenue of heat loss for the body, and is regulated by producing sweat and diverting heated blood to the skin for evaporative cooling.

The body attempts to maintain a state of internal thermal equilibrium. That is, the body regulates blood flow and sweat production to maintain a constant (or nearly constant) core temperature. Core temperature is the temperature of the deep body organs and is approximated by rectal temperature. As the body gains heat, due to either increased metabolism or by exposure to a hot environment, the heart beats faster and pumps more blood with each beat (i.e., increased cardiac output). In addition, the blood vessels in the skin dilate to allow the heated blood from the core to flow to the skin and to be cooled, especially by evaporation.

In addition to the cardiovascular response to heat stress, the body produces sweat that keeps the skin moist and is the principal medium for evaporative cooling. If the body can dissipate the metabolic and environmental heat buildup, no major problems occur. If not, serious physiological consequences, including death, can ensue.

Excessive heat stress leads to heat cramps, heat exhaustion, and heat stroke. Heat cramps are painful muscle cramps caused by excessive sweat loss. The cramping can occur during or after work, and usually affects those muscles most involved in the work.

Heat exhaustion is caused by excessive loss of water. The worker with heat exhaustion experiences dizziness, extreme weakness or fatigue, nausea, and headaches. Heat stroke is the most serious health problem and can often lead to death. Basically, in heat stroke, the body's heat dissipation system cannot cope with the heat stress placed on it. Either the sweat glands fatigue and cease producing sweat, or the system simply cannot adequately dissipate the heat load. Core temperature rises and the hot blood damages the vasomotor control centers in the brain; liver and heart damage can also occur. Blood vessels dilate and insufficient blood is returned to the brain and heart, and the person often will go into shock. Immediate medical attention is required to prevent death.

Figure 8-10, based on work by Bell (*7*), shows the number of minutes unacclimatized workers can tolerate various combinations of dry bulb temperature and relative humidity. The data were generated by young, fit men stepping on and off a stepstool, 12 times per minute. The men continued the activity until exhausted. As shown, at these relatively high temperatures and this work rate, collapse occurred in less than 2 h.

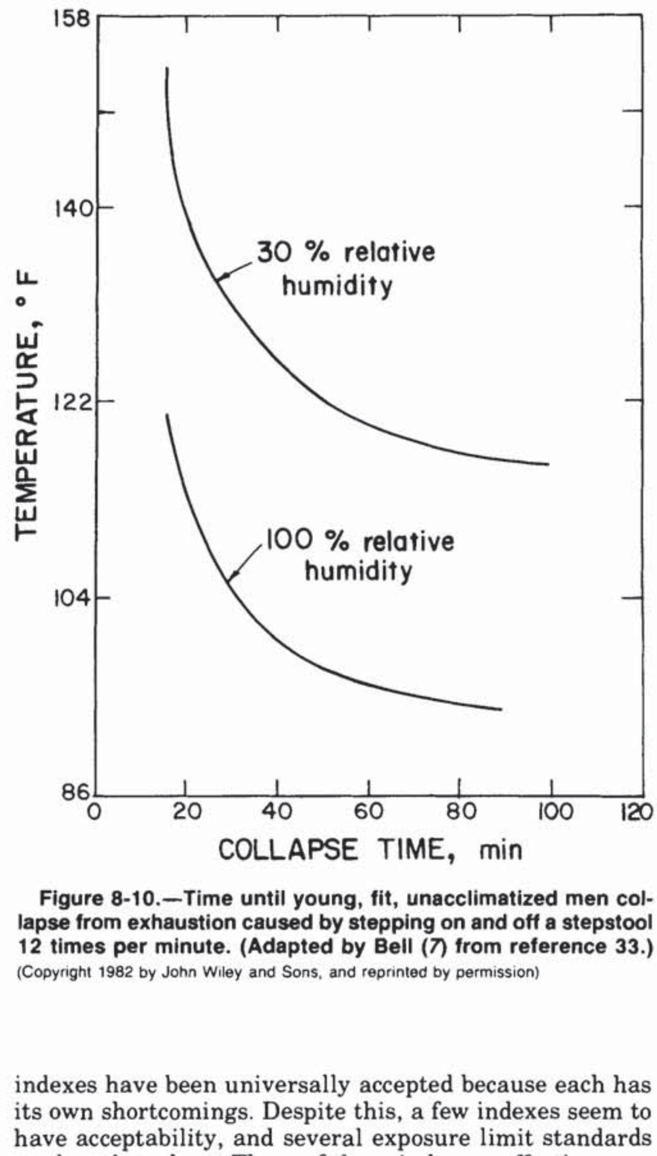


Figure 8-10.—Time until young, fit, unacclimatized men collapse from exhaustion caused by stepping on and off a stepstool 12 times per minute. (Adapted by Bell (*7*) from reference 33.)

Indexes of Heat Stress

Heat stress is the total heat load on an individual from environmental and metabolic sources. Heat stress is distinguished from heat strain, which is the biochemical, physiological, and psychological adjustments made by an individual in response to the stress (*27*).

Over the years, many attempts have been made to develop indexes of heat stress by combining several environmental and task variables into a single number to represent the heat load on an individual. None of a dozen or more indexes have been universally accepted because each has its own shortcomings. Despite this, a few indexes seem to have acceptability, and several exposure limit standards are based on them. Three of these indexes—effective temperature, wet-bulb-globe temperature, and Belding-Hatch heat stress index—are discussed in the following sections.

Jensen (*27*) compared these heat stress indexes and found very high correlations between wet-bulb-globe temperature and corrected effective temperature, but lower correlations between these measures and the Belding-Hatch heat stress index. Similar results have been reported by Morris (*30*).

Effective Temperature (ET)

ET is an index of the warmth felt by the human body on exposure to various combinations of air temperature, humidity, and air velocity, using as a reference the temperature of an environment with still, fully saturated (100% relative humidity) air. Thus, if a given combination of temperature, humidity, and air velocity yields an ET of 85° F, that environment would give the same thermal sensations as an environment of 85° F, 100% relative humidity, and no air velocity. As pointed out by Jensen (*27*), ET does not include the effects of radiant heat (e.g., the sun), and hence underestimates heat load in environments where radiant heat exists. Several investigations have proposed corrections to ET to take into account the effects of radiant heat. Another development in the ET index has been to relate the environments to 50%, rather than 100%, relative humidity, and to use equivalent skin wetness rather than thermal warmth felt. This scale is called corrective effective temperature (*16*).

Wet-Bulb-Globe Temperature (WBGT)

WBGT combines natural wet bulb temperature (NWB), globe temperature (GT), and dry bulb temperature (DB) into a single index using the following formula:

Indoor application–WBGT = 0.3 GT + 0.7 NWB, and outdoor application–WBGT = 0.2 GT + 0.7 NWB + 0.1 DB.

Natural wet bulb temperature is obtained by wrapping the end of a thermometer with wet gauze. This simulates the evaporative cooling capacity of the environment, taking into account the air movement and relative humidity in one measure. Globe temperature is obtained by placing a thermometer inside a copper sphere that is painted black. This measures the radiative heat load of the environment. Dry bulb temperature is simply the temperature reading from a dry thermometer suspended in the air. Figure 8-11 shows a typical manual setup for obtaining the temperature readings necessary to compute WBGT. As will be seen, WBGT is fast becoming the measure upon which exposure standards are being based. There are electronic instruments available that display WBGT directly, but they are expensive. A simplified measure proposed by Botsford (*9*), called the wet globe temperature (WGT), consists of a dial thermometer with a heat sensor enclosed in a small copper sphere, covered with a wet black cloth (a Botsball). It is designed to take into account all the forms of heat exchange that affect a person's response to a hot environment, i.e., evaporation, conduction, convection, and radiation.

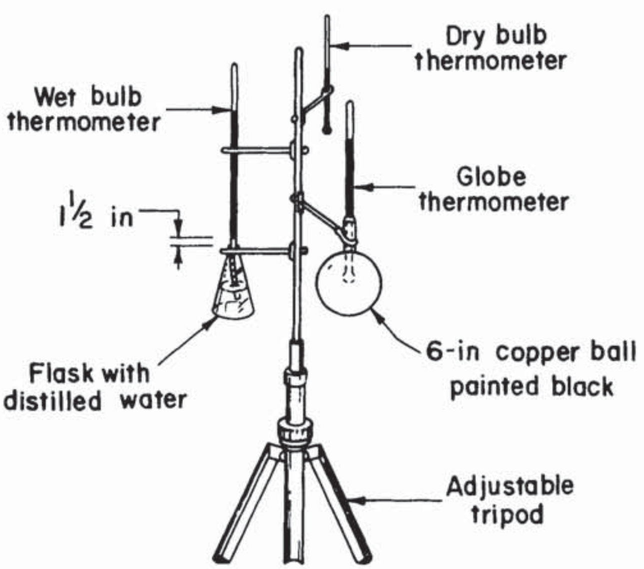


Figure 8-11.—Setup for manually obtaining temperatures used to compute wet-bulb-globe temperature.

Heat Stress Index (HSI)

HSI was developed by Belding and Hatch (*6*). It is one of the most comprehensive indexes available, but requires many measurements and uses a relatively complex formula. Basically, HSI is the ratio of the body's heat load from metabolism, convection, and radiation to the evaporative cooling capacity of the environment. The idea is that the heat load from these sources must be dissipated through evaporation. The ratio of heat load to evaporative cooling capacity of the environment therefore indicates the relative ease by which that heat load is dissipated. The index takes into account environmental factors, such as temperature, humidity, and air movement, but also includes metabolic rate and clothing effects.

Heat Stress Conditions in Mining

For the most part, heat stresses in undergound mines with adequate ventilation are not excessive. The major problem encountered in underground mining is high humidity, which reduces the body's capacity to dissipate heat by evaporation. Crooks (*11*) surveyed underground metal-nonmetal worksites in the United States and found the dry bulb temperature averaged 62° F and ranged from 37° to 79° F. Relative humidities, however, averaged 70%, and ranged from 13% to 99%. Over 25% of the worksites measured had relative humidities over 90%. The warmer, more humid, and slower airflows were found in production and development sites, where the heaviest physical labor occurs. It is in such sites that heat strain becomes excessive if precautions are not taken.

The wet bulb temperature in South African gold mines (much deeper than U.S. mines) was reported on by Van der Walt (*46*). Average temperature has been increasing for the last 20 yr, probably because of mining at even greater depths. It was estimated that half the total underground workforce in South African gold mines works in areas where the wet bulb temperature is above 86° F. This corresponds to a dry bulb temperature of 88° F and 90% relative humidity, or 92° F and 80% relative humidity. It is no wonder that from 1969 to 1980, 205 heat stroke accidents were recorded in South African gold mines, with 39 resulting in fatalities.

Performance Effects of Heat Stress

There are several specific effects of heat stress that reduce a worker's capability to perform efficiently and safely. Excessive heat reduces a person's capacity to perform physically demanding work. In addition, the physically demanding work increases the overall heat stress placed on the individual. This results in reduced work output. The performance of miners loading mine cars and of drilling rock as a function of ambient temperature was reported on by Misaqi (*29*). The results, presented in figure 8-12, show that as temperature increased, performance declined rapidly.

Heat stress also reduces one's ability to remain alert during lengthy and monotonous tasks, and reduces the ability to make quick decisions. In addition, heat stress can also, at times, contribute to frustration, anger, and other emotions. These effects, combined with slippery sweaty palms, dizziness, and fogging of safety glasses, can lead to higher accident rates in heat stress environments. For example, an investigation of the incidence of unsafe behaviors in a variety of industries as a function of WBGT was reported on by Ramsey (*34*). The results, shown in figure 8-13, indicate a U-shaped relationship, with the least incidence of unsafe behavior occurring between 62.6° F and 73.4° F WBGT. Above or below this optimum range, unsafe behaviors increased. The effect was most pronounced for jobs requiring moderate workloads, which represent most mining jobs. It is usually the case that reducing heat stress can pay off for everyone: reducing physiological stress on the workers, increasing productivity, and reducing accidents.

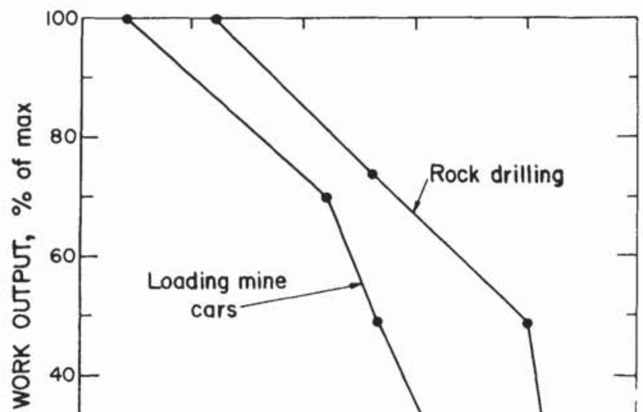


Figure 8-12.—Effects of ambient temperature on miners loading mine cars and drilling rock (*29*). (Courtesy of U.S. Mine Safety and Health Administration)

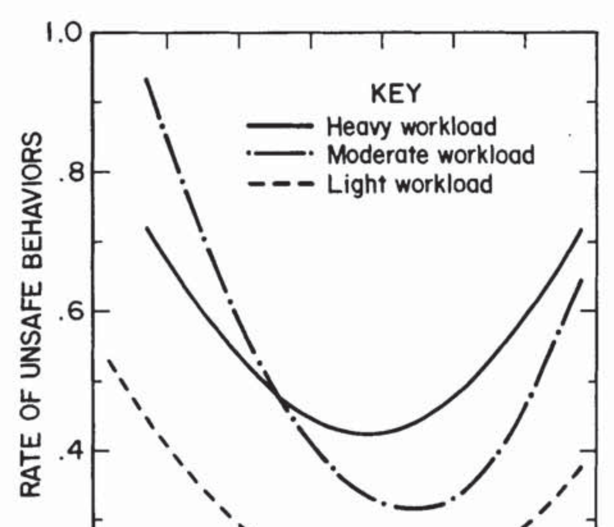


Figure 8-13.—Relationship between rate of unsafe behaviors and wet-bulb-globe temperature (*34*).

How Much Is Too Much

The National Institute for Occupational Safety and Health (NIOSH), as discussed by Dukes-Dobos (*14*), has proposed exposure limits based on the WBGT. These are similar to recommendations that have been accepted by the American Conference of Governmental Industrial Hygienists (*1*), the American Industrial Hygiene Association (*2*), and the International Organization for Standardization (*25*). Table 8-6 compares these standards for 8-h exposures at various levels of workload. It should be pointed out that the corrections for high-velocity airflow have been challenged by some investigators as not necessary (*22*). The various standards are very much in agreement, although the designations of light, moderate, and heavy workload differ markedly.

Table 8-6.—Comparison of proposed WBGT threshold values (*35*)

(Reprinted with permission by Taylor and Francis, Ltd)

	Resting	Light	Moderate	Heavy	Very heavy
ACGIH:					
Temperature . . °F . .	NP	86	80	NP	77
Energy . . . kcal/h . .	NP	100-200	201-350	NP	350-500
AIHA:					
Temperature . . °F . .	90	86	80	NP	NP
Energy . . . kcal/h . .	100	200	300	NP	NP
OSHA:					
Temperature . . °F . .	NP	[1]86, [2]90	[1]82, [2]87	[1]79, [2]84	NP
Energy . . . kcal/h . .	NP	<200	201-300	>301	NP
ISO:					
Temperature . . °F . .	91	86	82	[1]77, [2]79	[1]73, [2]77
Energy . . . kcal/h . .	<100	100-201	201-310	310-403	>403

ACGIH American Conference of Governmental Industrial Hygienists.
AHIA American Industrial Hygiene Association.
NP Nothing proposed.
OSHA Occupational Safety and Health Administration.
ISO International Organization for Standardization.
[1] Low-velocity ventilation.
[2] High-velocity ventilation.

Standards are also available for intermittent work in a hot environment. These, however, diverge markedly, according to Henschel (*22*), because there are very few data available to provide guidelines. The relative physiological impact of short and long heat exposures is not known, nor is the extent of the effect of the rest area temperature on strain or if short rest and short work periods result in the same strain as long rest and long work periods. However, if the continuous work recommended exposure levels are adhered to, even for intermittent work, one would be confident of erring on the side of safety.

Protection From Heat Stress

A number of measures can be taken to protect workers from heat stress. At a minimum, workers exposed to hot environments should be given specific training in the symptoms and mechanism of heat stress, and how to protect themselves against heat stress. Work done in hot environments can often be redesigned to reduce physical activity and hard labor. Work should be mechanized where possible and paced to give frequent rest periods, and the overall exposure time to heat should be minimized. Heavy physical work in surface mining can often be scheduled for cooler times of the day. Cool rest areas should also be provided to maximize the benefits of rest.

Workers must be supplied with fresh drinking water and encouraged to drink, even if they are not thirsty. As it turns out, thirst is not a good indicator of dehydration. Water must be replenished on a regular basis, in quantities that match the sweat loss incurred. If the workers eat normal meals and snacks, salt need not be added to the drinking water, nor should salt tablets be used. The use of salt in hot environments has a long history, but current evidence strongly discourages this practice. Ingestion of salt actually retards the acclimatization process, leads to high blood pressure, and does not mitigate the negative effects of heat stress (*41*). Recommendations by the American College of Sports Medicine suggest that fluid loss should be replaced with water having a 2.5% glucose (sugar) content. The temperature of the replacement water should be 45° to 55° F.

Workers should be specifically selected to work in hot environments; the following characteristics among workers increase the likelihood of experiencing heat stress in hot environments:

1. The taking of alcoholic drinks or narcotic drugs.
2. The taking of antihistamines or diuretic drugs.
3. Cardiovascular diseases.
4. Sickness, especially if vomiting and diarrhea are symptoms.
5. Body weight less than 110 lb (*47*).
6. Over 45 yr of age (*41*).
7. Poor physical condition.

The work area should be redesigned, if feasible, to increase airflow by installing fans, ventilation tubes, or air conditioning. To shade surface workers from the sun, tent covers can be erected.

Proper clothing should be insisted upon. On hot sunny days, lightweight cotton shirts and pants reduce the radiant heat load, and facilitate evaporation by soaking up sweat and bringing it to the surface. Head covering is important outdoors. Clothing should be loose fitting and not interfere with evaporative heat loss. Under extreme conditions, ice jackets can be worn to increase tolerance to heat stress (*42*).

Probably the most promising approach to reducing the ill effects of heat stress is to institute a systematic acclimatization program for those who must work in hot environments. The Republic of South Africa has been a leader in developing and testing various methods for efficiently and safely acclimatizing workers and identifying those who are at high risk (*38, 41, 43*). Acclimatization is required for workers who have to work in wet bulb temperatures of 82° F or above. In South African mines, 0.25 million men must undergo acclimatization each year. The acclimatization procedure involves several components: (1) climatic room acclimatization; (2) ascorbic acid (vitamin C) supplements; (3) microclimate suits; and (4) heat tolerance testing.

The climatic room acclimatization involves working for 4 h/d at a metabolic load that is increased progressively from 150 kcal/(m²/h) on the first day to 240 kcal/(m²/h) on the eighth day. The climatic room is controlled at 89° F wet bulb. Workers are monitored for abnormal reactions and given treatment if needed. Strydom (*41*) found that this procedure reduced the acclimatization period from 12 to 8 days, and required only 4 h/d as against full shifts.

Workers are also given 250 mg of vitamin C per day, starting before acclimatization and continuing throughout the process. Results showed that acclimatization time was reduced from 8 to 4 days; and, in addition, fewer men were found to be heat intolerant. Without vitamin C, 3% to 5% of the men could not acclimate; with vitamin C, less than 1% could not be acclimated.

Use of ice jackets (microclimate suits) was found to reduce the ill effects of heat stress without retarding acclimatization. Results showed that workers would become acclimatized to heat while doing their normal underground tasks wearing an ice jacket for 6 days. Finally, a procedure for screening workers to identify those who do not need acclimatization (the hyper-heat-tolerants) and those who would not respond to acclimatization has been developed.

In South African mines, despite increased average working temperatures (due to mining at increased depths), Strydom (*41*) found that heat stroke cases have steadily declined over the last 20 yr, due in great part to the widespread use of systematic acclimatization procedures.

COLD STRESS

As the ambient temperature declines, the body takes defensive actions to maintain its thermal balance. The first defense is to constrict the blood vessels in the skin and extremities, thereby keeping the warm core blood away from the cold surface. A second defense is shivering, which serves to increase metabolic heat production and hence reduce or halt overall heat loss. Excessive fluid loss can also occur in cold environments. and cold-induced dehydration may persist for several days.

The body can tolerate more cold stress than heat stress. Deep-body temperature can decline to 78° F before death occurs. There have even been cases of people (usually children) who have survived body cooling to 60° F if the drop occurred rapidly.

Whereas there are a host of competing indexes of heat stress, there is really only one index of cold stress: windchill index (or temperature). Table 8-7 presents the temperature equivalent of various combinations of local temperature and wind speed as given by Siple and Passel (*40*).

Table 8-7.—Equivalent temperatures based on windchill index (*40*), degrees Fahrenheit

(Reprinted with permission by American Philosophical Society)

Air temp . . . °F . .	40	20	10	0	-10	-20
Calm	40	20	10	0	-10	-20
5-mph wind	37	16	6	-5	-15	-26
10-mph wind	28	4	-9	-21	-33	-46
20-mph wind	18	-10	-25	-39	-53	-67
30-mph wind	13	-18	-33	-48	-63	-79
40-mph wind	10	-21	-37	-53	-69	-85

Frostbite

One common disability caused by exposure to cold is frostbite; i.e., localized freezing of body tissue. Frostbite can be either superficial, involving only the skin, or deep, extending below the skin. At a windchill temperature of -25° F, exposed flesh may freeze within a minute. A temperature of 5° F and a 15-mph wind combine to create such a condition.

Performance Effects of Cold

Cold, even if not severe enough to cause body cooling, can still affect performance, especially that involving motor skills and cognitive ability. For example, whenever hand skin temperature falls below about 68° F, manual dexterity deteriorates rapidly. Tasks that require use of handtools or small parts are most affected by the cold. Localized warming of the hands, however, can reduce the negative effects of cold on performance. However, if the entire body is not kept warm, general body shivering will interfere with the performance of fine motor-hand coordination tasks.

The results dealing with the effects of cold in cognitive performance are less clear cut than those on motor performance. Cold is likely to decrease the performance of complex mental tasks that contain an element of time estimation (time seems to go more slowly in the cold), due to the distraction caused by the cold stress.

Protection From Cold Stress

It appears that little acclimatization to cold takes place, except in the case of extremely long-term exposures. The best protection is clothing that remains dry and insulates the worker against the cold. Localized warming of the hands using heat lamps may be beneficial under certain conditions. Adequate diet, high in carbohydrates, fats, and protein, is also important to fend off the effects of cold.

DISCUSSION

This chapter has briefly reviewed the effects of illumination, noise, whole-body vibration, and climate on miner health and performance. It is important to remember that in the mining industry, combinations of environmental stressors exist. Mining machines generate noise and vibration and are often used in low-light environments. In many cases, these environmental factors can produce levels of stress that seriously degrade performance and compromise employee health. Technologies are available for controlling such environmental factors and their application is well within the state-of-the-art. What is needed on the part of the mining industry is a more active awareness of the severity of the problem and a commitment to reduce it.

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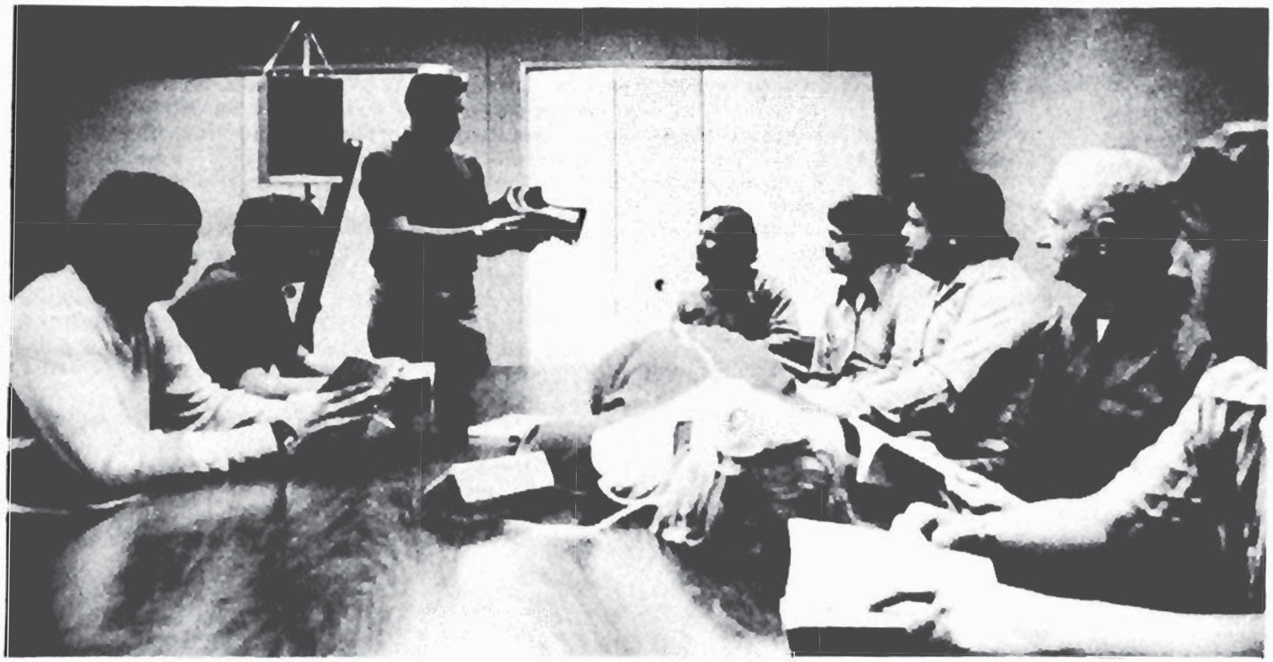
CHAPTER 9.—TRAINING



Training is an important and expensive enterprise in the mining industry.

Human factors seeks to modify the job to fit the person, while training seeks to modify the person to fit the job—in this sense the two oppose one another. Conversely, a well-designed (human-factored) job reduces the requirements for training, and an effective training program can reduce the human factors design requirements—in this sense they complement one another. It would be impractical, if not impossible, to design a job in such a manner that no training was required. By the same token, it would be extremely unwise to expect the training function to overcome all human factors deficiencies present in the design of a job. The fact is that both human factors and training are necessary for efficient and safe operations.

Both human factors and training seek to change behavior; human factors does it through design, while training does it by modifying skills, knowledge, and attitudes. In addition to the commonality of goals, human factors also has a role in the design of effective training programs. A training program can be viewed as any other system, and human factors can contribute to the design of such a system. Human factors has contributed to (1) the design of training hardware, such as simulators and training aids, (2) determining training needs, and (3) evaluating the effectiveness of the training programs.

Training is an important and expensive enterprise in the mining industry. In 1983, for example, the U.S. mineral industry employed over 400,000 miners and provided approximately 4.5 million hours of formalized health and safety instruction. In addition, the U.S. mining industry provided over 80,000 miners with occupational training to support organizational goals and comply with Federal and State training requirements. The mining industry spends approximately $200 million on new hire, refresher, and occupational training per year (*21*).[1]

EFFECTIVENESS OF TRAINING

Assessing the effect of training on behavior is a difficult task in the operational environment. Several problems present themselves that make the interpretation of results difficult. First is the problem of defining what is meant by training. Often, a training program involves several components, including classroom training, on-the-job training, and company support programs such as safety campaigns. It is difficult to determine which components of a program are effective and which are not.

A second problem is one of experimental control. Often, a control group (i.e., untrained miners) is not used, making it impossible to determine what the injury or production rates would have been without the training. Usually, only before- and after-training measurements are made. Factors in the work setting, other than training, may have changed at the same time that training was started and could have influenced safety or productivity.

A third problem is that the measures used to evaluate the effect of training may not be sensitive enough to detect real changes in behavior. Both injury rate and production rate are influenced by all sorts of factors, including luck, or lack of it. A crew may be working more safely and more efficiently, but because of extenuating circumstances (e.g.,

[1] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

poor roof conditions, equipment breakdown, outbreak of flu), its safety and productivity records do not reflect the positive effects of training.

With these problems in mind, a review is made of a few studies that have attempted to assess the effects of training on behavior. One conclusion from the literature is that generalized training is not as effective as training targeted to change specific behaviors. A second conclusion is that a coordinated, multifaceted program, involving classroom training, on-the-job training, and followup, is more effective than a single-shot training experience.

The results of a maintenance training program in South African mines were reported by Robertson (*22*). In a 3-week course, rock cutter operators were trained to diagnose faults in their machines using a step-by-step troubleshooting procedure, and to repair the malfunctions without aid from maintenance workers. Maintenance worker involvement in repairs decreased from 46% to 3%. Average repair times were reduced by 21%, and productivity increased by 30%.

The outcome of a forklift training program targeted at specific unsafe behaviors was discussed by Cohen (*5*). The program involved a classroom presentation of incorrect and correct ways to handle specific hazardous situations, group discussion of the recommended behaviors, and a final test in which all members of the group scored each other as they performed a series of tasks using a forklift. In addition, on-the-job daily feedback in the form of verbal and posted summaries of group performance (percentage of correct behaviors on the job) was given to the group. The supervisor, in a positive, constructive, and confidential manner, coached the workers on correct work procedures. Results showed reductions in unsafe behaviors of 70% and 40% at two separate companies where the program was applied.

A structured 2- to 3-day training program with on-the-job training, using a continuous miner simulator, was reported by Morris (*19*). After training, production increased an average of 7.15 st per month, per unit-shift.

The results of a study conducted at four salt mines in which supervisors were trained to use social reinforcement (praise) to increase safe behaviors were presented by Uslan (*27*). The training program was general in nature, rather than targeted to specific behaviors. Eye, hand, and back injuries were monitored before and after training of the supervisors. The results were mixed. Injuries declined at two mines, remained relatively stable at one, and increased in the other mine. The lack of clearcut results was probably due, in part, to the nonspecific nature of the training, and to the fact that the training was directed toward changing the behavior of supervision rather than that of the workers.

TRAINING: WHAT IS REQUIRED

In the United States, miner training regulations are described in the Federal Mine Safety and Health Act of 1977, as amended. In addition, some States have also established regulations for miner training. A brief review of the essential features of these requirements will be presented as well as a comparison with those set forth in other countries. This section should not be considered a complete review of existing regulations, nor should it serve as a substitute for the actual regulation of governing bodies.

Training Requirements in the United States

The Federal training regulations for new underground miners set forth a minimum of 40 h of training, of which 32 h are classroom training and 8 h are at the jobsite. Eight hours of training must be received before a new miner can go underground. For new surface miners, Federal regulations specify only a minimum of 32 h of training, of which 8 h occur before miners begin their actual work assignments. In addition, 8 h of annual refresher training is required of all miners. The topics required for training new miners, newly employed experienced miners, and annual refresher training are listed in table 9-1 for both underground and surface mining (*9*).

Besides the Federal training regulations, some States impose additional requirements. Of the 15 States that produce coal in the United States, only five have requirements beyond the Federal regulations. Kentucky requires 90 working days of experience, within sight and sound of a certified miner, followed by an examination for certification. Indiana requires a 6-month apprenticeship with an experienced miner before a new miner can work alone. Pennsylvania requires 1 yr of apprenticeship under close supervision, followed by an oral, practical examination. Illinois requires a 1- to 2-yr (maximum) apprenticeship, followed by oral and written examinations, and first-aid and mine rescue training; those with an associate degree in coal mine technology or a bachelor's degree in engineering can waive 6 months of apprenticeship. West Virginia requires 80 h of instruction, followed by an examination to qualify as an apprentice; the new employee then works 6 to 8 months (maximum), within calling distance of a foreman, assistant foreman, or designated experienced miner (*20*).

Training Requirements in Other Countries

An excellent review of training requirements and practices in foreign countries was provided by McAteer (*16*). No attempt will be made to provide all the details of the various foreign training requirements here, only brief overviews for a few of the major European countries will be given.

Great Britain has some of the most comprehensive training requirements of any country. New miners must receive 100 days of training before they can work underground, and they cannot work within 30 ft of the face until they have completed 120 days of training. To become a certified miner requires 3 yr, including over 300 days of formal instruction and 100 days of work under constant supervision.

The Federal Republic of Germany requires a 3-yr apprenticeship, including formal schooling 3 days per week. Six months of training is required before a miner is permitted to work underground. In addition, 20 days of aboveground training, under simulated mining conditions, is also required. When workers are away from their jobs for 6 months, 20 days of training is required (10 classroom and 10 at the face) before they can resume work.

In Poland, prospective miners enter mining school at the age of 14 or 15 and take 3 yr of classroom and job instruction. A 3-yr apprenticeship is required, including 200 h of training at a mine training center. Sixteen hours of annual refresher training is required of all miners.

Table 9-1.—Content of underground and surface mine health and safety training, by type (*9*)

Topic	Introductory for—		Annual refresher for working miners
	New miners	Newly employed experienced miners	
UNDERGROUND			
Statutory rights and responsibilities of supervisors	X	X	
Self-rescuer and respiratory devices	X		X
Entering and leaving the mine, transportation, communication	X	X	X
Introduction to the work environment	X	X	
Mine map, escapeways, emergency evacuation, barricading	X	X	X
Roof and ground control, ventilation plans	X	X	
Health	X		X
Cleanup, rock dusting	X		
Hazard recognition	X	X	
Electrical hazards	X		X
First aid	X		X
Mine gases	X		X
Health and safety aspects of assigned tasks	X		
Mandatory health and safety standards		X	X
Prevention of accidents			X
Explosives			X
SURFACE			
Statutory rights and responsibilities of supervisors	X	X	
Self-rescue and respiratory devices	X		X
Transportation and communication	X	X	X
Introduction to the work environment	X	X	
Escape and emergency evacuation, firewarning and firefighting	X	X	X
Ground control, highwalls, water hazards, pits and spoil banks, illumination and night work	X	X	X
Health	X		X
Hazard recognition	X	X	
Electrical hazards	X		X
First aid	X		X
Explosives	X		X
Health and safety aspects of assigned tasks	X		
Mandatory health and safety standards		X	X
Prevention of accidents			X

France has no specific training requirements. However, training usually includes 2 weeks of surface classroom training and an examination, 3 to 4 months of training at an underground training face, and 2 to 3 months of working under close supervision at an actual production face.

Discussion

From even this short overview of training requirements, it is obvious that the U.S. requirements fall short of those in other countries. Some authorities suggest that this accounts, in great part, for the lower injury and fatality rates per million labor-hours experienced by European countries. The fact that so many countries do require extensive new-miner training and apprenticeship suggests that more could be done in the United States to instill good working habits in new miners.

TRAINING PRACTICES IN THE UNITED STATES

In the previous section, training requirements in the United States and other countries were discussed. In this section, a brief overview of U.S. training practices is presented. In essence, this is how the mining industry is meeting and, in many cases, exceeding the training requirements placed on it by the Government. Over the years, a few studies have attempted to summarize the mining industry's training experiences. Training at over 300 mines was reviewed by Adkins (*1*), while Digman (*9*) reviewed classroom training practices at 14 sites. Major sources of mine-related training in the United States were reviewed by Short (*24*). Several general themes emerge from these reports.

1. The first-line supervisor plays a central role in most training programs conducted by the mines.
2. There is a danger that technical compliance with Government training regulations assumes more importance than the goal of reducing mine accidents.
3. There is tremendous diversity among programs in terms of resources allocated, methods used, competency of instructors, and use of followup methods.
4. Instructional skills among trainers seem to be less well developed than are technical skills.
5. On-the-job training is used extensively, but is often difficult to monitor, correct, or improve when it is inadequate.
6. Training is provided by mine companies, vocational schools, State agencies, Mine Safety and Health Administration (MSHA), equipment manufacturers, consultants, and trade associations, with mining companies providing, far and away, the majority of the training.
7. It is difficult to demonstrate, statistically, that one training method is better than another for reducing accidents.

Keeping in mind the diversity of training that exists in the mining industry, Adkins (*1*), nevertheless, represented a typical new underground miner indoctrination training experience. The description is worthwhile and is reproduced here to give a conception of the methods used most often in miner training.

> The process begins with the personal safety equipment—hard hat, protective glasses, safety boots, leg bands, belt and self rescuer. The new man is shown, lectured on, and issued this equipment. Use of the self rescuer is shown in film, on poster and demonstrated by each individual, and then, as shown by too many disasters, forgotten. Next comes a brief introduction to the mine environment (including the geology, mine plan, ventilation, roof control and mining methods) through lectures aided by various slides, films or tapes, posters, mock-ups, and charts. This will be followed by a mine tour to illustrate and reinforce what the new man has been told by the instructor in the classroom.
>
> Most new employee programs continue the indoctrination with lectures and demonstrations covering the topics of oxygen deficiency and methane detection devices and first aid. Films, posters, and simulation devices are used to supplement the lecture presentations and to give the student an opportunity for "hands on" experience, as feasible. More lectures from various company departments on organizations and policy, and from state and union representatives on the local laws and working agreement, plus some qualification testing, will constitute the balance of new employee indoctrination. Other than exposure to slogans and either monthly (the usual case) or weekly safety meetings, the average miner will not receive any more classroom training unless he needs annual qualification or moves on to maintenance or supervision duties.

CHARACTERISTICS OF SUCCESSFUL SAFETY PROGRAMS

There have been several attempts to identify characteristics of successful safety programs. The approach taken has been to either examine exemplary safety programs or to compare companies having high and low accident rates. For example, 192 Wisconsin factories with high and low accident rates were compared by Cohen (*4*); two successful task training programs in two open-pit taconite mines were described by Couillard (*6*); and safety directors of 12 coal companies that had won awards for extended periods of work without lost-time injury were interviewed (*8*). In addition to these studies, a review of the literature available up to 1977 was provided by Cohen (*3*).

These various studies and reviews show remarkable consistency with respect to the characteristics of successful safety programs. One conclusion that stands out is that there is more to a successful safety program than just training. For purposes of this presentation, the characteristics of successful safety programs will be divided into three classes: management, training and incentives, and accident reduction.

Management

The most consistent finding in all the studies investigating successful programs is management commitment. Top management must be sincerely committed to reducing injuries, and be willing to back up that commitment with resources and support. Other management-related characteristics of successful programs reported in the literature follow.

1. Safety personnel were part of top management, and adequate staff was available to carry out the safety function. The ranking safety official was not subordinate to production personnel.
2. Active safety committees were supported by management, and there were provisions for short, daily safety meetings.
3. Close, frequent contacts between workers and supervisors or foremen were evident, enabling open communication on safety and other job-related matters.
4. A more humanistic attitude toward disciplining violators of safety rules was evident. In disciplinary actions, measures other than suspension were used more often.
5. There existed a well-developed selection and job placement system that matched worker capabilities to job demands.

Training and Incentives

Several factors emerged from the literature relative to the conduct of training and safety incentive programs.

1. Formal training must be reinforced, on the job, by first-line supervisors.
2. A mixture of different safety activities (e.g., training, safety promotional campaigns, off-the-job safety activities, inspections) is more effective than concentrating on only a few.
3. Trainers must be trained to train.
4. The primary goal of training should be improved job performance, of which safety is one part.
5. There must be a readiness to change and modify training programs to keep up with changing needs.
6. Training programs should be competency-based so that workers are evaluated on their ability to perform their jobs.
7. Greater opportunities should be made available for general and specialized job and safety training.
8. Greater efforts must be made to influence the safety consciousness of workers by enlisting family and community involvement in company safety campaigns.

Accident Reduction

Successful programs usually include activities designed to reduce accidents, such as the following.

1. High levels of housekeeping and orderly workplace conditions.
2. Application of engineering controls, as well as non-engineering techniques, to reduce accidents. (Engineering controls include good human factors design of equipment, environments, and procedures.)
3. More frequent formal inspections of worksites.
4. Continual examination and modification of safety rules to improve their effectiveness.
5. Well-developed procedures for reporting and investigating accidents.

Undoubtedly, all of these factors contribute to a successful program. Unfortunately, it is not possible to say which factors are the most critical or which are simply the consequence of others. Management commitment, however, is probably the most important factor, because all the others are dependent on management approval.

BASIC CONCEPTS IN HUMAN LEARNING

There exists a vast amount of research literature, spanning more than 100 yr, that deals with human learning. For the most part, the research involves laboratory studies of relatively simple learning tasks. The applicability of much of the literature to complex, real-world learning situations is tenuous. Over the years, there have been numerous attempts at developing theories to explain human learning; but, unfortunately, none of them has accounted for all the intricacies involved in the process. What has emerged from the research literature and theory building is a set of concepts and basic principles that appear to be valid in a wide range of learning situations. The purpose of this section is to introduce the more important concepts and principles to provide a basis for understanding the learning process and the role of training.

Learning Versus Performance

The learning process is never directly observed. Instead, it is found that learning has taken place by observing an individual's behavior prior and subsequent to experiences called training. What this means is that it is not known whether individuals have learned until they have performed. The verbal statement, "I understand how to do that," should not substitute for actual performance. A person demonstrates the acquisition of a skill by performing a skilled act. Any training method that does not provide ample opportunity for the trainee to perform allows little opportunity for the trainer, or trainee for that matter, to determine what has been learned and what has not been learned.

Performance Feedback

People usually do not make an effort to change or improve their behavior unless they perceive that it needs to be changed or improved. Job performance often deteriorates so slowly that no one really notices. However, once workers are made aware that their performance has deteriorated, they usually improve quickly, assuming, of course, that they have the skills and support necessary to improve.

To provide performance feedback requires that a person's behavior be observed, quantified, and presented in a meaningful way. For example, the mean time to complete a task or number of reworks might be the type of performance data to feed back to maintenance workers. The incidence of unsafe behavior is an appropriate measure for all workers. Whatever the performance measure used, it must be observable so that it can be measured; quantifiable, to permit the use of summary statistics; reliable, to the extent that everyone observing the behavior agrees whether or not it occurred, or to what degree it occurred; and valid, so far as it relates to the goal to be maximized, e.g., safety, productivity, maintenance efficiency.

For example, a study in a bakery to assess the effectiveness of training and performance feedback on the incidence of safe behaviors was performed by Komaki (*13*). The approach illustrates how performance feedback can be used to modify behavior. First, accident reports were reviewed, hazards clearly defined, and workers closely observed to determine which specific areas needed the most attention. From this preliminary analysis, specific unsafe behaviors were targeted for modification. This is an important point; the training and feedback were not comprehensive or general in nature, but rather dealt with a set of explicit behaviors and situations.

To assess the effect of this program, baseline data were collected for 5.5 weeks. During this period, the incidence of safe behaviors was recorded. The intervention or treatment involved a training component that consisted of a slide presentation dealing with the hazards and tasks and showed how to perform the tasks safely. A list of the safe behaviors was given to each worker. This is also an important point; training focused on what should be done, rather than just what should not be done. Too often a safety training program overstresses the negative, "don't do this, don't do that," but never really tells the trainee what to do or how to do it correctly.

In addition to the training, performance feedback was given of the percentage of times safe behaviors were used on the job. Workers were shown a graph of the results of the baseline observations that indicated that they had been performing safely about two-thirds of the time. The graph was posted with an unplotted section to be completed as the intervention phase progressed. The intervention phase lasted for 11 weeks, at which time a reversal phase was introduced.

During the reversal phase, feedback was discontinued, but the list of safety reminders remained. Figure 9-1 shows the results of the experiment. As can be seen, the incidence of safe behavior improved dramatically during the intervention period, and remained high until the performance feedback was discontinued during the reversal phase. In a subsequent study (*14*), the effect of safety training, apart from performance feedback, was assessed. The study found that while safety training alone resulted in improved performance, training combined with feedback yielded even better performance. Cohen (*5*), in a carefully developed study, reported similar results for safe forklift operation. This study, however, found that the incidence of safe behavior remained high for months after feedback was discontinued. This was attributed to the development of informal peer

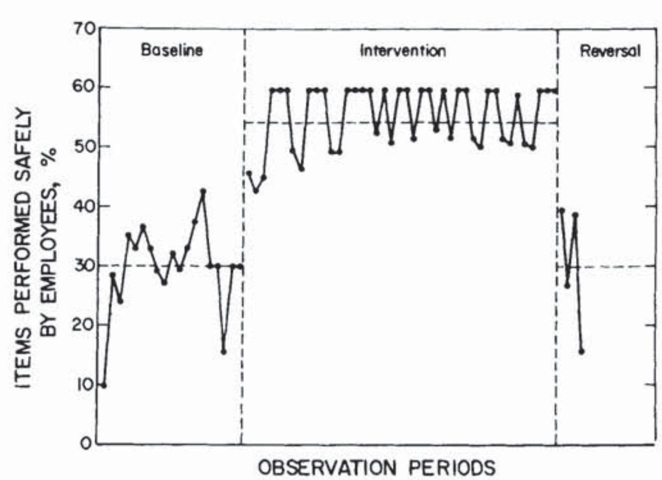


Figure 9-1.—Results of an experiment that demonstrates effectiveness of performance feedback on incidence of safe behaviors (*13*). (Copyright 1978 by the American Psychological Association, and reprinted by permission of the author)

group norms that stressed and accepted the safe methods of performing the job. In essence, the safe way became the accepted, normal way of doing the work (the dream of every safety director).

One of the most common findings about performance feedback is that it affects motivation. Studies have shown that compared to trainees given no feedback, those receiving some feedback were less bored, reported for training more frequently on time, and had more favorable attitudes toward the training.

The amount and the timing of feedback in the training process is critical. Burdening a trainee with too much information may be as bad as not providing any information. The new trainee may be able to absorb only a small amount of information. Too much detail can be both confusing and, because of initial inadequate performance, discouraging.

Reward and Punishment

A general axiom of human behavior is that people tend to repeat behaviors that are rewarded (positive reinforcement). The practical problem is that what is rewarding to an individual is not always known. A person may engage in a particular behavior for any of a number of reasons, such as to receive positive recognition from a supervisor, to reduce the time required to complete a task, to appear daring because he or she likes to take chances, or to receive positive recognition from a work group engaging in the behavior. To be effective, positive reinforcement should be (1) given as soon as possible after a behavior has occurred, (2) valued by the person, and (3) specific and directed to a particular behavior. For example, being told by a supervisor who is not respected that one has done a good job probably would not be very reinforcing. Telling workers at the end of shift that they did a good day's work would do little to reinforce specific behaviors of individual workers. Providing a year-end bonus is too far removed in time from the occurrence of the behaviors one is trying to reinforce to be very effective. A bonus based on overall mine productivity or safety probably is an ineffective reinforcer, because an individual worker cannot relate the reward to his or her behavior.

One thing is certain, if a behavior has been reinforced and reinforcement is discontinued, the behavior will disappear. That is, the frequency of the behavior will decrease, and eventually the behavior will subside. This is called extinction. It is important, therefore, that the work situation be structured so that behaviors acquired during training will be reinforced on the job by supervisors, coworkers, etc.

With respect to extinction of behaviors following cessation of reinforcement, it is well accepted that a behavior will persist longer if the original reinforcement was intermittent rather than continuous. In the real world, it is impossible for a supervisor to give positive reinforcement each time a job is done well; and, in fact, it is probably better that it not be done every time. Eventually, the supervisor will not be able to reinforce the behavior; but, the behavior will persist longer if the supervisor did not always reinforce the worker in the past.

An example of the use of positive reinforcement to change behavior comes from a study performed in four salt processing plants by Uslan (*27*). First-time supervisors were trained in the systematic application of positive reinforcement in the form of verbal praise to increase the frequency of safe work behaviors. The results indicated a reduction in injuries at two sites and no reduction at the other two sites. When the data were corrected for hours worked, a third site showed a reduction in injuries. The results were not overly dramatic; but, upon reflection, this is not surprising. The problem was that the behaviors were the target of the praise, but the number of accidents was the measure used to assess the effects of the praise. The relationship between behaviors and accidents is not perfect. The reinforcement may have been very effective in increasing the incidence of safe behavior; but, due to other circumstances (e.g., work practices, environmental conditions), accident rates may not have decreased significantly. It is for this reason that safety program effectiveness is better judged by assessing the effect on behavior, rather than by tallying accidents. An effective safety program would be expected to reduce accidents, but assessing the effect on behavior provides a more immediate and valid measure of effectiveness. Similarly, a job skills training problem is better evaluated based on behavior changes than on productivity.

The use of punishment is not the same as failing to reinforce. The evidence suggests that punishment inhibits behavior rather than eliminating it, as would be the case for behaviors that are not reinforced. In the case of punishment, a behavior that leads to the avoidance of the punishment is reinforced. Often, failure to reinforce a negative behavior may have a better long-range effect than would a reprimand (punishment) from a trainer, even though the reprimand gives the trainer some temporary relief or satisfaction. There are at least three reasons for this.

1. Punishment may suppress a behavior, but the behavior may appear again if the source of punishment is not present at a later time.
2. Punishment can be disruptive and have its effects on larger behavioral segments than on an undesired behavior itself.
3. Repeated punishment from the same person may have the effect of altering the perception of that person, so that he or she is avoided and loses his or her effectiveness as a source of positive reinforcement.

Perhaps the most efficient use of punishment would be to combine mild and informative punishment for an incorrect behavior with reward for a correct behavior.

Learning From Models and Examples

People learn vicariously through observing behavior of others and the consequences of that behavior. The literature on vicarious learning and its application to on-the-job training in the mining industry was reviewed by Thurlow (*25*). The notion of a model involves a person or persons who set a standard of performance that others try to attain. A model can be a supervisor, coworker, relative, or famous person. Research has found that people tend to favor models similar to their own ability over those whose behavior they can match only through great effort. People exposed only to high standards are more likely to adopt them than people exposed to conflicting standards. Further, the high standards set by a model are less likely to be adopted by trainees if the model imposes lenient standards on himself or herself.

The practical implications of this are that supervisors, trainers, and other models should adopt a consistent standard of behavior; and they must be willing to meet that standard in their work. Telling workers to "do what I say, not what I do," is unlikely to make much of a positive impression on them.

METHODS OF TRAINING

Although there are many ways of categorizing training methods, this section is organized by the degree to which each method approximates the actual working conditions under which a trainee will ultimately work. There are all sorts of training methods, but this section will concentrate on only six: classroom, part-task simulation, full-task simulation, simulated mine environments, training sections in an actual mine, and on-the-job training. This list is ordered from the most removed from the actual work situation to the actual work situation itself. The objective of this section is to present some data and examples of each of these training methods as they apply to the mining industry.

Most mine training programs use several of these training methods; the most common combination is probably classroom training followed by on-the-job training.

Classroom Training

Classroom training has always been a part of miner training, and appears to be gaining additional popularity as a prime method of presenting new-worker orientation and safety training mandated by Government agencies. Traditionally, classroom training involves a lecture-discussion format, supplemented by films, slide presentations, and equipment mockups and models. Trainees may or may not be tested to assess their level of learning. In some cases, trainees may have an opportunity to practice a skill; for example, putting on a self-rescue device.

The major shortcoming of classroom training is that, in most cases, the trainee is a passive receiver of information and has no opportunity to practice what has been learned in a realistic setting. The major advantage is that a great deal of information can be imparted to a large number of people, inexpensively. Classroom training is probably best suited for presenting overview and general orientation information, or for promoting group discussion and developing group norms and attitudes.

A survey of 108 apprentice miners in West Virginia (*18*) showed that miners liked classroom training, thought it was valuable, and preferred study within a group rather than self-study. However, these same miners strongly preferred self-paced instruction, which is difficult to implement in a group situation. The miners recommended using short textbooks and tests for each part of a course, but felt that studying was valuable even without examinations. They also liked movies and felt they learned best when movies were used. Unfortunately, this survey did not assess whether movies, indeed, resulted in better learning.

Part-Task Simulation

Part-task simulation extracts from an entire task or job a small part for training. Part-task simulators usually consist of hardware devices that give a trainee an opportunity to practice, over and over, one part of an overall task. An example of a part-task simulator is the onboard simulator of abnormal conditions (OBSAC) developed under a Bureau of Mines contract (*15*). This device, shown in figure 9-2, is used to train haulage truck drivers to recognize and respond to abnormal equipment conditions. The OBSAC, which is electrically connected to the mobile equipment via an adapter kit, allows the instructor to control the readings of certain gauges, actuate visual and audible alarms, and degrade braking and steering performance. Functional gauges of the OBSAC prototype include water temperature, oil pressure, voltmeter, transmission-converter oil temperature, transmission-clutch oil pressure, starting air pressure, and brake air pressure. A digital stopwatch, part of the console, enables the instructor to determine the reaction time of trainees to observe an emergency or abnormal condition and initiate the proper action.

The OBSAC training is blended into the general haulage, loading, and dumping procedures; that is, once a trainee starts handling rock in a normal operating manner, the instructor adjusts a gauge by a certain amount. A good example is the engine oil pressure; the instructor intentionally adjusts the gauge so that it does not rise upon startup. If, on startup, trainees do not observe the engine oil pressure within 5 s, they lose three points. During normal operation, the instructor may drop the reading 25 psi, and if the trainee does not notice it within 15 s, he or she loses points.

Field tests of OBSAC were carried out at two surface minesites (*11*). The overall reaction to the OBSAC was very favorable among the trainees because it vividly simulated abnormal situations in a realistic operational setting. One major advantage of this device is that abnormal conditions are presented at will, and the reactions of the trainees are observed under a variety of conditions. This part-task simulator is somewhat unique in that it is operated in the actual work environment.

Full-Task Simulation

Full-task simulations involve simulating all, or a significant portion, of a job in a training environment. Typically, such simulators are very expensive and complex. Their main advantages are that they allow the instructor to develop specific training exercises to meet the capabilities of the students; they allow the students to practice exercises over and over again; they provide integrative training; and they permit learning in a safe, standardized environment where student errors will not destroy equipment or endanger lives.

An example of a full-task simulator is the shuttle car training systems (SCTS) developed under a Bureau of Mines contract (*23*). Figure 9-3 shows a cutaway diagram of the SCTS. It is designed to provide control, familiarity, and practice in procedures associated with tramming, turning, loading, and dumping. The system includes inby and outby projector systems that show actual in-mine environmental conditions, and are tied to the shuttle car controls. This enables the trainee to perceive and judge the relationship of the shuttle car to corners and intersections, and to maneuver through work sections. The simulator also provides bumping and pitching movement, as well as integrated sounds and vibration system, all computer controlled.

Simulated Mine Environments

Part- and full-task simulators attempt to reproduce the equipment used in mining, usually in an environment far removed from the actual working environment. OBSAC is an exception in that it is used in an actual mine environment. Full-task simulators often only reproduce the visual aspects of an environment. Simulated mine environments offer an opportunity to conduct training in a systematic, planned fashion, without being concerned with production demands, changing conditions, etc. In Europe, training galleries (simulated mine environments) are more common

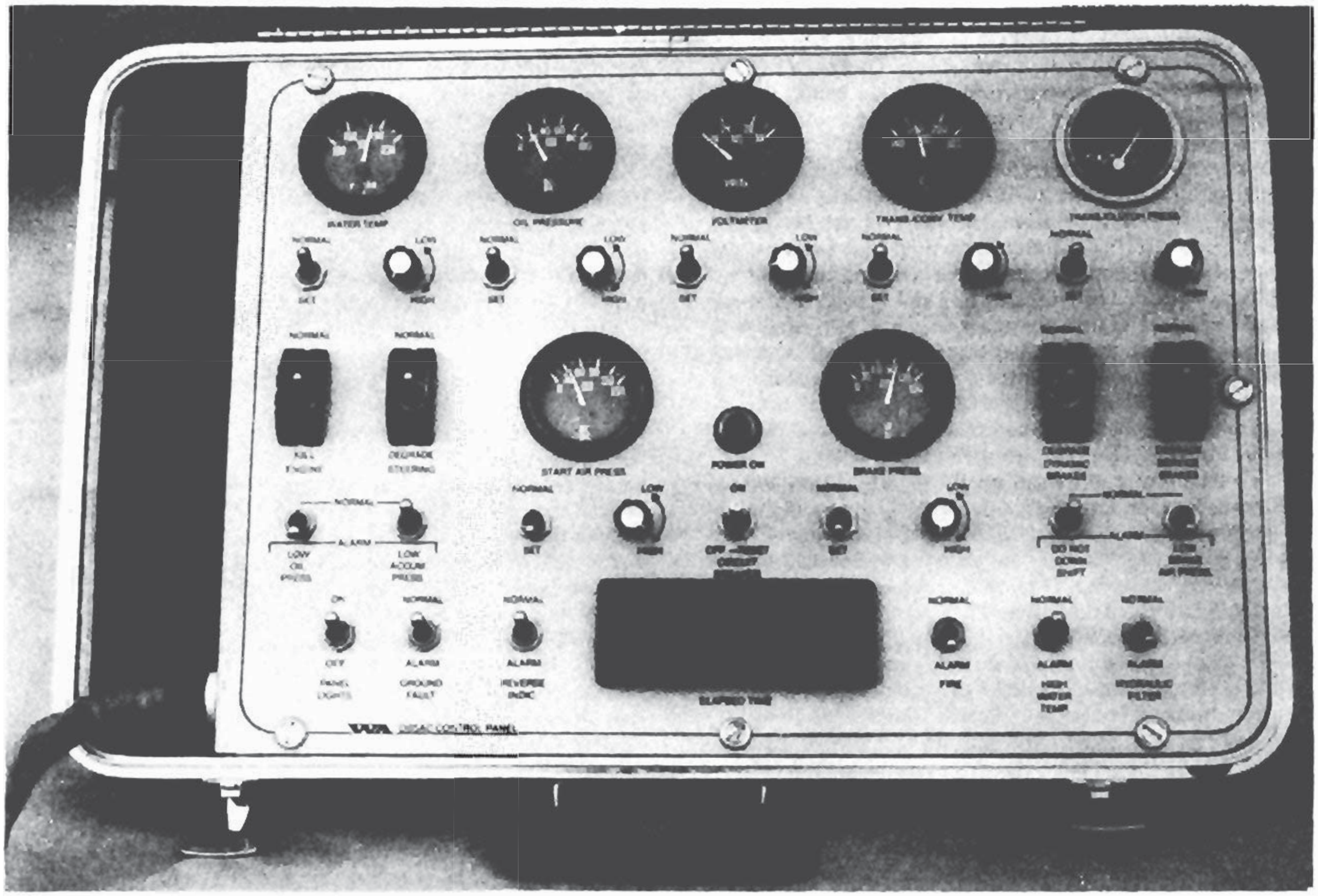


Figure 9-2.—OBSAC part-task simulator held in instructor's lap in port seat of a haulage vehicle (*15*).

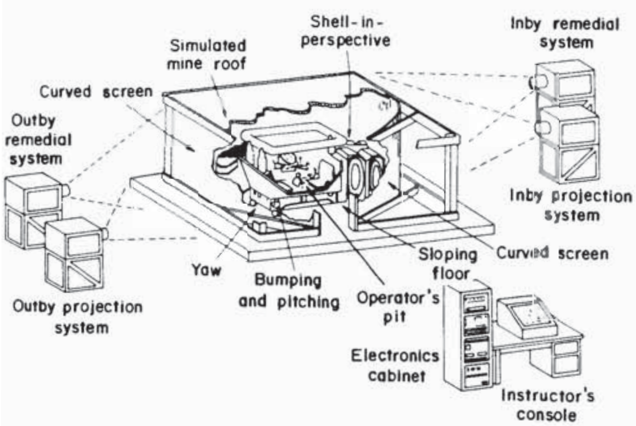


Figure 9-3.—Shuttle car training system full-task simulator (*29*).

than in the United States. Some European mine rescue stations use them to train rescue teams. In some, smoke can be pumped into the simulated mine for additional realism.

One example of a U.S. simulated underground mine was built by U.S. Steel at its Cumberland Mine (*12*). It consists of four entries and three crosscuts, and contains a power center, fans, continuous miner, conveyor belt, shuttle car, scoop car, and roof bolter. Students with no experience practice jobs such as rock dusting, posting, building stoppings, and hanging brattice cloth. This simulated mine is also used to train experienced miners in the use of new equipment, and to develop teamwork in a section crew.

Training Sections in an Actual Mine

Several companies have allocated sections of their mines strictly for training purposes, which is a cost-effective alternative to building a simulated mine environment. Here, training can be conducted without the pressures and constraints inherent in using actual production sections for training. An additional advantage is that efficiency is usually increased; that is, the necessary materials are available, and several trainees can engage in a task at one time, while others observe. A trainee can be stopped when an error is made and instructed in the proper manner of performance, without concern for productivity. The sequence of training tasks can be controlled and need not be compromised because of production demands.

On-the-Job Training

The most commonly used, and abused, method of training in the mining industry is on-the-job training (OJT). OJT encompasses informal procedures, wherein a new worker is assigned to an experienced worker to follow around and learn the ropes. Such training is often unstructured, haphazard, and incomplete. The senior person may perceive the new miner as a hindrance who is taking valuable time away from the primary goal—productivity. OJT may include a structured program where workers are assigned specific sequences of tasks, and are monitored and evaluated by people whose primary responsibility is training.

An example of structured OJT is the job safety skills training (JSST) program at Monterey Coal Co. (*17*). The training is conducted by a specially trained team on the working section. JSST team members give close personal attention to the safety performance and attitudes of individual miners in the unit as they go about their work routines. As part of the training, a mock emergency is staged (the foreman is injured) to force the workers to decide for themselves what must be done. The focus is on building teamwork and leadership rather than testing first-aid procedures. Monterey Coal reports a 50% reduction in nonfatal-days-lost injuries since the program started.

OJT often generates high levels of motivation in students; and, because the training is taking place in the actual work environment, transfer of training to everyday work is almost assured. The major weaknesses of OJT are that it often must take a back seat to production, and it is limited by production demands. Thurlow (*25*) listed several other limitations of OJT.

1. The optimum sequence of training tasks cannot be arranged without interfering with ongoing work.
2. Some tasks as encountered on the job are too complex, fast-paced, or pressured to give an effective demonstration or practice opportunity for the trainee.
3. The use of expensive equipment may be such an economic loss that it may be difficult to find opportunities for trainees to practice on the equipment. Trainees may then be assigned to semiskilled duties that do not interfere with the ongoing work, but also do not provide the planned training opportunities.
4. If the instructor is a production worker, attention to production demands interferes with his or her capacity to train.
5. Generally, no diagnostic measures are available from OJT unless special provisions are made. Production records have distinct limitations as indexes of employee performance.

The cost-benefit ratio of OJT may not compare favorably with off-production training sections. With training sections, more trainees can be trained by a single instructor than is possible in a good OJT program. The cost of unstructured OJT is low, but so are the results. The costs of structured OJT programs are as high, or higher than when using training sites and a small cadre of instructors. And, of course, there are greater dangers to life and property involved in OJT as compared to using training sections.

Most mine training programs use several of these training methods; the most common combination is probably classroom training, followed by OJT.

DEVELOPING A TRAINING PROGRAM

The development of a training program should be an orderly, logical process to insure that the training addresses the needs of the organization and meets the objectives set forth for the training program. This logical, orderly process is called instructional systems design (ISD) and has been used by the military and large corporations for many years to develop effective training programs. ISD is a series of interrelated activities. Although each application of ISD uses a slightly different set of activities, all have certain features in common. Figure 9-4 depicts an ISD approach to training development, and will serve as a model for discussion. All ISD methodologies start by assessing training needs and writing training objectives. Somewhere in the process, criteria and evaluation measures are developed to assess the effectiveness of the training program. The training program is developed, evaluated, and revised based on objective performance data where appropriate. The following is a brief discussion of each box in figure 9-4. For a more complete discussion of the ISD approach, the reader is referred to Goldstein (*10*) or Tracey (*26*).

Assess Training Needs

A potential training need can be defined as the difference between desired and actual performance. It must be stressed, however, that all such discrepancies may not be training related. In previous chapters, the importance of task and equipment design has been discussed, as have the effects of environment on human behavior. A discrepancy between desired and actual performance is often corrected more cost effectively through the application of human factors design criteria than through training. Therefore, in determining training needs, it is first necessary to identify where behavior is not meeting expectation, and then to determine the best course of action for reducing the discrepancy: whether by means of human factors design changes, training, or a combination of both.

Assessing the difference between desired and actual performance requires that one know what is desired and what is the level of actual performance. In some cases, both types of information are collected separately and compared. For example, a standard or expectation may have been developed that a particular maintenance job should take 2 h to

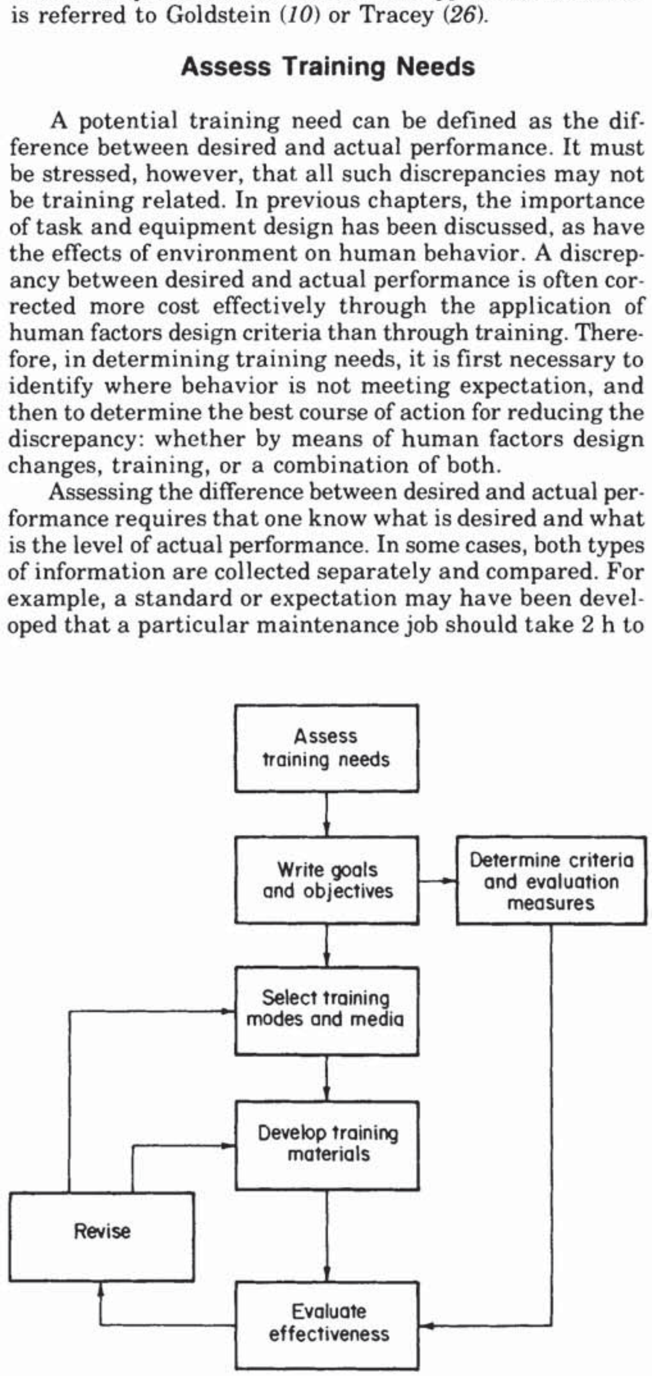


Figure 9-4.—Instructional system design approach to development of training programs.

complete; when, in fact, it is actually taking an average of 4 h. In those cases where specific standards against which to compare performance do not exist, it is necessary to rely on expert judgment. For example, a maintenance supervisor would be asked if the performance of some of the mechanics needs to be improved.

There are many sources of information that can be used to identify potential training needs, some of which are listed in table 9-2. It is usually best to use a variety of sources, as each one taps different aspects and populations.

Table 9-2.—Sources of information for assessing training needs

Opinions	Supervisor round-table discussions.
	MSHA inspector discussion.
	Worker surveys and questionnaires.
	Employee performance evaluations.
Statistics	Accident reports.
	MSHA inspector reports.
	Industry statistics.
	Absenteeism data.
	Maintenance records.
	Productivity records.
Performance measures.	Job skill tests.
	On-the-job observations.
	Paper-pencil tests of job knowledge and procedures.

If used properly, accident data can be an excellent source of training needs information. First, it must be recognized that the data are incomplete; that is, many unsafe acts do not result in accidents and, hence, are not a part of the data base. Second, one must develop long-term trend information based on meaningful categories, so that slowly increasing trends can be identified. A tabulation of injuries by part of body may not reveal as much information as a tabulation of injuries by worker activity or type of accident. Safety directors often do not keep long-term trend data, except perhaps for total accidents; and they only identify a problem when there is a rash of similar accidents over a short period of time. The slow buildup problems are often missed.

Write Goals and Objectives

Based on the assessment of training needs, the next step in the process is to write the goals and specific objectives of the training program. Goals are more comprehensive than objectives. Each goal will have a number of objectives associated with it. An effective, meaningful instructional objective should meet the following three criteria (*28*):

1. Identify, as precisely as possible, what an individual will be doing to demonstrate that an objective has been reached.
2. Describe the important conditions under which an individual must demonstrate competence.
3. Define the criteria or standard of acceptable performance expected.

Specific objectives serve several purposes. First, they help insure that both the instructor and the student understand what is to be gained from the training. Second, they focus the training on behaviors that are measurable.

Some examples of specific behavioral training objectives include

1. Given four dirty and two clean respirator filters, the student can pick out the four dirty filters.
2. For each of the three types of respirators used in the mine, the student can list how often the filter must be checked and replaced.
3. Given a type X respirator, the student can disassemble and replace the filter in less than 1 min.
4. The student can identify each of the three types of respirators used in the mine and indicate what each protects against.

In writing objectives, it is critical to specify what is really important for the student to learn, rather than that which is easy to measure. For example, it may not be important whether a person can name every part of a respirator, although this is easily determined. What may be more important is that the person can disassemble, inspect, clean, and reassemble the respirator in a specified time. The latter objective is more difficult to measure, but may be the critical behavior that one wants to develop.

Determine Criteria and Evaluation Measures

Evaluation measures flow directly from the objectives and should be specified before the actual training materials and programs are designed. Training directors often develop the evaluation measures after they have developed the training course. The problem with this is that the evaluation measures may be based on the course content, which may or may not be designed to meet the training objectives. It is important to develop the evaluation measures directly from the objectives so that they can be used to evaluate the training in determining if the objectives are being met. Evaluation measures can include paper-and-pencil tests, performance on a simulated task, on-the-job performance, supervisor ratings, and student opinion surveys.

Select Training Modes and Media

The type of training modes and media used depends in great part on what skill is being trained. Role playing, group discussion, and case study are effective in training attitudinal and decisionmaking skills. Simulators and on-the-job training are effective for training perceptual and motor skills. Movies and slides are effective for training perceptual skills and job knowledge. The proper mix of modes and media must be carefully selected and should not merely be whatever is available.

Develop Training Materials

Training materials can be developed in-house, purchased from outside sources, or purchased from outside sources and tailored to the specific needs and problems of a particular mine. The Bureau's Pittsburgh (PA) Research Center has compiled an extensive list of commercially available training materials appropriate to the mining industry that is available to individuals and companies. In-house development of materials includes slide presentations using actual people and areas of the mine to illustrate training points, videotapes of job procedures (*7*), posters summarizing key points, and models and mockups of equipment to demonstrate correct actions.

Effective training materials should include short tests so that students and instructors can assess the progress being made during a training program. The training should be divided into small modules so that students can digest one module before going on to the next. This also gives the student a sense of accomplishment when each module is successfully completed.

Evaluate Effectiveness

The evaluation measures, developed from the training objectives, are used to test the trainees and assess whether the training objectives were met. In addition, other evalution data are collected. Student opinions should be solicited; they are an excellent source of data on how a training program could be improved. Followup on the job is critical. Training personnel should seek supervisor opinions as to whether training has improved job performance and what areas need to be stressed further in training. Accident, production, and maintenance records should be reviewed to assess any positive impact of the training.

Revise

Based on the evaluation data, changes are made to the modes, media, and content of training programs. Objectives should not be revised based on the evaluation; they should be revised based on a reassessment of training needs. Every training program will need to be revised at some time. Materials go out of date, training needs change, and the types of students change. All of these necessitate the constant review and revision of a training program.

SAFETY AWARENESS PROGRAMS

Safety awareness programs typically include various communications, promotional devices, and contests aimed at increasing employee awareness of the importance of working safely. Probably one of the most extensive awareness programs is that undertaken by Consolidation Coal Co. (*2*). The following sections briefly describe this program and summarize the elements that contributed to its success.

Consol's Program

The Consol program was a four-pronged approach. It involved (1) establishment of a corporate-wide safety department and corresponding departments in each operational region, (2) an intensive safety training program, (3) an all-out safety engineering program, and (4) a safety communications program to heighten awareness among all employees.

A symbol (the A-OK hand signal: with index finger and thumb forming a zero) and a slogan (Consol's Goal—Zero Accidents) were selected and used consistently on all communication and promotional materials. It was recognized that to be effective, both the workers and their families had to be involved. Family involvement was accomplished by sending a quarterly safety newsletter to the families. In addition, all sorts of promotional items were mailed to the homes, including packets of sugar, salt, mustard, ketchup, baggies, and handy wipes—all with the symbol and slogan printed on them—to be packed in lunchboxes as reminders. Potholders, Christmas wrappings, and toboggans were given away, again all emblazoned with the safety symbol and slogan. To keep the link between job safety and family salient, safety posters were displayed at the mines with pictures of employees' children and messages such as, "Dad, work safely so you can give me away at my wedding" or "Work safe, Dad, we need you at home."

In addition, the workers were also given safety slogan items to maintain their awareness of the program, including fishing knives, leg bands, belt buckles, caps, and retroreflective stickers for their helmets. Paycheck stuffers were included to promote specific safety concerns. Extensive signage was used at the minesites, including safety clocks and thermometers. Even the jumpsuits of the mine rescue teams had the safety symbol and slogan on them.

To complement the communications, safety awards were given. Workers earned points for safe work performance and could use them to purchase gifts. Jackets and caps were used regionally to reward a good safety record. Gold pins were given to superintendents whose operations had no lost-time accidents for a year, and safety trophies were given to operations with 1 million work-hours without an accident.

In 1978 it was reported that the program was costing approximately $200,000 per year, but during the first 6 yr of the program, the accident frequency rate was reduced by almost 60%.

Elements of a Successful Program

There are several aspects of the Consol program that accounted for its success. These elements have also been found to be essential for such programs in other industries as well. First, and perhaps foremost, is top management's total commitment to the program. Second, an awareness program must be part of a larger safety program, with strong emphasis on training and engineering-human factors approaches to accident reduction. Third, it is important that the worker's family is made an integral part of the awareness program. It has also been suggested that the community be included. Fourth, a wide variety of devices must be used to get the message across. Safety slogan items must be changed periodically, and new items must be introduced to keep interest high. The prizes and gifts must be updated and expanded.

It is impossible to determine which specific aspects of the Consol program were effective and which were not. In all likelihood, it was the totality of the program that was effective. It is much like analyzing how a dam holds back water. Examining each individual stone would lead to the conclusion that each stone, by itself, would not hold back the water, yet all the stones together hold back the water very effectively.

Safety Signs

Unfortunately, many companies rely on safety signs as their primary method of increasing safety awareness. There are some characteristics of effective signs that are worth pointing out, in addition to those dealing with such issues as attention-getting, visibility, and comprehensibility.

First, safety signs must reinforce other aspects of a company's safety program. Signs should correspond to aspects being stressed in training or at weekly safety meetings. In essence signs should be part of a focused campaign aimed at a select number of safety problems. For example, signs may be directed toward the use of lockouts in electrical maintenance work. The message would be stressed by supervisors on the job and in safety meetings, better lockout designs would be installed, new job procedures developed, etc.

Second, the signs should be directed to specific safety problems rather than general messages. The emphasis should be on what to do, rather than just what not to do. (Note that the Consol program used general be-safe type signs; by themselves, they probably would not have been very effective.) Signs showing specific actions are usually more effective. It is usually agreed that, where possible, the consequences of not performing the action should be illustrated on the sign. For example, if the message on a sign was to block the wheels of vehicles parked on an incline, the sign might also show a runaway vehicle hitting a person.

Third, signs should be placed where they are needed. A block-the-wheels sign, for example, should be hung on inclined roadways where vehicles are likely to be parked, and on the vehicles themselves. It would do little good to hang them in the clean room or lunch area. Related to the place-them-where-you-need-them principle is that one should not overdo the placement of signs. If there are safety signs everywhere a worker looks, the signs may quickly lose their significance and be ignored.

DISCUSSION

This chapter has reviewed training and similar endeavors as they relate to the achievement of organizational goals—increased safety and productivity. The chapter is not meant to be a how-to guide for developing training programs, but rather as a survey of the utility, methods, and lessons learned from the field.

Training often aims at redirecting and increasing motivation. Chapter 10 deals with the topics of motivation and organizational development which can be viewed as a logical extension of the training function to embrace the entire organization and the interactions of its parts.

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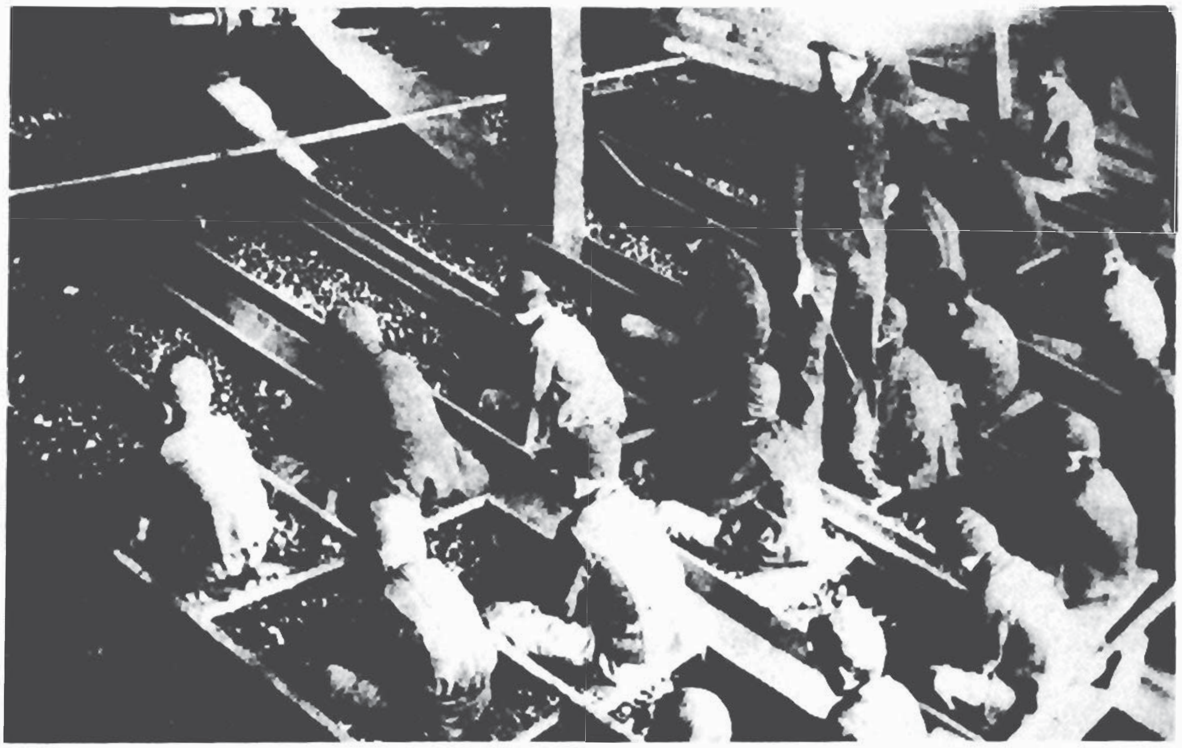
CHAPTER 10.—MOTIVATION AND ORGANIZATIONAL DEVELOPMENT



The link between organizational climate and safety and productivity has become apparent. Work organization concepts of bygone days are now only seen in photographs found in the National Archives.

Throughout this report, the effects of equipment and environment on human behavior have been emphasized. The topics have been rather technical, with a definite engineering flavor. The importance of motivation has been occasionally alluded to as a determinant of performance, but it has not been discussed in depth; that is the purpose of this chapter.

Chapter 8 discussed environmental factors, including illumination, noise, vibration, and heat, that influence behavior. In this chapter another environmental factor influencing behavior—organizational climate—will be discussed. The effects of organizational climate on behavior are more psychological in nature than are the effects of the factors discussed in chapter 8. In keeping with the emphasis on changing the job to fit the person, this chapter will present the process of organizational development, and specific attempts made to alter the organizational climate in the mining industry.

MOTIVATION

The term "motivation" is rather loosely used to describe the drive, thrust, or energy behind an individual's behavior. In addition, a goal-oriented function of motivation is inferred. People are not just motivated; they are motivated to do something or obtain something. Motivation, then, is responsible for the intensity, direction, and persistence of behavior.

Motivation and Performance

Motivation is related to performance, but it is not the same thing as performance. Performance is a function of ability and motivation. Many theories suggest the following equation to express this relationship:

$$\text{Performance} = f(\text{ability} \times \text{motivation}).$$

The multiplicative relationship is important and implies that, if either motivation or ability are zero, performance will be zero. In essence, all the motivation in the world will not yield satisfactory performance unless a person has the ability to perform satisfactorily. The converse is also true; a person with all the ability in the world will not perform without the motivation to do so.

Ability refers to how well a person can perform at a given time. As such, ability is considered to be a function of aptitude, training, and experience. Thus

$$\text{Ability} = f[\text{aptitude} \times (\text{training} + \text{experience})].$$

Aptitude is an enduring, inalterable quality of an individual that imposes a fixed limit on his or her level of potential performance. As such, aptitude determines whether an individual can be brought through training and/or experience to a specified level of performance. Notice, this expression implies that without aptitude, all the training and experience will not give an individual the ability to perform.

One important implication of all this is that not all performance problems that occur in organizations are caused by low motivation. Problems can be caused by low aptitude; inadequate training and experience; or poorly designed jobs, equipment, and environments that exceed whatever abilities people may have.

Motivation and Needs

For centuries, psychologists and philosophers have tried to explain why some objects or outcomes seem to be desired by people, while others are not. People have needs; and it is assumed that if these needs are better understood, a better understanding of why people act as they do follows.

There have been many attempts to classify human needs. Probably the most influential theory of human needs, and by far the most widely used classification system for the study of motivation in organizations, is the hierarchical classification scheme of Maslow (*11-13*).[1] He postulates five categories of needs as follows:

1. Physiological needs, including the need for food, water, air, etc.
2. Safety needs, including the need for security, stability, and the absence from pain, threat, or illness.
3. Belongingness and love needs, which include the need for affection, fellowship, love, etc.
4. Esteem needs, including both the need for personal feelings of achievement or self-esteem, and the need for recognition or respect from others.
5. The need for self-actualization, that is, the feeling of self-fulfillment or the realization of one's potential.

According to Maslow, these five needs categories exist in a hierarchy of importance, such that the lower or more basic needs (physiological, safety) are inherently more important than the higher needs. This means that, before any of the higher level needs will become important, a person's physiological needs must be satisfied. Once the physiological needs have been satisfied, their strength or importance decreases, and the next higher-level need becomes the strongest motivator of behavior. At the highest level of the hierarchy, a slightly different thing occurs. For self-actualization, increased satisfaction of the need leads to increased need strength. The more you get, the more you want—but, according to Maslow, this only occurs at the top-level need.

Maslow does say that the hierarchy is not rigidly fixed for all people. He clearly states that physiological needs are at the bottom, and self-actualization needs are at the top; but the order of the middle needs may vary from person to person.

This theory suggests, for example, that as people are promoted and their lower-level needs become satisfied, they will become more concerned with self-actualization and growth. If these higher order needs are not addressed, people may become dissatisfied with their jobs. The theory also suggests that if a person's job security is threatened, that person will abandon all else in order to protect it.

Maslow, however, is not the last word on needs theories. Some theorists take exception to parts of his theory because the empirical evidence has not always supported it. Some believe that there are fewer levels of needs, that all can be o-erating at the same time, and that failure to satisfy a higher order need can cause a lower order need to increase in importance.

A Theory of Motivation

Theories of human needs, such as that of Maslow, are useful for explaining what outcomes will be attractive to an individual; but they are not sufficient to explain the individual's behavior. The reason is that such theories do not include many of the factors that are known to influence motivation. There have been numerous theories of motivation over the years, but one has attracted considerable attention and research support in the work environment; i.e., expectancy theory (*16*).

Expectancy theory states that people will expend effort (motivation) toward a performance goal if they perceive that their efforts will result in attaining that level of performance, and the attainment of that level of performance will lead to desired outcomes. The theory utilizes three main concepts: valence, effort-performance expectancy, and performance-outcome expectancy. Each of these are explained, in reference to figure 10-1 (*10*), in the following sections.

Valence

The valence of an outcome refers to the affective response of a person to an outcome. An outcome can have a positive valence, in which case the outcome is something a person desires or wishes to attain; a neutral valence, as when a person is indifferent to the outcome; or a negative valence, as when a person prefers not to attain the outcome. Examples of outcomes include a pay raise, working with a friend, losing one's job, working in less hazardous and more pleasant surroundings, being praised by one's supervisor, gaining a sense of accomplishment, being ostracized from a group, being injured, etc.

Effort-Performance (E-P) Expectancy

E-P expectancy is simply a person's estimate, in a given situation, of the probability that he or she will attain a performance level if he or she puts in the effort. Figure 10-1 shows two levels of performance, satisfactory and unsatisfactory; but these could also represent alternative performances, such as doing the job safely and unsafely.

Performance-Outcome (P-O) Expectancy

P-O expectancy is the perceived probability that a level of performance will lead to an outcome. Some outcomes are certain to follow from performance, such as a feeling of accomplishment when a difficult task is satisfactorily completed. Some outcomes will occur, regardless of the performance level attained (e.g., outcome C in figure 10-1). Other outcomes may or may not occur, depending on the situation.

The Model

Expectancy theory postulates that for each outcome that can result from a level of performance, people multiply the P-O expectancy by the valence (V). These are summed for all the outcomes attached to a performance level to obtain an overall valence for the performance level. This overall

[1] Italic numbers in parentheses refer to items in the list of references at the end of this chapter.

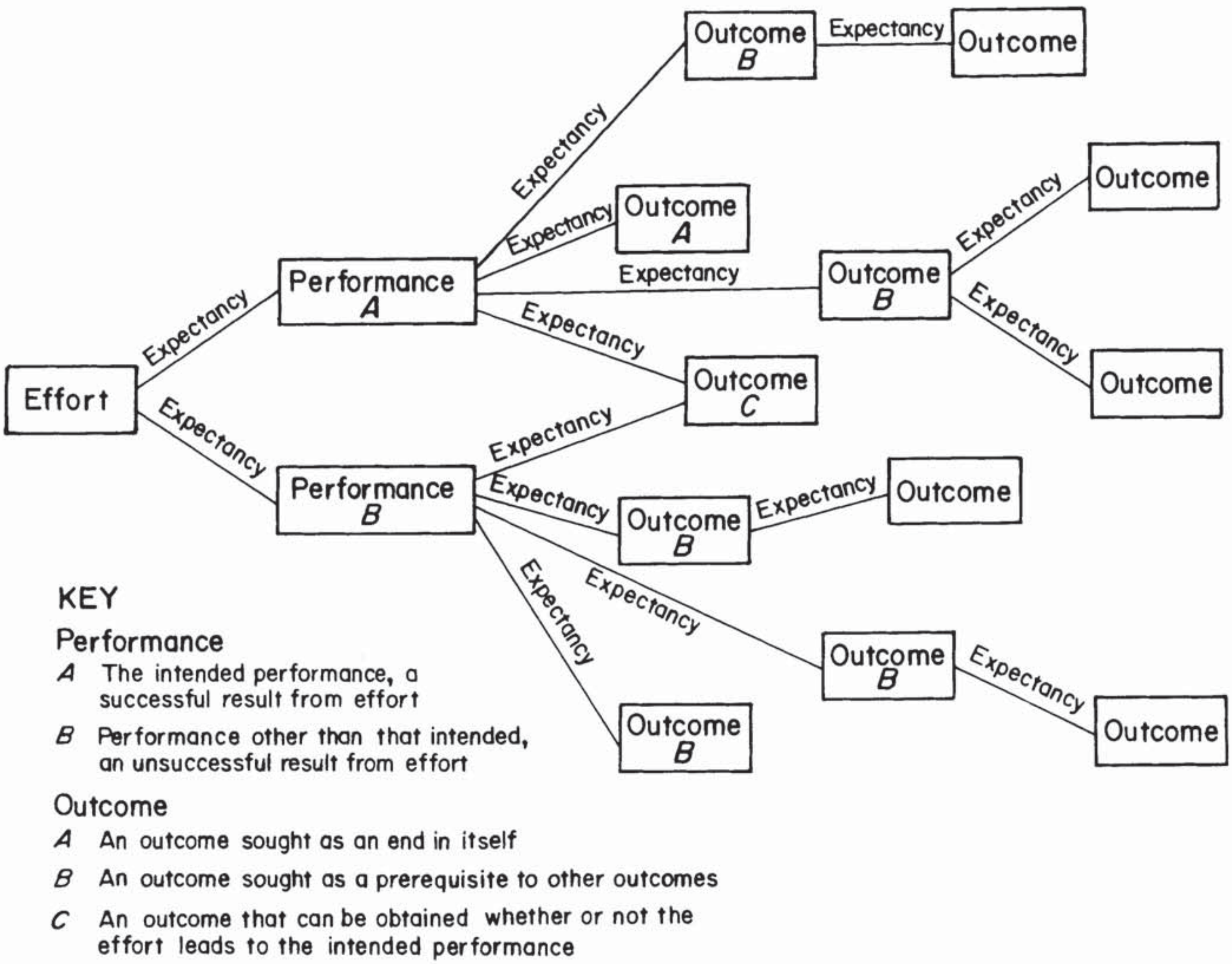


Figure 10-1.—Schematic representation of expectancy theory of motivation (*10*). (Courtesy of Brooks and Cole)

valence is then multiplied by the E-P expectancy to determine the level of motivation a person will experience toward attaining the performance level. This is done for various performance levels, and the level of performance with the highest motivation level is the one that a person, in theory, will choose to attain. In formula format:

$$\text{Motivation} = (\text{E}-\text{P}) \times [(\text{P}-\text{O}) \times (\text{V})].$$

There are several implications of this model. People will not pursue a performance if it is perceived that the attainment of the performance will result in a net negative overall valence, unless all other performance levels will result in even more negative valences. Attaining a high level of productivity may get the praise of a supervisor and maybe even a promotion, but it may also result in the loss of friends and being overly fatigued at the end of the day. Depending on the P-O expectancy and valence of each of these, the overall valence could be positive or negative. On a smaller scale, wearing safety glasses may result in fewer injuries (positive valence), but it can also result in discomfort and lower visual ability due to fogging (negative valence). Whether people wear saftey glasses depends on their P-O expectancies and valences for these and other outcomes.

Implications of the Model

Table 10-1 lists the major factors that influence E-P and P-O expectancies. People often have an inaccurate perception of a situation, which can lead to incorrect P-O or E-P expectancies. They may not understand the high probability of an accident if certain unsafe procedures are followed, or they may perceive that the safe way of doing a job is more difficult or time consuming than an unsafe way. Proper training can often correct such misconceptions. Training can also alter E-P expectancies by increasing a person's self-esteem and ability to perform the work. The way a work group and supervisor reward performance also affects the P-O expectancies. If safe behavior is rewarded, then the P-O expectancy for that outcome increases. If a person is criticized for reduced production because he or she chose to use a safe job procedure, P-O expectancies will also be affected.

P-O expectancies are influenced by the valence of the outcomes themselves. To most people, positive outcomes are believed more likely to occur than negative outcomes. People also tend to discount the possibility that very negative things (e.g., injury or death) will happen to them. Is it any wonder that people will engage in behaviors that will save

Table 10-1.—Factors that influence performance-outcome (P-O) and effort-performance (E-P) expectancies (*10*)

(Reprinted with permission by Brooks and Cole)

E-P	Self-esteem Past experiences in similar situations. Actual situations. Communications from others.
P-O	Past experiences in similar situations. Attractiveness of outcomes. Belief in self versus fate. Actual situations. Communications from others.

a little time (positive valence and high P-O expectancy), but will expose them to danger of bodily harm (high negative valence, but low P-O expectancy).

One goal of mine management, then, should be to structure a situation so that positively valenced outcomes occur when desirable behaviors are performed, and that either negatively valenced outcomes occur when undesirable behaviors occur; or, at the least, positively valenced outcomes do not occur. In addition, training should be aimed at reinforcing the connection between performance and outcome, and at increasing the expectancy that the performance desired will be attained if effort is expended.

ORGANIZATIONAL CLIMATE

Organizational climate refers to the collective perceptions held by employees about aspects of their organizational environments. These perceptions have a psychological utility in serving as a frame of reference for guiding appropriate and adaptive task behaviors. Perceptions that make up organizational climate include whether management is perceived as caring about the individual workers; whether management listens to workers' suggestions and complaints; whether productivity is stressed more or less than safety; whether the coworkers support one another and work together, etc.

An important component of organizational climate that he called safety climate or the concern for safety was distinguished by Zohar (*18*). Organizational climate, including safety climate, is assessed by the use of questionnaires administered to employees of a company. Usually, a rating form is used to solicit perceptions on specific dimensions. Zohar, for example, used a 49-item questionnaire to measure safety climate, in which employees marked a 5-point scale for each item (strongly disagree–disagree–neutral–agree–strongly agree). The questionnaire tapped the following perceptions:

Perceived importance of safety training programs.
Perceived management attitudes toward safety.
Perceived effects of safe conduct on promotion.
Perceived level of risk at workplace.
Perceived effects of required work pace on safety.
Perceived status of safety officer.
Perceived effects of safe conduct on social status.
Perceived status of safety committee.

Zohar also found strong correlations between the scores on the safety climate questionnaire and the rankings by safety inspectors of the overall safety records of 50 companies.

One of the first studies to investigate the relationship between organizational climate and accidents in the mining industry was carried out by Sanders (*15*). Miners from 22 underground coal mines were administered questionnaires that examined their perceptions of such things as decision decentralization, shared autonomy, management receptiveness, production pressure, feedback, management supportiveness and concern for working conditions, and worker morale.

Using a sophisticated cross-lagged correlational design that required testing at each mine approximately 6 months apart, the following conclusions were made based on the data:

1. When decisions are decentralized, when management is flexible and innovative in trying new procedures and programs, and when morale is high, disabling injuries decrease.
2. As disabling injuries increase, feedback, continued employee development, and consistency of orders improve. That, in turn, appears to decrease injuries.
3. Production pressure appears to lead to an increase in disabling injuries. The increase in disabling injuries, in turn, leads to a decrease in production pressure.

A basic conclusion from this study was that certain organizational climate and managerial practices affect injury rates; and, further, that injury experiences have an effect on other climate and managerial issues. Therefore, in order to reduce accidents, one must not only focus on the worker and the physical environments, but must also focus on the broader organizational context and managerial practices within which the miner works. The techniques used to change the broader organizational context and managerial practices are in the province of organizational development.

ORGANIZATIONAL DEVELOPMENT

Organizational development (OD) is a long-term effort that examines and alters management policies, practices, and organizational dynamics in a systematic way for the purpose of assisting a company to solve its major problems and to achieve its major goals (*1*). OD recognizes that the key unit in an OD activity is the ongoing work team, including both the supervisor and his or her subordinates. This is in contrast to the more traditional management development approach that concentrates on the individual managers and supervisors, rather than on the intact work groups.

Another distinguishing feature of OD is the use of a change agent to initiate and guide the OD activity. The change agent is a third party, external to the particular part of an organization that is initiating the OD activity. This change agent usually does not make recommendations in the traditional sense, but rather intervenes in the ongoing processes of the organization, and assists the organization in understanding and changing how it goes about solving problems.

A final distinguishing characteristic of OD is that the activities generally follow an action research model. Basically, an action research model consists of (1) a preliminary diagnosis of an organization's (or work group's) problem, (2) data gathering from the group to further diagnose the source of its problems, (3) data feedback to the group that summarizes the findings from the data gathering, (4) discussion by the group of the findings, (5) action planning by the group to solve the problems uncovered, (6) implementation of the action plan, and (7) monitoring and evaluating the action plan to insure that the problems are indeed being solved.

Actually, OD is more of a philosophy than a specific methodology. OD activities take many different forms. To provide an appreciation for OD, four OD projects that were carried out in the mining industry will be reviewed: the Rushton autonomous work group experiment, the Hecla team-building project, the Texasgulf leader-match study, and the use of quality circles by mining companies.

Rushton Autonomous Work Group Experiment

This project began in 1974 and was sponsored by the Department of Commerce and the Ford Foundation. It represents probably the most comprehensive OD activity initiated in the coal industry. The implementation and results are fully detailed by Goodman (7). The Rushton experiment was and is one of the more controversial OD interventions, perhaps because of the extensive attention it generated (*3, 14, 17*) and the problems it encountered.

Background

The Rushton Mine was owned by Pennsylvania Mines Corp., which was part of Pennsylvania Power and Light. The mine was located in central Pennsylvania and employed about 200 people. The workers were members of the United Mine Workers of America (UMWA). The project can be considered as being composed of two phases. The first phase involved the OD intervention on three shifts (each composed of eight-person crews) in one of the four working sections of the mine. The second phase involved efforts to expand the intervention to the other three working sections.

Autonomous Work Groups

The OD intervention involved setting up autonomous work groups. Basically, the miners in a crew organized and managed themselves. They performed all the different tasks, traded individual job assignments periodically, and learned all work conditions. Specifically, authority for daily production decisions was delegated to the mining crew. The foreman's job was to concentrate on safety, planning, and coordinating activities (not on daily production decisions). Key features of the plan were that each member of the crew was to learn all other jobs in the section, and all the members of the crew would receive the same top rate of pay. Further, two additional workers were added to each crew to do support work.

A joint labor-management committee, consisting of five members from the union and five members from management, was to supervise the day-to-day project activities. All grievances were to go to the joint committee prior to going through the traditional grievance procedure. In addition to these efforts, an extensive training program was instituted, and a gain-sharing plan (like a profit-sharing plan) was to be instituted. This plan, however, was never implemented. The training consisted of classroom training, 2 full days per week for 3 weeks, covering the autonomous work group concept, reviewing all job tasks, job safety analysis, and Federal safety laws. Other changes, such as the introduction of different performance appraisal systems and department-wide conferences, were also included.

Results

For the better part of 2 yr, the program worked well. The crews organized and solved problems collectively. Informal leaders emerged and took over, while the foremen devoted their time to safety measures.

The following are some quotes from the miners involved during the period of the experiment:

> Well, you're your own boss. You got your section and run things our own way and talk things over when you have to.
>
> Before, when a timber was down, you'd say the hell with it. Now you do something—it's your section. If something's wrong, we fix it now.
>
> We see that the work gets done, that the safety law is kept up. We learn how to run all the equipment. You want to come to work now. We all work together, like a team.

But, fellow workers who were not involved in the program called them the Communist crews. They were envious of the freedom, flexibility, and higher pay of the experimental sections. The jealousy and suspicion among the other miners at Rushton caused the UMWA local to withdraw its support by a narrow vote in 1977.

Management went ahead with a modified version of the program and tried to expand it to other working sections. Lacking the support of the union, mine officials found it hard to gain the same spirit of cooperation from the mines. Miners who did not take part in the original experiment balked at taking the initiative in making decisions regarding their work. The foremen again took over the sections, and again had the dual and sometimes conflicting responsibilities for safety and production.

Although productivity did not shoot up as anticipated, it did increase 3%. Job attitudes and safety, as measured by the number of safety violations and inspectors' ratings, shifted in a positive direction. However, accident rates showed little, if any, change due to the intervention; but they were low even before the experiment began. The level of job skills in the workforce definitely increased; and, at least among the miners involved in the experiment, a greater sense of teamwork developed. Both the management and the union felt that the project led to improved attitudes toward each other; and these attitudes probably facilitated the process of labor-management relationships during that period.

Hecla Team-Building Project

During the period of March 1980 through May 1982, the Bureau funded a demonstration project at the Hecla Mining Co. Lucky Friday Mine, located in the Coeur d'Alene region of northeastern Idaho (*4*). The purpose of that project was to investigate the feasibility and effectiveness of OD activities for the mining industry. The overall contract consisted of the Hecla project and the Texasgulf project (which will be discussed in a subsequent section).

The OD activities at the Lucky Friday Mine primarily consisted of team-building and problem-solving activities, as well as the necessary skills training required to support those activities. A brief overview of the procedures used and the results obtained at the Lucky Friday Mine is presented, drawing heavily from Fiedler (*4*).

Background

The Lucky Friday Mine was a deep-vein, hard-rock mine (silver and lead), employing about 270 miners represented by the United Steelworkers of America. A comparison or control mine, at which no OD interventions were made, was also included in the study. The comparison mine was the Star Mine, also owned by Hecla Mining Co. and located within a few miles of the Lucky Friday Mine. The Star Mine employed about 360 nonunion miners. The safety records of both mines were considered to be poor.

As is so often the case in field research, anything that could go wrong did. During the intervention period, silver prices increased 800% and then fell dramatically. Also during the period, the Lucky Friday Mine experienced a 9-week work stoppage that made assessment of the impact of the OD intervention difficult.

Team Building

The primary intervention was through team-building and problem-solving meetings in which a boss and his or her immediate subordinates identified and resolved major problems to make their unit more effective. Some of the assumptions that underlie team building are (1) work teams are the basic building blocks of an organization; (2) effective team functioning requires good leader-member relations, clear team goals, clarification of role expectations, and individual and group problem-solving skills; (3) teams can improve their performance by systematically solving the major problems that confront them; and (4) enhancing work team performance makes individuals more competent and organizations more successful.

The classic or team-building, problem-solving approach introduced at Hecla was governed by several principles.

1. Start team building, problem solving at the top of the organization and work through all levels.
2. Focus attention on intact work teams consisting of superiors and subordinates.
3. Focus on getting the job done; that is, find better ways to accomplish the team's mission by solving major problems and seizing opportunities.
4. Be data based; that is, discover problems, opportunities, and solutions through fact-finding and diagnostic procedures.
5. Be interaction oriented; i.e., develop and implement action plans to cause desired changes. Follow up and evaluate actions to ensure a general team-building, problem-solving framework, but use additional OD techniques as they are appropriate.

The technique of team building involved a series of meetings in which high-priority issues facing the team were systematically examined and resolved. These meetings usually were conducted with the aid of a consultant who acted as a facilitator. Problems were defined and clarified, alternative solutions were evaluated, preferred solutions were implemented, and the effects of actions were monitored for desired results. Team building had two expected outcomes: the team's mission would be better accomplished, and working relationships among team members would be improved.

Five, day-long, team-building meetings with the president and staff led to a formal statement of company philosophy and goals. An agreement on corporate strategy related to safety and productivity was developed. A statement of each department's goals, functions, responsibilities, and authority was also drawn up.

Team-building meetings were held with the top-management team at the Lucky Friday Mine, as well as with the operations team that included the shift bosses. These meetings involved the mine manager, mine superintendent, mine foremen, shift bosses, and auxiliary support supervisors. These meetings dealt more intensively with issues of organizational coordination, communication, and cooperation. For example, support units were not delivering the needed services; some individuals and work units were not meeting others' expectations of what they should be accomplishing. The outcomes of these meetings were improved methods for getting the job done and detailed strategies for reducing mine accidents and injuries.

During the last phase of the project, team-building meetings were held with shift bosses and their work crews. The meetings addressed four main questions:

1. What is preventing us from doing the job in the way we think it ought to be done?
2. What are we doing that helps us get the job done?
3. How can we get the job done more safely?
4. How can be make this a better place to work?

Performance Appraisal System

The development of a reliable and acceptable performance evaluation system became the first accomplishment of the project. This was essential for several reasons. First, supervisors and managers needed feedback on the way in which their own supervisors viewed their effectiveness in dealing with production and safety problems. Second, an appropriate performance system focused attention on the areas of performance seen by management as important. Thus, including safety as one of the prominent areas in which supervisors and managers were judged had an almost immediate effect on the emphasis lower level managers placed on safety-related issues. Third, the project itself required data that would reflect changes in performance in safety-related areas. The performance appraisal consisted of three evaluation forms (one for managers, one for professional and technical employees, and one for clerical personnel) based on a key traits and behaviors format.

Safety Activities

The OD project activities at Hecla included a review and critique of Hecla's 40-h safety training course. The organization's safety functions were also analyzed in various team-building meetings. These resulted in specific changes, including the following:

1. Reassignment of responsibility for the safety engineering, and safety inspection and enforcement.
2. Upgrading the mine safety person position from shift boss to foreman rank.
3. Commitment to give safety training to each new supervisor.
4. Commitment to develop a year-long schedule of safety incentive programs at the Lucky Friday Mine.

Supervisory Skills Training

This aspect of training was given a high priority from the outset. The most critical areas for training were considered to be in company policies, record-keeping practices, standard production methods, and supervisory and leadership skills. Part of this instruction was handled by a commercially produced management training package. Other needed skills were taught by Hecla staff members.

Results

In terms of productivity (average tons per worker-shift) and assay values of the silver and lead (a measure of the amount of waste rock extracted), the results were mixed, at best, and not very impressive. From the start of the OD intervention until the 9-week strike, productivity and assay values were dropping at Lucky Friday. After the strike, both improved. One would be hard pressed, however, to attribute this to the OD intervention. Figure 10-2 shows these results using the 1979 preintervention period as a baseline of 100%.

With regard to safety, the results were more clear cut and dramatic, as shown in figure 10-3. As can be seen, the incidence rate of lost-time injuries was reduced by 46%, decreasing from 21.1 injuries per 200,000 employee-hours of exposure in 1980 to 11.4 injuries per 200,000 employee-hours in 1981. In 1982, that rate was reduced even further (to 4.0 for the month of January). The improvement in lost-time injuries from 1980 to 1981 was the equivalent of 540 worker-shifts at the Lucky Friday. During this same time, the accident rate at neither the Star Mine nor the other district mines changed appreciably, although they did show some signs of decreasing early in 1982. These results strongly suggest that the OD intervention had a significant effect on safety at the Lucky Friday Mine. Thus, the efforts to reduce accidents appear to have been quite successful. Mine Safety and Health Administration (MSHA) officials responsible for the Idaho district expressed the belief that the personnel at the Lucky Friday Mine were making exceptional progress toward improving their safety record.

Cost

The cost of the OD intervention project at Lucky Friday Mine was approximately $200,000—not including the time put into the meetings by Hecla management and workers. Hecla has trained in-house consultants for continued OD interventions at its mines.

Texasgulf Management Training Study

The Texasgulf management training study was part of the same Bureau contract that supported the Hecla team-building project and is described in the same report by Fiedler (*4*). Although most practitioners of OD would argue that the intervention at Texasgulf was not really OD but was more along the lines of traditional management training, the project is reviewed here rather than in chapter 9, because it makes an interesting comparison with the intensive OD-type intervention carried out at Rushton and Hecla.

Background

The target site for the management training program was a trona mine owned by Texasgulf and located near Granger, WY. The mine employed about 500 workers, half underground and half surface in the processing mill. Training was conducted for managers and supervisors of both groups, starting in 1979. As was the case with the Hecla project, Murphy's law prevailed. In 1980, the mine began an effort to double its output. As a result, only 2 of the 15 key managers retained the same job they held at the beginning of the study.

The intervention began with a series of interviews to (a) familiarize the consultants with the organization, (b) identify the major goals of management and supervisors, and (c) develop a list of critical behaviors to construct a performance evaluation scale for assessing the effects of the intervention. The training program itself consisted of the following four basic elements.

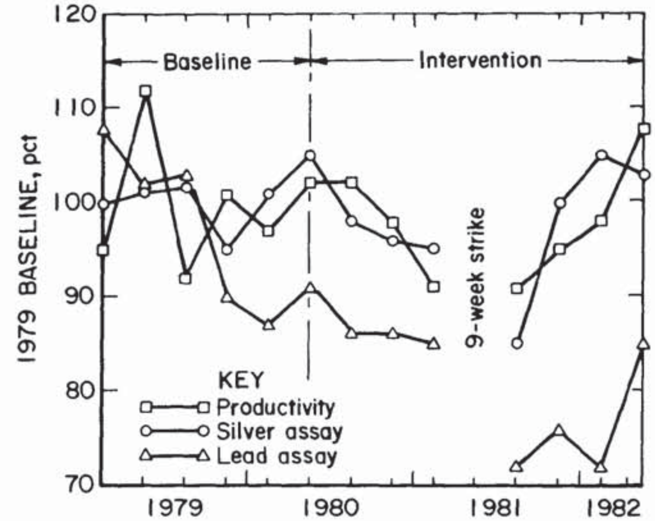


Figure 10-2.—Results of organizational development intervention at Lucky Friday Mine, showing productivity and assay values of silver and lead as a percentage of 1979 baseline, preintervention period.

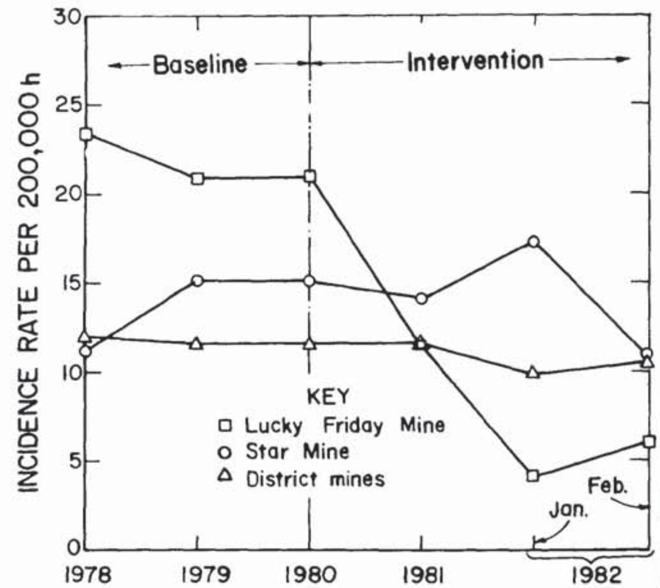


Figure 10-3.—Incident rates of lost-time accidents for the Lucky Friday Mine, Star Mine, and other mines in the Coeur d'Alene mining district.

Objective Supervisory Performance Appraisal

A performance appraisal system was designed so that managers and supervisors could become aware of their own strengths and weaknesses, and those of their subordinates.

The rating scales concentrated on supervisory behaviors—how the supervisor acts, and how he or she can change ineffective behaviors. This type of performance evaluation has been found effective by other industries in motivating employees to improve their behavior at work.

Leadership Training

The intervention used the leader match program developed by Fiedler (*6*). This program is based on a generally accepted view in the leadership area that the performance of leaders or managers depends both on their personalities and on the specific situations in which they operate. The method further assumes that it is generally much easier to change critical components of the leadership situation than one's personality or deeply ingrained habits of interpersonal interactions with subordinates.

Leader match teaches individuals to diagnose their own leadership styles, as well as to diagnose the leadership situations. The leaders are given detailed instruction on various methods for modifying the situations to match their particular management approaches and personalities. The instruction is provided by a trainer who uses a detailed manual, aided by videotaped illustrations, slides, and/or transparencies.

This approach has been used by the U.S. Office of Personnel Management and the military services, as well as by many organizations in the private sector. Validation of this method is described by Fiedler (*5*).

Supervisory Skills Training

This training method used videotaped vignettes in actual and staged settings that taught the supervisor how to deal with specific problems with employees. The problems addressed included reinforcing safe behavior, correcting an employee, overcoming resistance to change, handling an irate employee, and creating a cooperative work team.

Institutionalization

Finally, to assure that the training would actually be used and would remain a permanent part of the organization, key personnel in the Texasgulf training department learned to administer the training methods.

Results

Productivity (tons per worker-hour) changed in the positive direction during the intervention. On average, the Texasgulf Mine increased productivity by 1.7% during the period of the intervention, whereas in the industry as a whole, productivity decreased by 2.9% during this period. The accident rate also improved during the last year of the intervention, while the average for the industry remained relatively constant.

The Texasgulf Co. commissioned an independent management consulting firm to conduct a company-wide job satisfaction and attitude survey in 1979, prior to the beginning of the intervention, and again in May of 1981, 4 months after the intervention had ended. Of particular interest in this survey are the data relating to employee satisfaction and dissatisfaction with the mine's safety efforts. The comparison of the ratings of satisfaction prior and again shortly after the intervention showed satisfaction decreased only among administrative personnel and warehouse workers who were not the focus of the management training program. Satisfaction increased most dramatically, by 23%, among the underground mine personnel, and 19% among mill personnel, both of whom were involved in the intervention.

Cost

The development of the management training program and conduct of the study cost approximately $100,000, with most of the money being spent on development of the videotaped training modules and training manuals. This does not include the training of the mine managers and supervisors who attended all training sessions. Fiedler (*4*) concluded that the management training program was far less costly, and apparently no less effective in terms of the criteria evaluated than was the more intensive OD intervention carried out at Hecla's Lucky Friday Mine.

Quality Control Circles

In the last decade or so, there has been a steady and dramatic growth of quality control (QC) circles in the United States. QC circles are considered to be a Japanese management innovation, but actually the original ideas underlying the concept were introduced by U.S. experts in postwar Japan. A brief review of some of the characteristics and assumptions of QC circles follows, based on Goodman (*8-9*).

A QC circle is a group of up to about 10 workers who voluntarily participate in improving a variety of performance indicators (e.g., quality, downtime, scrap, or rejects). The team meets on company time, and the foreman or a designated senior worker acts as the team leader. Training is an important part of QC circles; time must be allocated to teaching workers both elementary problem-solving techniques and certain statistical data collection methods. Most organizations that use QC's have a QC facilitator who works with several circles in a given plant. Often a human resources staff person, the facilitator has received special training in working with groups. The facilitator's job is to provide support and followup activities to insure that the circle remains viable. While the circle leader runs the circle meetings, the facilitator helps the group when special problems arise, interfaces with other groups in the organization, and provides assistance to the team leader.

Several basic assumptions underlying the idea of quality circles follow.

1. Joint problem solving should be a continuous process.
2. Problem-solving activities should improve quality, costs, productivity, and safety.
3. QC circle involvement should increase the technical and leadership skills of the work force.
4. Change should be more enthusiastically accepted because the workers will have been directly involved in proposing improvements.
5. Recognition and participation in the problem-solving process should be desirable to workers.

The benefits expected from the institution of QC circles include the following.

1. For the worker, QC circles should provide a clear opportunity to participate, to become involved in work, and to work with management. The circles should also provide powerful mechanisms for training workers in a variety of problem-solving, leadership, group-process, and presentation skills. In addition, QC circles should be designed to provide recognition for the workers.

2. For the company, the benefits should be in increased quality, lower downtime, greater organizational loyalty, and the availability of the resources of all employees for solving problems.

3. The current state of knowledge of QC circles should make introducing them relatively easy.

QC circles are not without costs, or disadvantages, including the following.

1. For foremen, QC circles can just mean more work placed on them by the company. Unless a foreman sees the QC circle as beneficial to his or her work, the circle will not be successful. As with some of the other OD changes, the circle could increase the workload and stress on the first-line supervisor. Some of this stress will be transferred to other levels of management.

2. Most companies with QC circles use support personnel or QC facilitators. These individuals must receive special training, which represents an additional cost of running the program.

3. Time is lost when workers meet; however, organizations using the plan find no drop in productivity because of the motivational influence the circle meetings seem to have.

QC Circles at the Captain Mine

The QC circle program at the Arch Mineral Corp. Southwestern Illinois Coal Corp. Captain Mine, a surface coal mine located near Percy, IL, was described by Chironis (*2*). This program included a steering committee that set the overall goals for the circles and monitored the program. The steering committee consisted of four department heads, two employees (union), and a facilitator who was individually responsible for coordinating and directing the circles and for training the circle leaders. Specifically excluded from QC circle discussions were the topics of benefits and salaries, employment policies, discharge policies, and grievances and work rules. The circles were to concentrate on improving teamwork, company communications, and morale.

An ideal group size for a QC circle is five to eight. At the Captain Mine, 22 people volunteered to be in the circle; 7 were selected by drawing lots. Meetings were held approximately once a week, with each meeting lasting about 1 h. A project or problem was picked by the members of the circle, and the leader advised management of the selection. Typically, a number of problems were identified and listed by the circle. A partial list of problems identified by the QC circle of the Captain Mine included the following.

Excessive downtime because of truck failures.

Excess spillage off end of stacker.

Tendency for some jobs to be started but not finished.

Lack of walkways between new plant and breaker building.

Lack of sufficient number of tractors.

Tendency for some chutes to plug up.

Insufficient housekeeping.

Insufficient orientation of new tipple employees.

Frequent misplacement of tools.

Insufficient organization of tipple supply yard.

Problem analysis is performed by the circles, with the assistance of appropriate technical experts as needed. The circle makes its recommendations directly to management by using a formal management-presentation procedure. This assures that management is fully cognizant of the problem selection, analysis, and recommended solution.

Results

QC circles have not been extensively used in the mining industry, so that reports of results are not available. Even in industries where QC circles are widespread, little good data are available about their effectiveness. The Captain Mine did report several innovative solutions to problems identified, and a generally positive attitude toward the program by both management and workers. Several additional circles were formed at the Captain Mine.

DISCUSSION

The importance of motivation for safe and productive work habits is known by everyone in the mining industry. The link between organizational climate and safety and productivity is becoming more apparent. Organizational development as a means of positively altering the climate of an organization has just started to make inroads into the mining industry—and then only with large mining companies. The years ahead should see increased use of team-building and quality circle techniques, with more emphasis on middle-sized companies.

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APPENDIX A.—STATIC ANTHROPOMETRIC DATA FOR MALE AND FEMALE MILITARY PERSONNEL[1]

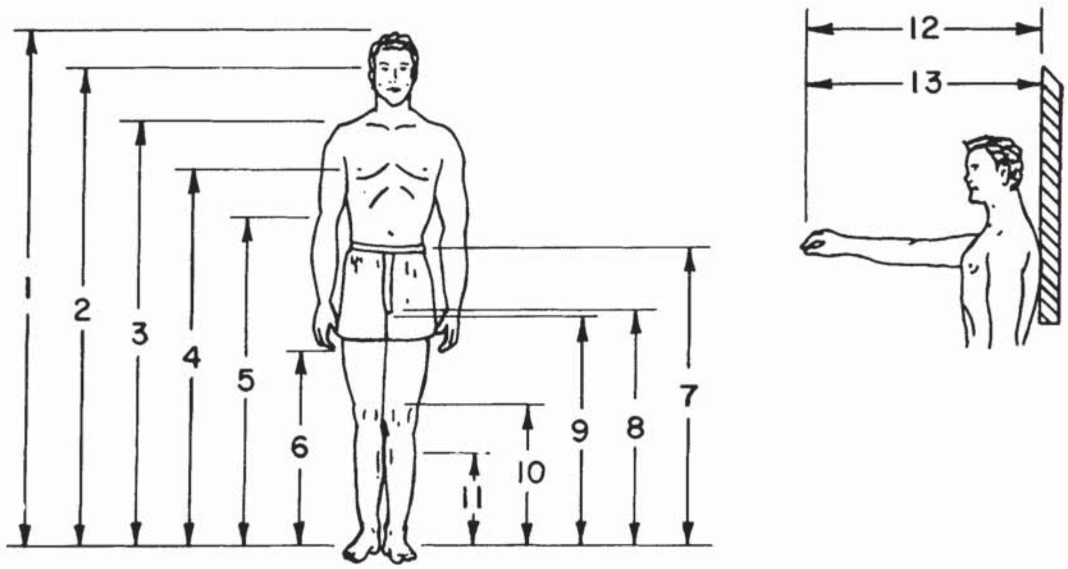


Figure A-1.—Standing body dimensions.

Table A-1.—Standing body dimensions, inches

Figure reference		5th percentile		95th percentile	
		122.4-lb male	102.3-lb female	201.9-lb male	164.3-lb female
1	Stature	64.1	60.0	73.1	68.5
2	Eye height	59.5	55.5	68.2	63.9
3	Shoulder (acromiale) height	52.6	48.4	60.7	56.6
4	Chest (nipple height)[1]	46.4	43.0	53.7	50.3
5	Elbow (radiale) height	39.8	37.4	46.4	43.6
6	Fingertip (dactylion) height	24.4	22.2	29.2	27.0
7	Waist height	38.0	36.6	45.3	43.4
8	Crotch height	30.0	26.8	36.1	33.0
9	Gluteal furrow height	28.8	26.2	34.5	31.9
10	Kneecap height	18.7	17.2	23.1	20.7
11	Calf height	12.2	11.4	16.0	14.4
12	Functional reach	28.6	25.2	35.8	31.7
13	Functional reach, extended	33.2	28.9	39.8	36.5

[1] Bustpoint height for women.

[1] From U.S. Department of Defense MIL-STD-1472B, "Human Engineering Guide to Equipment Design," Dec. 31, 1974.

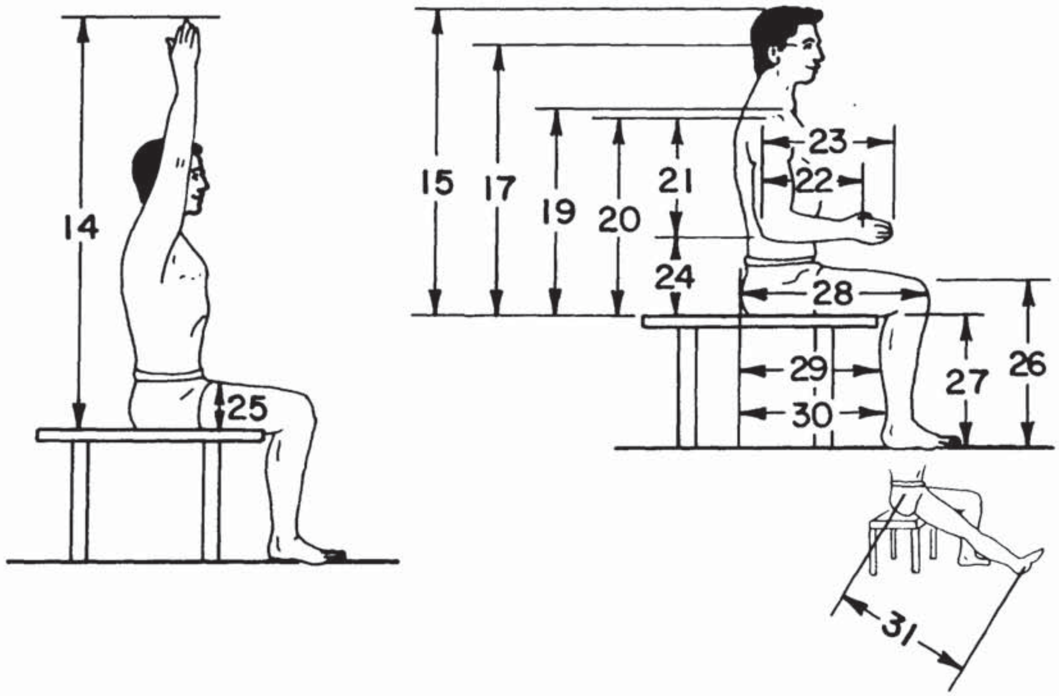


Figure A-2.—Seated body dimensions.

Table A-2.—Seated body dimensions, inches

Figure reference		5th percentile		95th percentile	
		122.4-lb male	102.3-lb female	201.9-lb male	164.3-lb female
14 . . .	Vertical arm reach, sitting	50.6	46.2	58.2	54.9
15 . . .	Sitting height, erect	32.9	31.1	38.2	35.8
16 . . .	Sitting height, relaxed	32.1	30.5	37.3	35.3
17 . . .	Eye height, sitting erect	28.3	26.6	33.3	31.2
18 . . .	Eye height, sitting relaxed	27.6	26.1	32.5	30.7
19 . . .	Midshoulder height	22.3	21.2	26.7	24.6
20 . . .	Shoulder height, sitting	21.3	19.6	25.7	23.7
21 . . .	Shoulder-elbow length	13.1	12.1	15.8	14.4
22 . . .	Elbow-grip length	12.5	11.6	15.1	14.0
23 . . .	Elbow-fingertip length	17.3	15.7	20.5	18.7
24 . . .	Elbow rest height	6.9	6.4	11.0	10.6
25 . . .	Thigh clearance height	NA	4.1	NA	6.9
26 . . .	Knee height, sitting	19.6	18.5	23.7	21.8
27 . . .	Popliteal height	15.6	15.0	19.7	18.0
28 . . .	Buttock-knee length	21.6	20.9	25.9	24.9
29 . . .	Buttock-popliteal length	17.9	17.1	21.5	20.7
30 . . .	Buttock-heel length	17.9	17.1	21.5	20.7
31 . . .	Functional leg length	43.5	39.2	50.3	46.7

NA Not available.

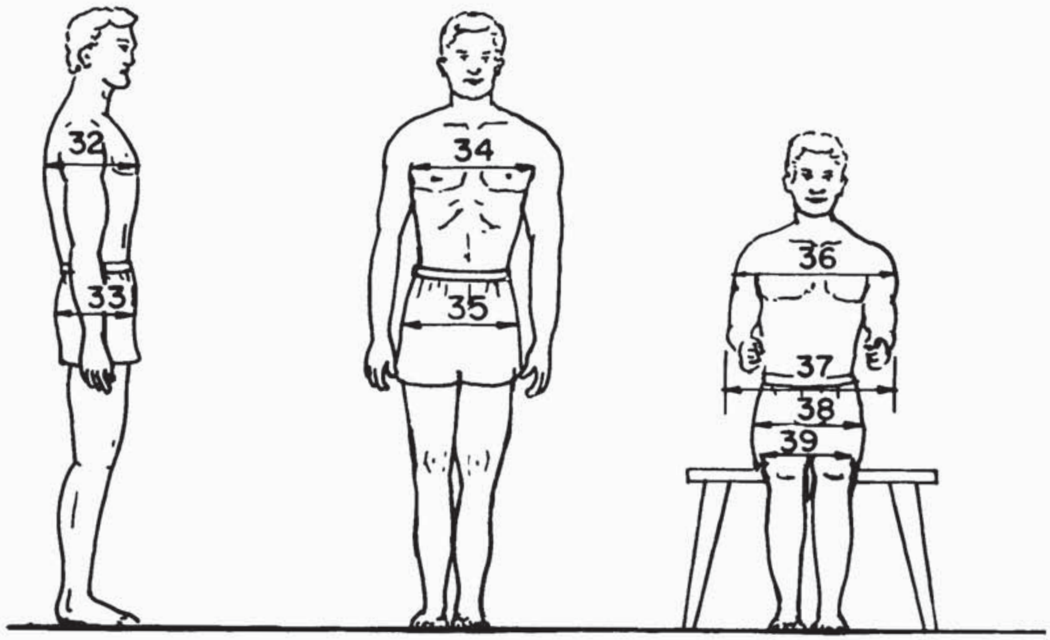


Figure A-3.—Body depth and breadth dimensions.

Table A-3.—Body depth and breadth dimensions, inches

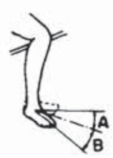
Figure reference		5th percentile		95th percentile	
		122.4-lb male	102.3-lb female	201.9-lb male	164.3-lb female
32 . . .	Chest depth[1]	7.5	7.7	10.5	10.7
33 . . .	Buttock depth	NA	7.2	NA	9.6
34 . . .	Chest breadth	10.8	9.9	13.5	12.4
35 . . .	Hip breadth, standing	11.9	12.4	14.5	15.6
36 . . .	Shoulder (bideltoid) breadth . .	16.3	15.0	19.6	18.0
37 . . .	Forearm-forearm breadth	15.7	13.0	21.1	17.7
38 . . .	Hip breadth, sitting	12.1	13.0	15.1	17.3
39 . . .	Knee-knee breadth	8.4	9.1	10.5	12.0

NA Not available.
[1] Bust depth for women

APPENDIX B.—TYPICAL JOINT MOBILITY DATA SHOWING 5th and 95th PERCENTILE MALE AND FEMALE LIMITS

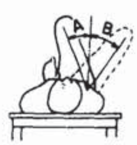
No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
1	Ankle extension (A)	18°	58°	36°	64°
	Ankle flexion (B)	23°	47°	9°	29°

No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
2	Knee flexion	129°	159°	121°	147°



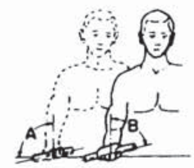
No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
3	Knee rotation Medial (A)	15°	55°	25°	63°
	Knee rotation Lateral (B)	23°	63°	40°	72°

No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
4	Hip flexion	92°	134°	56°	104°



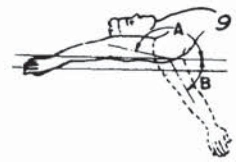
No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
5	Hip abduction (A)	33°	73°	Unknown	
	Hip abduction (B)	11°	51°	Unknown	

No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
6	Hip rotation, sitting Lateral (A)	16°	45°	40°	72°
	Hip rotation, sitting Medial (B)	16°	46°	25°	63°

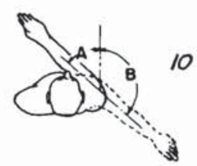


No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
7	Forearm supination (A)	77°	149°	61°	117°
	Forearm pronation (B)	37°	117°	77°	127°

No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
8	Elbow flexion	26°	159°	140°	163°



No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
9	Shoulder flexion (A)	168°	208°	151°	184°
	Shoulder extension (B)	38°	84°	25°	58°

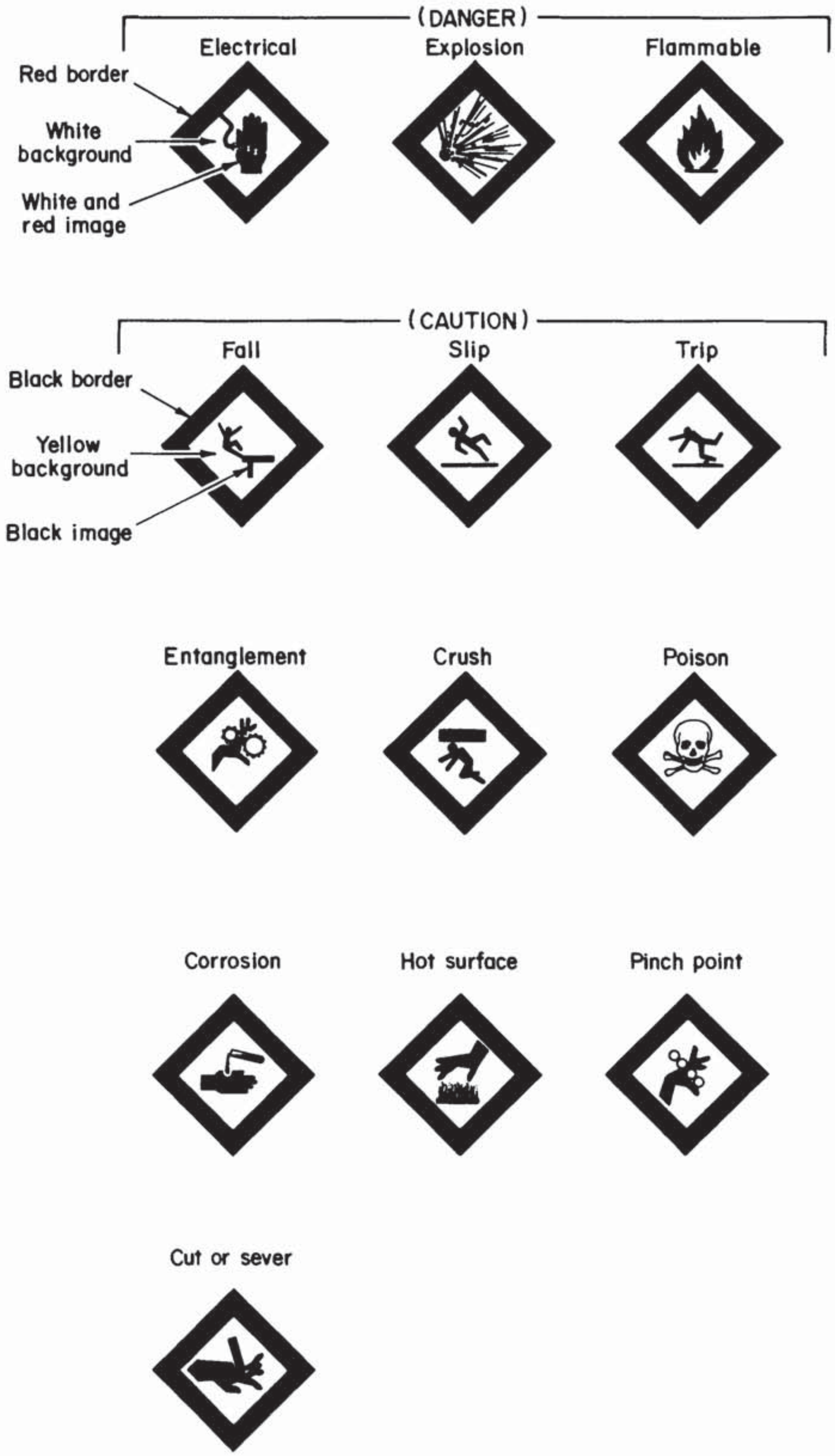


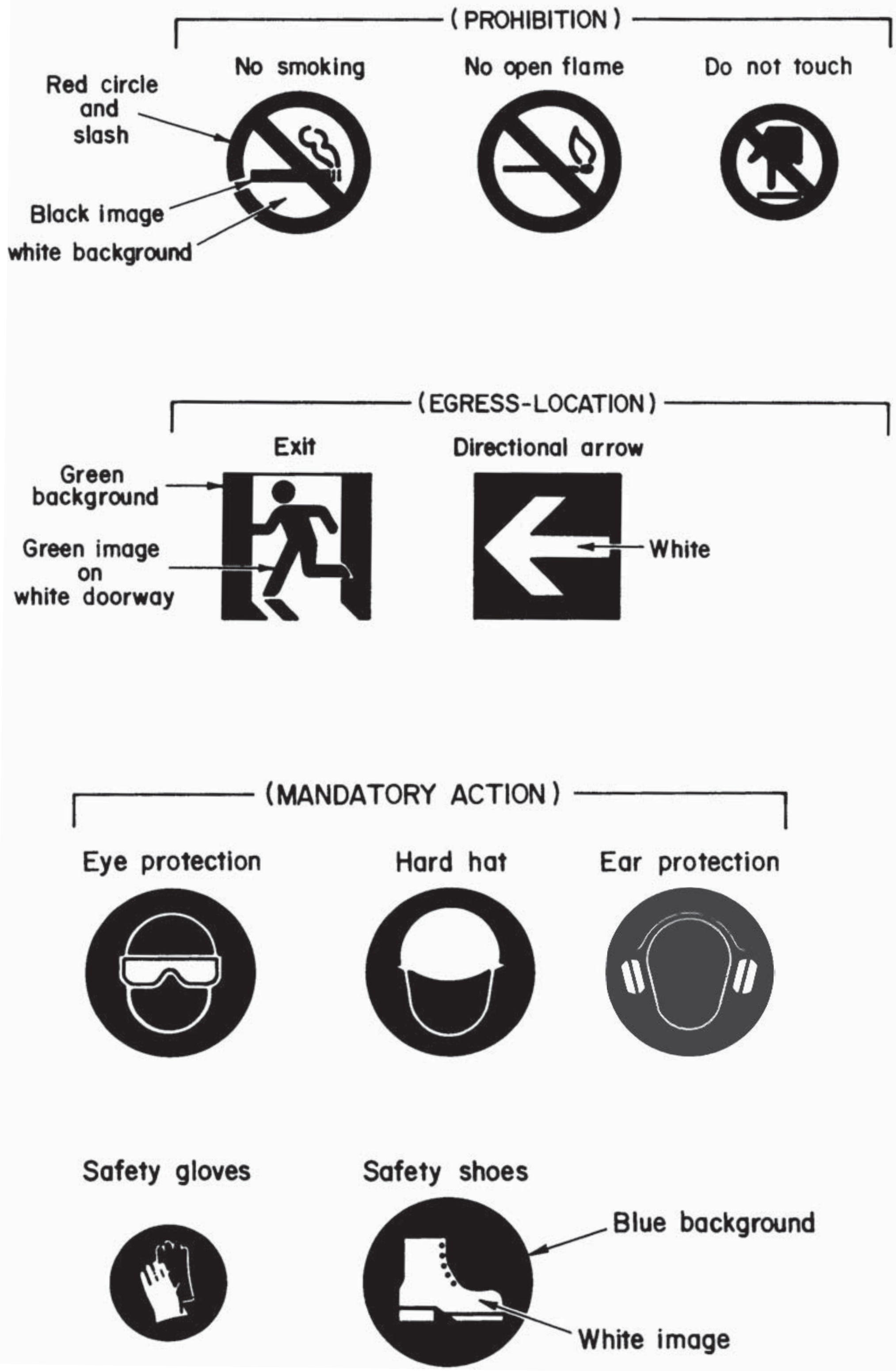
No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
10	Shoulder abduction (A)	33°	63°	Unknown	
	Shoulder abduction (B)	106°	162°	Unknown	

No.	Percentile	Male 5th	Male 95th	Female 5th	Female 95th
11	Shoulder rotation Lateral (A)	13°	55°	15°	52°
	Shoulder rotation Medial (B)	61°	133°	139°	181°

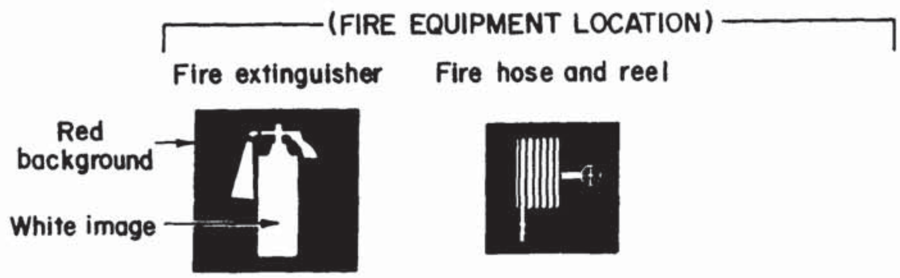
Figure B-1.—Typical joint mobility data. (Copyright 1972 by John Wiley and Sons, and reprinted by permission)

APPENDIX C.—EXAMPLES OF PICTORIAL SAFETY SIGNS RECOMMENDED FOR USE IN THE MINING INDUSTRY




(PROHIBITION)
No smoking
No open flame
Do not touch
Red circle and slash
Black image
white background
(EGRESS-LOCATION)
Exit
Directional arrow
Green background
Green image on white doorway
White
(MANDATORY ACTION)
Eye protection
Hard hat
Ear protection
Safety gloves
Safety shoes
Blue background
White image


(SAFETY LOCATION INFORMATION)
First aid
Eyewash
Safety shower
Green background
White image
White background
Green image


(FIRE EQUIPMENT LOCATION)
Fire extinguisher
Fire hose and reel
Red background
White image

APPENDIX D.—SUMMARY OF SELECTED DATA REGARDING DESIGN RECOMMENDATIONS FOR CONTROL DEVICES

Device	Displacement		Resistance	
	Min	Max	Min	Max
Hand pushbutton, 0.5-in min size: Fingertip operation	0.125 in	15 in	10 oz	40 oz
Foot pushbutton, 0.5-in min size:				
Normal operation	0.5 in	NAp	NAp	NAp
Wearing boots	1 in	NAp	NAp	NAp
Ankle flexion only	NAp	2.5 in	NAp	NAp
Leg movement	NAp	4 in	NAp	NAp
Will not rest on control	NAp	NAp	4 lb	20 lb
May rest on control	NAp	NAp	10 lb	20 lb
Toggle switch, 0.125- to 1-in-diam control tip, 0.5- to 2-in-length lever arm	30°	120°	10 oz	40 oz
Rotary selector switch, 1- to 3-in length, 0.5- to 1-in width, 0.5-in depth:				
Visual positioning	15°	[1]40°	10 oz	40 oz
Nonvisual positioning	30°	[1]40°	10 oz	40 oz
Knob, continuous adjustment, finger-thumb,[2] 0.5- to 1-in depth, 0.375- to 4-in diam, 1.5- to 3-in hand-palm diam	NAp	NAp	NAp	4.5-6 in/oz
Crank,[2] 0.5- to 4.5-in radius for light loads and 0.5- to 20-in radius for heavy loads:				
Rapid, steady turning:				
< 3- to 5-in radius	NAp	NAp	2 lb	5 lb
5- to 8-in radius	NAp	NAp	5 lb	10 lb
For precise settings	NAp	NAp	2.5 lb	8 lb
Levers:[3]				
Fore-aft (1 hand)	NAp	14 in	NAp	NAp
Lateral (1 hand)	NAp	38 in	NAp	NAp
Finger grasp, 0.5- to 3-in diam	NAp	NAp	12 oz	32 oz
Hand grasp, 1.5- to 3-in diam	NAp	NAp	2 lb	20-100 lb
Handwheel,[2] 7- to 21-in diam, 0.75- to 2-in rim thickness	NAp	90°-120°	5 lb	[4]30 lb
Pedal, 3.5-in length, 2-in width:				
Normal use	0.5 in	NAp	NAp	NAp
Heavy boots	1 in	NAp	NAp	NAp
Ankle flexion	NAp	2.5 in	NAp	10 lb
Leg movement	NAp	7 in	NAp	180 lb
Will not rest on control	NAp	NAp	4 lb	NAp
May rest on control	NAp	NAp	10 lb	NAp

NAp Not applicable.

[1] When special requirements demand large separations, max should be 90°.

[2] Displacement of knobs, cranks, and handwheels should be determined by desired control-display ratio.

[3] Length depends on situation, including mechanical advantage required. For long movements, longer levers are desirable (so that movement is more linear).

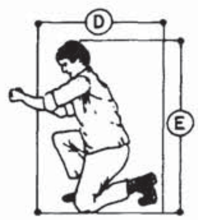
[4] For 2-handed operation, max resistance of handwheel can be up to 50 lb.

Source: McCormick, E., and M. Sanders. Human Factors in Engineering and Design. McGraw-Hill, 5th ed., 1982, 615 pp.

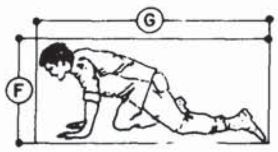
APPENDIX E.—SELECTED DATA ON ACCESS SPACE REQUIRED TO PERFORM MAINTENANCE TASKS[1]

	Dimensions, in Minimum	Preferred
A. Height	48	
B. Width	27	36

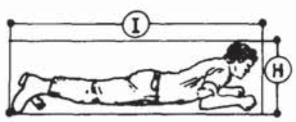
	Minimum	Preferred
C. Width	26	40



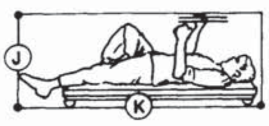
	Minimum	Preferred
D. Width	42	48
E. Height	55	



	Minimum	Preferred
F. Height	31	36
G. Length	59	

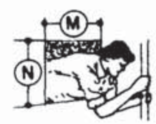


	Minimum	Preferred
H. Height	17	20
I. Length	112	



	Dimensions, in Minimum	Preferred
J. Height for - -		
Inspection	18	
Using small tools, making minor adjust-ments	24	
Reasonable arm extension	32	
K. Length	76	

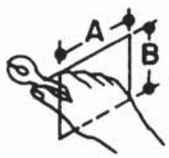
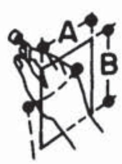
	Minimum	Preferred
L. Crawl through pipe diam	25	30

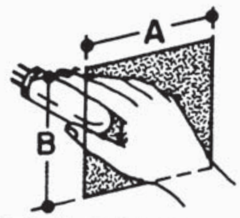
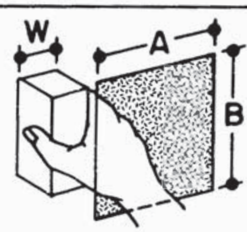
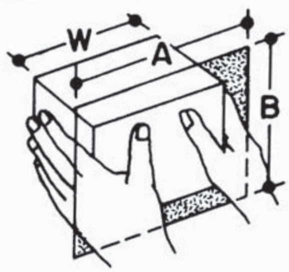
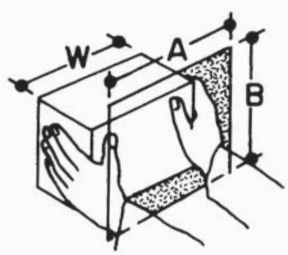
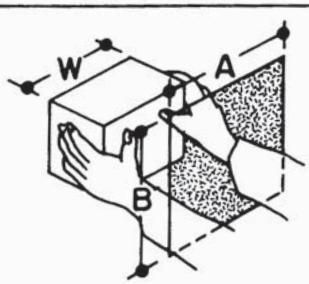


	Minimum	Preferred
M. Shoulder width	21	24
N. Height	15	20

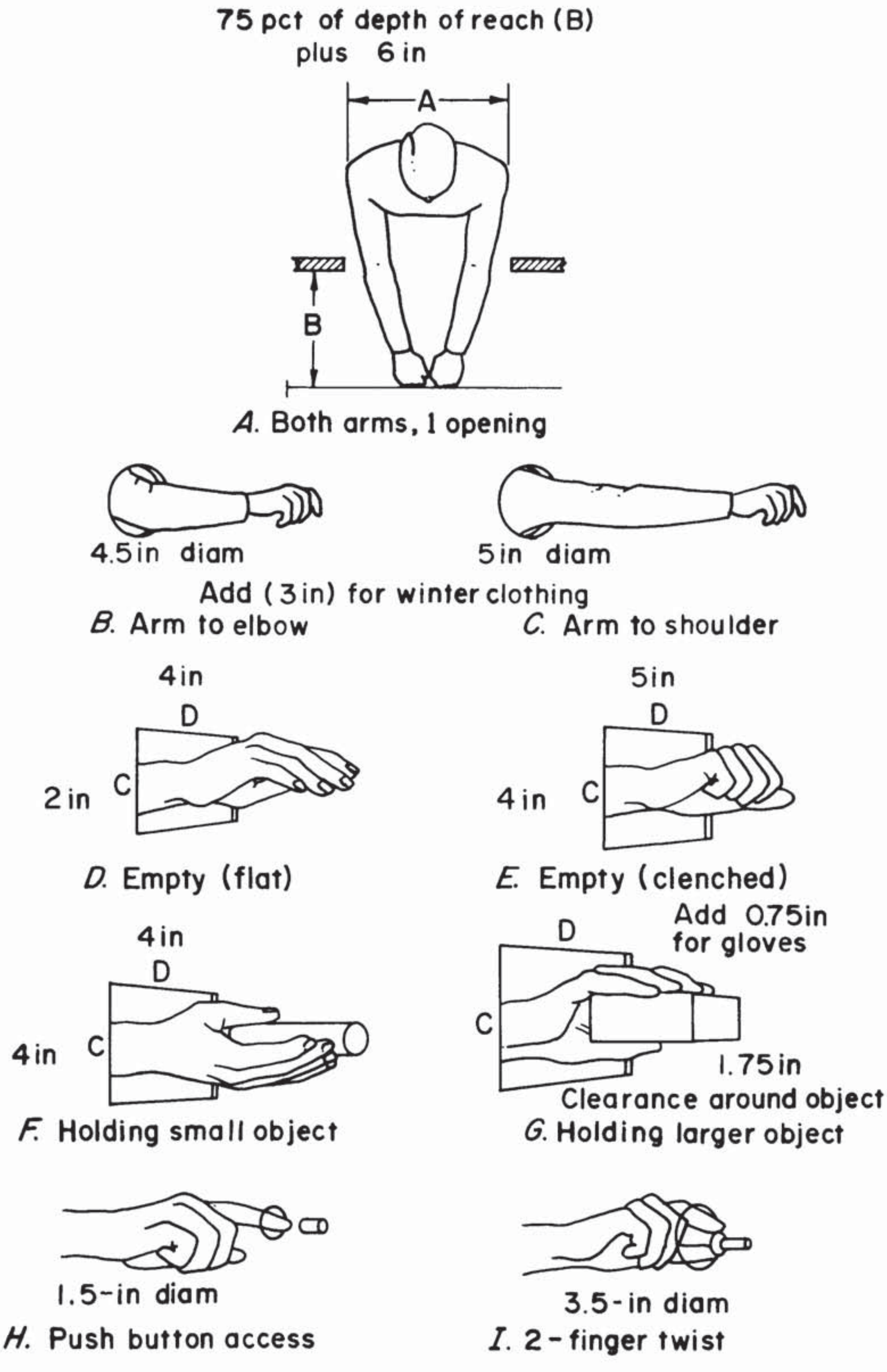
	Minimum	Preferred
O. Square	18	22
Round	22	24

[1] From U.S. Army Missile Command MIL-HDBK-759A, "Military Standardization Handbook: Human Factors Engineering Design for Army Material," 1981.

Opening dimension	Dimension, in A	Dimension, in B	Task
	4.3	4.7	Using common screwdriver, with freedom to turn hand through 180°.
	5.1	4.5	Using pliers and similar tools.
	5.3	6.1	Using "T" handle wrench, with freedom to turn hand through 180°.
	10.6	7.9	Using open-end wrench, with freedom to turn wrench through 60°.
	4.7	6.1	Using Allen-type wrench with freedom to turn wrench through 60°.
	3.5	3.5	Using test probe, etc.

Opening dimensions	Dimensions, in A	B	Task
	4.3	4.7	Grasping small objects (up to 2 in or more wide) with one hand.
	W + 1.8	5*	Grasping large objects (2 in or more wide) with one hand.
	W + 3	5*	Grasping large objects with 2 hands, with hands extended through openings up to fingers.
	W + 6	5*	Grasping large objects with 2 hands, with arms extended through openings up to wrists.
	W+6	5*	Grasping large objects with 2 hands, with arms extended through openings up to elbows.

* Or sufficient to clear part if part is larger than 5 in


75 pct of depth of reach (B)
plus 6 in
A
B
A. Both arms, 1 opening
4.5 in diam
5 in diam
Add (3 in) for winter clothing
B. Arm to elbow
C. Arm to shoulder
4 in
D
2 in
C
D. Empty (flat)
5 in
D
4 in
C
E. Empty (clenched)
4 in
D
4 in
C
F. Holding small object
D
Add 0.75 in
for gloves
C
1.75 in
Clearance around object
G. Holding larger object
1.5-in diam
H. Push button access
3.5-in diam
I. 2-finger twist

INDEX

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