Assessment and Evaluation of Noise Controls on Roof Bolting Equipment and A Method For Predicting Sound Pressure Levels in Underground Coal Mining

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ABSTRACT

Assessment and Evaluation of Noise Controls on Roof Bolting Equipment and A Method For Predicting Sound Pressure Levels in Underground Coal Mining

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Over-exposure to noise remains a widespread and serious health hazard in the U.S. mining industries despite 25 years of regulation. Every day, 80% of the nation's miners go to work in an environment where the time weighted average (TWA) noise level exceeds 85 dBA and more than 25% of the miners are exposed to a TWA noise level that exceeds 90 dBA, the permissible exposure limit (PEL). Additionally, MSHA coal noise sample data collected from 2000 to 2002 show that 65% of the equipment whose operators exceeded 100% noise dosage comprise only seven different types of machines; auger miners, bulldozers, continuous miners, front end loaders, roof bolters, shuttle cars (electric), and trucks. In addition, the MSHA data indicate that the roof bolter is third among all the equipment and second among equipment in underground coal whose operators exceed 100% dosage.

A research program was implemented to: 1) determine, characterize and to measure sound power levels radiated by a roof bolting machine during differing drilling configurations (thrust, rotational speed, penetration rate, etc.) and utilizing differing types of drilling methods in high compressive strength rock media (>20,000 psi). The research approach characterized the sound power level results from laboratory testing and provided the mining industry with empirical data relative to utilizing differing noise control technologies (drilling configurations and types of drilling methods) in reducing sound power level emissions on a roof bolting machine; 2) distinguish and correlate the empirical data into one, statistically valid, equation, in which, provided the mining industry with a tool to predict overall sound power levels of a roof bolting machine given any type of drilling configuration and drilling method utilized in industry; 3) provided the mining industry with several approaches to predict or determine sound pressure levels in an underground coal mine utilizing laboratory test results from a roof bolting machine and 4) described a method for determining an operators' noise dosage of a roof bolting machine utilizing predicted or determined sound pressure levels.

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NOMENCLATURE

Symbol	Description	Units
α	Sabine or Absorption Coefficent	
σR	Standard Deviation of Reproducibility	
θ	Temperature	degree Celsius
λ	Wavelength of Sound	
A	Area of Rock Core	in^2
avthrust	Average Thrust During Test	lbs
avspeed	Average Rotational Speed During Test	rpm
C∘	Unconfined Compressive Strength (Corrected)	psi
C	Unconfined Compressive Strength	psi
CL	Criterion Level	dBA
D	Diameter of Rock Core	in
d_{min}	Minimum Distance Between Microphones	m
DUT	Device Under Test	
ER	Exchange Rate	dBA
FRF	Frequency Response Function	g/n
Hz	Hertz	
kHz	Kilohertz	
L	Length of Rock Core	in
L_{pi}	Sound pressure level at the i^{th} measurement Position	dB
L_p	Mean of Sound Pressure Levels	dB
L_w	Sound Power Level	dB of dBA

NOMENCLATURE

Symbol	Description	Units
$\overline{L_v}$	Surface Average Velocity Level	dB or dBA
L_{wA}	Average Sound Power Level	dBA
L_p (underground) (Patterson)	A-weighted Sound Pressure Level	dBA
L_w (aboveground) (Patterson)	A-weighted Sound power Level	dBA
MSHA	Mine Safety and Health Administration	
MSHA-PEL	MSHA-Permissible Exposure Limit	%
NIOSH	National Institute for Occupational Safety and Health	
NIOSH-REL	NIOSH-Recommended Exposure Limit	%
N	Newton	lbs
N_s	Number of Source Positions	
P	Load at Failure (rock core)	lbs
PRL	Pittsburgh Research Laboratory	
PEL	Permissible Exposure Limit	
pendepth	Penetration Depth During Test	in
penrate	Penetration Rate During Test	in/sec
R^2	Coefficient of Determination	
RTime	Run Time	sec
S	Surface Area	m^2
S_0	Reference Surface Area	m^2
setthrst	Thrust Setting Prior to Drilling	lbs

NOMENCLATURE

Symbol	Description	Units
setspd	Rotational Speed Setting Prior to Drilling	rpm
SPL	Sound Pressure Level	dB or dBA
spdb	Linear Sound Power For Test	dB
spdba	A-weighted Sound Power for Test	dBA
TWA	Time-Weighted Average	dBA
T60	Decay Time	sec
TC	Criterion Time	h or sec
V	Volume	m^3

DEDICATION

TO MY DECEASED FATHER AND MOTHER, MY DAUGHTER, MORGAN AND WIFE, DEB

For providing me with the motivation and determination to reach one's full potential

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The list of those deserving of mention is extensive and includes dedicated and extraordinary individuals from the National Institute for Occupational Safety and Health (NIOSH) and the West Virginia University (WVU). Each organization, contributed extensively to my ability to conduct the research and complete the dissertation. The individuals who provided substantial insight and direction include Professor Syd Peng, WVU (my Advisor and Committee Chair), Dr. Gerald Finfinger, NIOSH, Mr. Pete Kovalchik, NIOSH and Dr. Güner Gürtunca, NIOSH. Each played an integral role in the research endeavor and continued to provide me with a significant amount of devotion, intelligence and eagerness to mentor me thru this process.

CHAPTER 1

INTRODUCTION

Over-exposure to noise remains a widespread and serious health hazard in the U.S. mining industries despite 25 years of regulation. Most other categories of illnesses and injuries associated with mining have improved dramatically, with the exception of hearing loss. The use of heavy equipment, the drilling and cutting of rock and coal, and the confined work environment are the major factors that contribute to high levels of noise exposure during mining operations. Every day, 80% of the nation's miners go to work in an environment where the time weighted average (TWA) noise level exceeds 85 dBA and more than 25% of the miners are exposed to a TWA noise level that exceeds 90 dBA, the permissible exposure limit (PEL) (1).

In January 1995, the Physical Agents Effects Branch, located in the National Institute for Occupational Safety and Health (NIOSH), Division of Biomedical and Behavioral Science, Cincinnati, Ohio, began collaboration on a project with the Mine Safety and Health Administration (MSHA) that was designed to determine the prevalence of hearing loss among miners. Two reports were forwarded to MSHA: one for coal miners, and one for metal/non-metal miners (2). After removing potentially invalid audiograms through a quality assurance process, the first report contained an analysis of 17,260 audiograms for 2,871 coal miners, and the second report reviewed 22,488 audiograms on 5,244 metal/non-metal miners. For comparison purposes, hearing thresholds were calculated for a similar-aged population of non-exposed individuals by using Annex A from ISO-1999 (ISO 1990) (3). The noise levels that would be predicted to cause the amount of hearing loss observed for the miners were also calculated from the ISO-1999.

The results of these investigations showed that miners developed hearing loss much more quickly than those in the non-occupational noise-exposed database used by ISO-1999, and that the miners experienced a greater severity of hearing loss than would

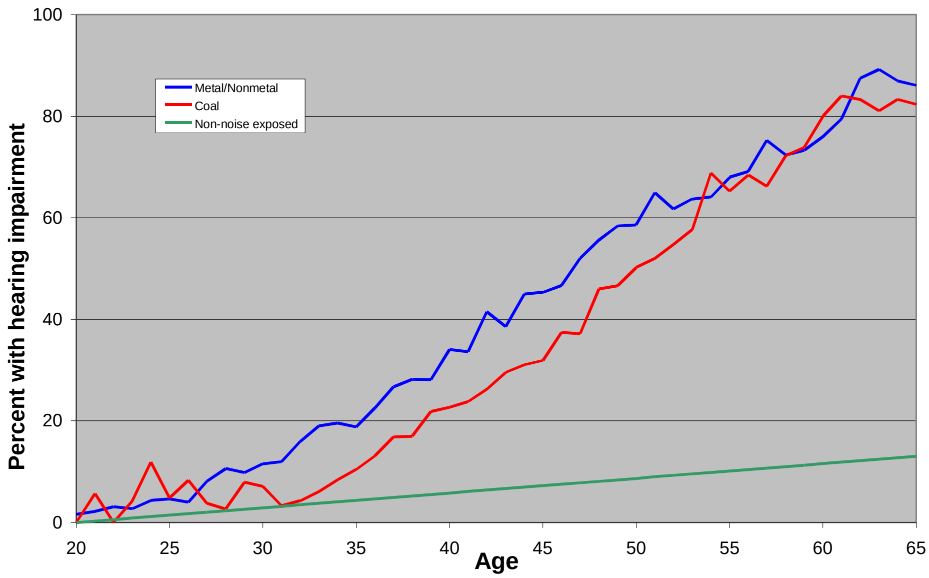

Figure 1.1 Analysis of Audiograms for Coal and Metal/Non-Metal Miners

be expected for non-occupational noise-exposed persons of the same age and gender. Using hearing thresholds at 4000 Hz as an indicator, coal miners experienced hearing loss 2 ½ to 3 times greater than would be expected for persons not exposed to occupational noise. At age 55, 65% of the coal miners and metal/non-metal miners were found to have a hearing impairment. By comparison, only 10% of the non-occupationally exposed group had a hearing impairment at age 55 (Figure 1.1) (2). While Noise Induced Hearing Loss (NIHL) is the most common occupational illness in this country, this problem is especially acute among miners. NIOSH has recognized NIHL as one of the 10 leading work-related diseases and injuries in the Nation, and has emphasized its importance in the National Occupational Research Agenda (NORA).

Over the past decade, the Mine Safety and Health Administration (MSHA) has worked to develop a revised health standard for occupational noise exposure in coal, metal, and nonmetal mines. In December of 1996, the agency released its Proposed Rule in the Federal Register (30 CFR Parts 56, 57, 62, 70, and 71) (4). Unlike its predecessor, the proposed rule emphasizes the primacy of engineering controls as the strongest defense against excessive exposure to noise and the prevention of NIHL among miners and disallows reliance on personal hearing protection devices (PHPs) as a means of compliance with the standard. Despite the extensive work performed in the 1970's and 80's, NIHL is still a pervasive problem in the mining industries.

A new MSHA noise standard was published on September 13, 1999. This rule closely resembles the existing Occupational Safety and Health Administration (OSHA) Occupational Noise Exposure Standard and Hearing Conservation Amendment (29 CFR 1910.95), and replaced the different standards for occupational noise exposure in coal mines and in metal/non metal mines with a single new standard applicable to all mines. MSHA concluded in a recent survey that if an OSHA-like hearing conservation program was adopted, hypothetically, 78% of the coal miners surveyed would be required to be in a hearing conservation program (5). Although the proposed noise exposure limits would not totally eliminate the risk of material impairment, it is expected to reduce by two-thirds the number of miners currently projected to suffer a material impairment of their hearing.

Additionally, MSHA coal noise sample data (6) collected from 2000 to 2002 show that 65% of the equipment whose operators exceeded 100% noise dosage comprise only seven different types of machines; auger miners, bulldozers, continuous miners, front end loaders, roof bolters, shuttle cars (electric), and trucks. In addition, the MSHA data indicates that the roof bolter is third among all the equipment and second among equipment in underground coal whose operators exceed 100% dosage (Figure 1.2).

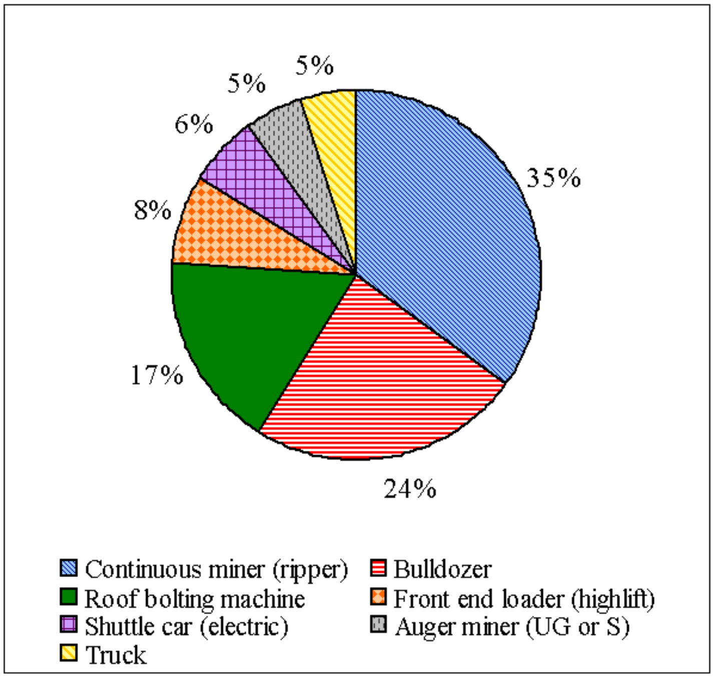

Figure 1.2 MSHA Coal Noise Sample Data – Percentage of Equipment Whose Operators Exceeded 100% Dose

Lesser elements in the hierarchy of controls for reduction of noise exposure, including administrative practices (e.g. job rotation), and the use of personal hearing protective devices (PHP's) have been the main sources of noise control in the past, relying on workers to properly wear and maintain their hearing protection. A balanced approach to the prevention of NIHL that includes not only education, surveillance, and intervention, but a research emphasis on engineering controls for noise is absolutely necessary. The development and utilization of engineering noise controls represent a permanent solution while the use of PHP's is seen as an interim solution. This research effort focuses on the development and assessment of engineering noise controls for mining equipment, specifically, roof bolters used in underground coal mining. The research will be conducted in a specialized laboratory using a standard roof bolter and a variety of operational conditions and settings representative of the underground coal mining industry as shown in figure 1.3 below. The data collected will provide information related to optimum drilling configurations, related to high compressive strength drilling media (>20,000 psi) for reducing sound power emissions from the machine. Additionally, the research will then persist, using a modeling approach, to predict the sound pressure level an operator is exposed to in an underground coal mine utilizing the sound power level data obtained from the laboratory.

Figure 1.3 Noise Testing of Roof Bolter in Reverberation Room

CHAPTER 2

LITERATURE REVIEW

Recent research focusing on engineering noise controls, specifically, on underground coal mining roof bolters is considerably limited. In 1983, the former Bureau of Mines developed a handbook entitled, "Mining Machinery Noise Control Guidelines, 1983" (7) which documented available noise control information of numerous pieces of mining equipment for dissemination to the mining industry. Several noise treatments were proposed within the handbook related to roof bolting machines in underground coal settings, which included; modifying the dust collection blower or changing to a quieter model; cover or enclose the hydraulic pump and sealing the enclosure around motor and pump-blower drives using the existing cover panels. A major manufacturer of roof bolting equipment, J.H. Fletcher, Inc. has supported most of the recommended controls, however, when the drilling or bolting process occurs with the machine, noise levels experienced by the operator still exceed regulatory limits, therefore overexposing the operator to noise.

NIOSH has performed numerous noise exposure surveys related to roof bolting operators in underground coal mines. The data suggests that 81% of the samples collected (a total of 16 samples of roof bolter operators), exceeded the MSHA Permissible Exposure Level (8). Additionally, representatives from MSHA conducted a series of environmental noise surveys in 12 underground coal mines (9). Approximately, 2,600 employees were included in the survey. The data suggested that 20% of all workers which are associated with face operations are exposed to noise levels which are in excess of the prescribed limits (MSHA Permissible Exposure Level). Specifically, while monitoring operators of roof bolting machines, the data suggested that noise levels exceeded 90 dBA during drilling and bolting activities, therefore contributing overexposure of noise to these operators.

Recent and prior research associated with noise controls for roof bolting machines utilized in underground coal (rotary) is significantly limited. Numerous attempts have been made to “quiet” percussive type drills (development of differing types of drill rod, utilization of water, etc.), mainly utilized in hard rock mining commodities that could possibly be applicable to rotary roof bolting machines. The noise radiated from percussive type drills can be classified into two different components: airflow noise due to the utilization of compressed air and mechanical noise, which generally is attributed by the impact and rattling of drill components; for example, drill rod noise.

Lesage, et. al (10) addressed an experimental approach to characterize the vibroacoustic behaviour of percussion drill steel rods under real operating conditions and laboratory controlled operating conditions. The contribution of longitudinal and flexural vibration related to noise generation was provided. The testing concluded that the bending waves within the drill steel were mainly responsible for the largest portion of noise radiation and the contribution of longitudinal waves to the noise radiation was found to be negligible.

Champoux, et. al. (11) addressed a method for determining the contribution of both longitudinal and flexural waves related to the radiation of noise associated with percussive type drill steel rods. The authors determined that in order to reduce the noise produced by the steel rod, one must understand significant aspects of the noise generation mechanism (12). A typical cylindrical steel rod was utilized as the test piece and hung vertically in a semi-anechoic room. A soft suspension was attached to a steel striking piece solidly attached at the top end of the rod. Being supported by the top, the steel rod was always aligned vertically. First, the vibration behavior of the structure was examined. The use of modal analysis was performed on the structure. Lateral impacts were administered using an impact hammer to exite predominantly the bending modes of the steel. Accelerometers were glued on the rod at several locations and transfer functions were recorded utilizing a two-channel frequency analyzer. The longitudinal modes and the corresponding frequencies were measured by impacting the striking end piece along the rod's longitudinal axis and the response was measured with an accelerometer installed on the striking piece and oriented in the same axis. To determine noise radiation characteristics, a sinusoidal excitation was used initially, and to generate a longitudinal excitation, a 50-pound shaker was attached vertically to the upper part of the rod. However the noise generated by the rod when excited by the shaker was very low. An impact hammer was then used to control the amplitude and location of impact with respect to the rod. The end of the impact handle was attached to a hinge allowing a well controlled rotation along a horizontal axis. The blows of impact were then always applied on the striking end piece of the rod in a direction parallel to the longitudinal axis. The impacts were applied on the longitudinal center line of the rod (axial excitation) and near the edge of the tip of the rod (eccentric excitation). The force amplitude peaks were on the order of 1,000 N (225 lbF). To record the noise, a microphone, located 20 cm (7.9 inches) from the rod was used. Results of the testing concluded that: 1) imperfection tends to create double peaks for the flexural modes; 2) flexural and longitudinal waves both contribute to the sound radiation; 3) for a given force amplitude, the longitudinal mode amplitude appears to be insensitive to impact force location and 4) flexural modes are very sensitive to imperfection of the rod and impact force location.

Stein and Aljoe (13) provided information on noise controls related to percussive-type drills. A concentric drill steel was designed for use as a drilling tool and noise control. The design differed from the typical drill steel because it was constructed of two members rather than the usual one member. The two members consisted of an inner pulse transmission rod and an outer torque transmission tube. The inner rod transmitted percussive energy to the bit just as the conventional steel would, however torque to the bit was eliminated. The other member, the torque tube, provided torque to the bit. The torque tube provided rotation to the bit and acted as a barrier to attenuate noise emitted for the inner rod. Testing of the concentric steel for noise output to the operator provided a 5 dBA reduction as compared to the standard steel.

Visnapu and Jensen (14) researched modifications on standard pneumatic rock drills to reduce the noise of the air exhaust, drill steel resonance noise and noise radiated by the drill body. The drill body was enclosed with a close-fitting case and muffler. The enclosure consisted of a metallic honeycomb skeleton filled with viscoelastic absorber on the inside and a durable outer shell, in which was designed to provide both exhaust and drill body noise muffling and absorption. Noise radiated by the drill steel was attempted to be reduced by utilization of a constrained-layer treatment consisting of a tubular metal cover bonded to the outside of the rod by a viscoelastic filler. The constrained-layer damped steels were prepared by slipping the metal tube over the drill steel, centering the steel in the tube, and then filling the space between the tube with liquid viscoelastic filler. Upon curing of the filler, part of the covering around the collar and shank was removed.

Tubes with wall thicknesses from 0.049 to 0.065 inch and outside diameters of 1-1/4 to 1-1/2 inches were bonded to 7/8-inch-diameter drill steels. Two viscoelastic fillers were selected, a two-part-mix urethane rubber, and a syntactic polyurethane foam. Noise testing related to the constrained-layer drill steels demonstrated to be an effective method for reducing drill steel noise. Results displayed a 3-6 dBA reduction when utilizing constrained-layer drill steels in comparison to standard steel.

Bartholomae (15) reported on an in-the-hole drill concept for noise control associated with percussive type drills. The concept eliminated the drill rod as a stress transfer mechanism so that the percussive motor is located just behind the drill bit. The motor is pushed into the borehole thru utilization of the drill pipe, which is used to rotate the percussion motor and drill bit to transmit the drill feed force. The noise reduction principle of the "in-the-hole" drill involved an operational effect. Once the borehole is started, the high energy noise from the percussive tool is contained entirely within the borehole, with the rock mass acting as an acoustic enclosure. This design was significantly different than standard percussive drills, in which the major noise producing components (drill hammer, drill steel, air exhaust) are located outside the borehole. Laboratory testing, for noise related to this concept, displayed that noise levels significantly decreased, 4 dBA (4 ft. into rock). However, mechanical difficulties associated with water leaks, percussion motor, etc. related to the drill eliminated any further testing. Future plans were to address the mechanical problems associated with the new design, since noise level reduction did show promise.

Paraszczak and Planeta (16) reported on the utilization of water-powered jackleg rock drills to be more efficient, faster and more comfortable (noise generation) than conventional pneumatic drills. The authors tested a water-powered hand-held drill in comparison to compressed-air jackleg drills in relation to: 1) penetration rate 2) energy consumption and 3) noise level to the operator. The tests concluded that the water-powered jackleg drill achieved faster penetration rates (approximately 10-30% higher than the pneumatic drills), along with less energy consumption (12 times less) and lower drilling costs (40% less). Additionally, a reduced noise level (11 to 25 dBA) and a reduced vibration level was achieved thru utilization of the water-powered jackleg drill.

Additionally, high pressure water jets to assist rotary drilling operations were examined by Hurel and Cagnioncle (17). The idea associated with this research was to extend the application of rotary drilling to harder and more abrasive rocks, by assisting conventional mechanical bits with high pressure water jets, since, for hard and abrasive rocks, recourse is taken to percussive drilling which involves disadvantages concerning both the level of the cost of the installation and the nuisances it produces (noise, vibration, dust, etc.). Laboratory tests examined the following mining applications: 1) blast hole drilling for driving galleries by the use of explosives and 2) drilling holes for roof bolting. The latter, drilling holes for roof bolting will be addressed due to the relevance to the research proposed. A test bench was set up and coupled with a data acquisition system which enabled the recording of thrust, force, rotation speed, pressure, rate of water flow, drilling penetration rate and energy consumption. The diameter of the roof bolting bits utilized for testing was 22 mm (0.87 inch). The testing program was developed to determine the advantages resulting from water jet assistance related to key drilling parameters (thrust, rotation speed, water pressure, etc.). The drilling tests were performed on rocks whose uniaxial compressive strength reached 190 MPa (approximately 28,000 psi). Results displayed the following: 1) the increase in flow rate, water pressure, etc. provided an increase in penetration rate, along with a decrease in cutting energy; 2) the water jet assistance was more efficient when the jets come thru the tungsten carbide inserts of the drill bit, allowing the high-pressure jets to act precisely in the area of contact between the rock and the drill bit, consequently acting upon the cutting process initiated by the tungsten carbide insert and 3) the orientation of the jets should be such that one is directed towards the perimeter of the drill bit and the other towards the hole axis. Testing of the water-jet design was also performed in a uranium mine. Three separate sites were chosen underground to verify that the drilling of holes for roof bolting was possible in different roof material in the mine workings. Drilling was performed on rock whose uniaxial compressive strength ranged between 50 and 200 MPa (7250 and 29,000 psi) and the water-pressure jet assistance was set to provide pressures between 220 and 240 MPa (32,000 and 35,000 psi). Results showed that in very hard rock strata, the penetration rate obtained was approximately 1.20 m/min (approximately 4 ft/min), whereas, in other bands, the penetration rate was measured to provide between 2 and 5 m/min (6.6 and 16.4 ft/min). Overall, the average penetration rate of drilled holes was approximately 1.80 m/min (approximately 6 ft/min). The penetration rates obtained for this study were comparable to those obtained with rotary percussion hammer drills utilized in the mine working.

This research effort will focus on evaluating and assessing several noise controls to be utilized during drilling activities in high compressive strength media (> 20,000 psi) associated with the roof bolting machine and then, consequently utilizing a modeling approach, predict sound pressure levels to roof bolting machine operators in an underground coal mine to examine noise exposure. The ultimate objective of the research is to provide the mining industry with valuable information to minimize or eliminate noise overexposure to roof bolter operators during the drilling portion of the work cycle of the machine.

CHAPTER 3

OBJECTIVE OF RESEARCH

The overall objective of the research is to determine, to characterize and to measure sound power levels radiated by a roof bolting machine during differing drilling configurations (thrust, rotational speed, penetration rate, etc.), along with utilizing a modeling approach for predicting sound pressure levels associated with roof bolter operators during the drilling cycle in high compressive strength rock media (>20,000 psi) utilizing the sound power level laboratory data measured. The determined sound power levels generated during the drilling cycle are of major interest because these levels represent the overall sound power being generated by the machine. These levels, determined from laboratory tests, can then be used to accurately assess the effectiveness of differing noise controls for reducing noise exposure to roof bolter operators. Utilizing sound power results obtained from the laboratory tests, a statistical model could then be developed for predicting sound power levels given differing drilling parameters (thrust, rotational speed, penetration rate, drill steel size and shape, drill bit size and drilling methods (vacuum, wet or mist). Additionally, utilizing the sound power levels related to differing drilling methods and parameters already determined and/or predicted, along with the utilization of knowledge related to the environmental noise characteristics associated with underground coal mining, sound pressure levels being experienced by roof bolter operators could then be determined and/or predicted to determine overall noise exposure using differing drilling configurations. The completion of the research will provide the mining industry with valuable information related to: 1) an understanding on how differing drilling configurations and drilling methods attribute to the sound power levels generated from a roof bolting machine while drilling into a high compressive rock media; 2) optimal drilling configurations and drilling methods in reducing sound power levels of the roof bolting machine; 3) a statistically valid equation for determining sound power levels of a roof bolting machine given differing drilling configurations and drilling methods; 4) a method for predicting sound pressure levels at the operator position and multiple locations in an underground mine related to the drilling cycle of a roof bolting machine and 5) a method for determining an operators' noise dosage relative to a roof bolting machine given any type of drilling configuration or drilling method utilized.

CHAPTER 4

SCOPE AND METHODS OF RESEARCH

The first phase of the research study was conducted in the PRL's reverberation room. The objective of the first phase was to conduct a myriad of sound power tests related to differing drilling parameters (thrust, rotational speed, penetration rate, drill steel size and shape, drill bit size) and drilling methods (vacuum, wet or mist) during the drilling cycle of a roof bolting machine in high compressive strength media (>20,000 psi). The laboratory results were then analyzed to provide the mining industry with valuable information related to optimum drilling configurations or parameters to be utilized when drilling into high compressive strength media (>20,000 psi) obtained from sound power levels collected in the laboratory. The second phase of the research was to use the data collected in the first phase of the research, and utilizing a modeling approach, predict the sound pressure levels the operator will experience in an underground coal mine in an effort in reducing noise exposure to the roof bolting operator. Procedures utilized for conducting the laboratory tests in the reverberation room are mentioned below.

4.1 Standard Operating Procedure for Conducting Noise Measurements (Sound Power) of Roof Bolting Machines in the Pittsburgh Research Laboratory's Reverberation Room

The following information presented below relates to the method used (utilizing the ISO 3740 series of acoustical standards) for determining sound power values (in 1/3 octave band frequencies) in the reverberation room at the Pittsburgh Research Laboratory (PRL) relative to the specific engineering noise control tests for the roof bolting machine.

4.1.1 Preface for Determining Sound Power Levels

The ISO 3740 series of acoustical standards specify various methods of determining the sound power levels of machines and equipment. The standards detail the acoustical requirements for the measurements appropriate for different test environments. Given the desired classification method for testing related to this research effort, the available test environment; a reverberation chamber, the expected characterization of the noise source; broad-band in frequency, and the desired output; A-weighted, octave and/or third octave sound power, the ISO 3743-2 (18) standard served as the reference standard for the research. The information discussed below relates to each section of the ISO 3743-2 standard and explains the rational behind the decisions made to meet the standard for testing the roof bolting machine in the reverberation room at PRL (19).

4.1.2 Introduction

The introduction of the standard lists the general guidelines to assist in selecting the most appropriate ISO 3740 series standard, given the purpose of the test and the testing conditions. The ISO 3743 standard explains conducting engineering grade experiments where A-weighted (replicates the human response of the ear) and octave band sound pressure levels are measured at prescribed microphone locations or along prescribed paths. The measurements are then used to calculate sound power levels. The standard methods are applicable for "small" machines, devices, components, and sub-assemblies, particularly those considered portable. The standard suggests that the device-under-test (DUT) (e.g. roof bolting machine) preferably be less than one percent of the test room volume but the standard does not specifically disallow the testing of larger devices. The ISO 3743-2 specifically documents requirements for testing in a special reverberation chamber, a facility that is available at the NIOSH-PRL and thus the ISO 3743-2 was considered the appropriate document to specify test procedures, analysis, and instrumentation specifications for this phase of the research study.

4.1.3 Scope

This section (scope) of the standard documents the engineering method to determine the sound power of small, movable noise sources in a specifically designed room having a specified reverberation time over the frequency range of interest. There are two test methods available, the direct and comparison method. The comparison method was selected for testing. The methods of the ISO 3743-2 are suitable for the measurement of all types of noise within a specified frequency range. The maximum volume of the device-under-test (DUT) and the lower limit of the frequency range for the test methods depend upon the volume of the test chamber. While the standard states that measurements on sources emitting noise below 200 Hz may be difficult, this statement assumes reverberation chambers much smaller than the chamber at the PRL. Table 4.1 provides the surface area and volume associated with the reverberation room at PRL. Additionally, Figure 4.1 represents a sketch of the reverberation room at PRL used for testing of the roof bolting machine.

Table 4.1 Reverberation Chamber-Surface Area and Volume

	Length (m)	Width (m)	Height (m)
Major chamber dimensions	18.31	10.37	6.73
	Surface Area (m^2)		**Volume (m^3)**
Front wall	69.80		1,277.84
Rear wall	78.02		
Right wall	123.22		
Left wall	132.99		
Floor	219.01		
Ceiling	189.84		
Chamber door protrusion	4.25		6.26
Trench	15.77		1.57
Left wall window	.43		0.07
Left wall entry door	1.03		.32
Right wall entry door	1.03		.32
TOTAL	**835.39**		**1,286.38**

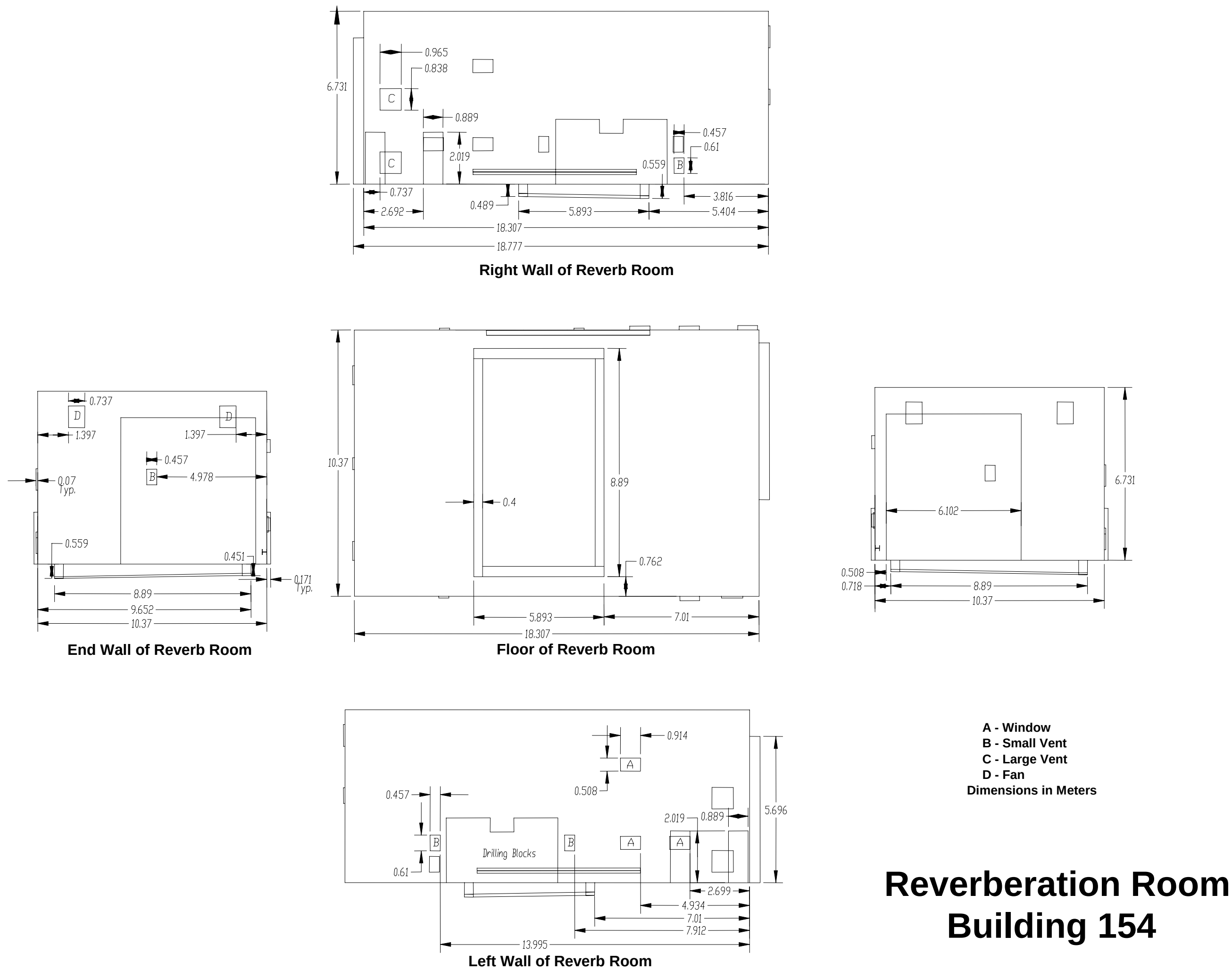

Figure 4.1 Plan view of the Reverberation Room at the PRL

The ISO 3743-2 standard also addresses measurement uncertainty. These uncertainties arise from several different factors, including environmental conditions and experimental techniques. Given the standard deviations of A-weighted (replicates the human response of the ear) sound power levels calculated from test results generated in the reverberation room utilizing a known noise or sound source, the standard deviations should not exceed those shown in Table 4.2. The cumulative effects of the measurement uncertainty in applying the procedures of ISO 3743-2 are taken into account in the standard deviations of Table 4.2 but they do not include changes in the DUT operating or mounting conditions. The measurement uncertainty depends on the standard deviation of reproducibility (σ_R) listed in Table 4.2 and the degree of confidence required. Given a normally distributed sound power spectrum, there is 90% confidence that the true sound power of a source lies within the range of $\pm$ 1.645 σ_R of the measured value and for a 95% confidence level, within $\pm$ 1.96 σR of the measured value.

Table 4.2 Estimated Values of the Standard Deviation of Reproducibility of Sound Power Levels

Octave Band Center Frequency (Hz)	**Standard Deviation of Reproducibility σ_R**
125	5.0
250	3.0
500 to 4,000	2.0
8,000	3.0
A-weighted	2.0

4.1.4 Normative References

Additional standards used in conjunction with the ISO 3743-2 standard are listed below.

Table 4.3 Normative References.

Number	Title
ISO 3741	Acoustics – Determination of sound power levels of noise sources Precision methods for broad-band sources in reverberation rooms.
ISO 3743-1	Acoustics – Determination of sound power levels of noise sources – Engineering methods for small, movable sources in reverberant fields – Part 1: Comparison method for hard walled test rooms.
ISO 3745	Acoustics – Determination of sound power levels of noise sources – Precision methods for anechoic and semi-anechoic rooms.
ISO 6926	Acoustics – Determination of sound power levels of noise sources – Requirements for the performance and calibration of reference sound sources.
ISO 7574-1	Acoustics – Statistical methods for determining and verifying stated noise emission values of machinery and equipment – Part 1: General considerations and definitions.
ISO 7574-4	Acoustics – Statistical methods for determining and verifying stated noise emission values of machinery and equipment – Part 4: Methods for stated values for batches of machines.
IEC 225	Octave, half octave and third-octave band filters intended for the analysis of sounds and vibrations.
IEC 651	Sound level meters.
IEC 804	Intergrating-averaging sound level meters.
IEC 942	Sound calibrators.

4.1.5 Definitions

A single definition is listed for a special reverberation test room. It is defined as "A test room meeting the requirements of this part of the ISO 3743-2". These are addressed in Section 4.1.6.

4.1.6 Requirements for a Special Reverberation Test Room

Guidelines for the design of a suitable test room, the reverberation time, and surface treatment are discussed within this section. The reverberation chamber walls and floor were designed to have Sabine absorption coefficients (the ratio of the sound energy absorbed by a surface of a medium or material to the sound energy incident on the surface) less than 0.16, meeting the requirements of the standard. Another issue relates to background noise, this ensures that at each microphone the background sound pressure level noise shall be at least four decibels (dB), and preferably ten decibels less than the DUT sound pressure level. Background noise is measured as part of the test procedure and past test results show that it is unlikely a problem will occur. There are also additional criteria listed for temperature and relative humidity. As stated in the standard, with the relative humidity expressed as a % and the temperature in degrees C, the product

$$\text{Relative Humidity} \times (\theta + 5 \text{ degrees C}) \qquad (1)$$

shall not differ by more than $\pm$ 10 % from the value of the product measured during the measurement of the reverberation time of the test room, where θ is the temperature in degrees Celsius. The temperature, relative humidity, and barometric pressure sensor data is fed into the data collection system to allow monitoring and recording of environmental data. Additionally, a four step process was utilized for testing the suitability of the test room. A small broad-band calibrated reference noise source was used following the procedures given in the standard ISO 6926 (20). Calibration report data, test data and the allowable difference between the two is provided in Table 4.4 below. The reverberation chamber passed the suitability test.

Table 4.4 Evaluation Test for the Suitability of the Test Chamber

Octave Band Center Frequency (Hz)	Calibration Report Sound Power Level (dB)	NIOSH Chamber Test Sound Power Level (dB)	Delta (dB)	Allowable Difference (dB)
125	83.1	83.1	0.0	± 5
250	84.7	84.7	0.0	± 3
500	85.4	85.4	0.0	± 3
1,000	89.1	89.1	0.0	± 3
2,000	90.1	90.1	0.0	± 3
4,000	87.8	87.9	0.1	± 3
8,000	84.3	83.6	0.7	± 4

4.1.7 Installation and Operation of Source Under Test

The acoustical properties of the reverberation chamber and the manner of source operation play a significant role in the sound power emitted by a device. The DUT shall be placed at one or more locations as if it were installed or used normally. If no such location may be found, then the DUT will be installed on the floor with at least one meter in distance between the DUT and the nearest wall. It may be necessary to test the DUT in multiple locations, if needed. Because roof bolter testing requires a rather large drill media, e.g. granite, as well as a large support stand, care must be taken to ensure that these do not radiate significant amounts of sound energy. To prevent this, the support stand, with the exception of its diagonal members and the short horizontal members along the minimum direction of the top of the structure, were filled with sand and two layers of urethane were bonded to the rock support members between the drill media due to a significant amount of vibration testing conducted (21). Finally, an additional layer of urethane was laid between the drill media and chain holding the media in place. All of this served to reduce vibration transmission and noise emission. See Section 4.2 - Modification of Steel Test Fixture for Roof Bolter Testing in the Reverberation Room.

During the measurements, the device was operated under normal conditions. Test parameters, e.g. rotation speed, thrust, etc., were selected beforehand and held constant before and while acoustical measurements were being made. These conditions were then reported.

4.1.8 Measurements in Test Room

The calculation of the approximate sound power level of the DUT is based on measured mean-square values of the sound pressure averages in time over an appropriate number of microphone positions within the test room. Each test shall last approximately 30 seconds.

No microphone position shall be closer to room boundaries than $\lambda/4$ where λ is the wavelength of the sound corresponding to the lowest third octave band frequency of interest (50 Hz). This value is d_λ and at 50 Hz, equals 1.72 meters. The minimum distance between any microphone position and the surface of the DUT is then calculated by:

$$d_{min} = 0.3 * V^{1/3} \qquad (2)$$

Where V, is the volume of the reverberation room

Or, for the NIOSH facility, d_{min} is 3.26 meters. The distance between any two microphone positions shall be at least $\lambda/2$, where λ is defined earlier. At 50 Hz, d_{min} equals 3.44 meters.

In summary,

Table 4.5 Minimum Distances of Microphones

Condition	Distance (meters)
Microphone to room boundary (50 Hz)	1.72
Microphone and surface of DUT	3.26
Microphone to microphone (50 Hz)	3.44

The number of microphone positions and source locations necessary to obtain the specified precision of the sound power levels depend upon the room and noise source properties. For each source, the minimum number of positions required in obtaining the specified standard deviations which are equal to or less than those given in Table 4.2 will be determined by the following. Given a particular DUT location, the sound pressure will be measured at six microphone locations that are spread throughout the reverberation chamber. An estimate of the standard deviation, s_M, in decibels, of the measured sound pressure levels will be established from the following equation.

$$s_M = (n\text{-}1)^{-1/2} \left[\sum_{i=1}^{n} (L_{pi} - L_p)^2 \right]^{½} \quad (3)$$

where

L_{pi} is the sound pressure level at the i^{th} measurement position (dB) (reference: 20 μPa)

L_p is the mean value of L_{p1}, L_{p2},…., L_{p6} (dB) (reference : 20 μPa)

n is the number of microphone positions, six.

The mean value, L_p shall be calculated by

$$L_p = 10 \log10[(1/6) * (10^{0.1Lp1} + 10^{0.1Lp2} +\ldots+ 10^{0.1Lp6})] \text{ dB} \quad (4)$$

The calculated values for s_M must be compared to the data listed in Table 4.6 to select a suitable combination of the minimum number of microphones, N_m, and source positions, N_s. Because the reverberation chamber is currently instrumented with fifteen microphones, 15 will serve as N_m, as this meets the requirements of the standard. Table 4.6 is used primarily to select, N_s, the minimum number of source positions for testing.

Table 4.6 Minimum Number of Source Locations

s_M (dB)	**Octave Band Frequency (Hz)**	**Number of Microphones, N_m**		
		3	**6**	**12**
		Minimum Number of Source Locations, N_s		
$s_M < 2.3$	125 to 8,000 and A-weighting	1	1	1
$2.3 \le s_M \le 4$	125	1	1	1
	250, 500, and A-weighting	2	2	1
	1,000 to 8,000	2	1	1
$s_M > 4$	125	3	2	2
	250 and A-weighting	4	3	2
	500	4	2	2
	1,000 to 8,000	3	2	1

The presence of irregularities in the frequency spectrum of an emitted sound can be determined from the values given above. Three ranges of the s_M are selected to define the presence of discrete frequencies or narrow bands of noise:

a) if $s_M > 4$ dB, a discrete tone may be present in the frequency band in question;

b) If 2.3 dB $\le s_M \le$ 4 dB, narrow-band noise components may be present in the frequency band in question;

c) If $s_M < 2.3$ dB, the frequency spectrum is probably broadband in nature.

The suspected presence of any narrow-band or discrete frequencies in the spectrum of the emitted sound will then be reported.

A third octave background noise level is measured at a minimum of twice per day, once in the morning and once in the afternoon. Additional measurements are taken if the background noise changes appreciably during the testing. The most recently collected background data will be included in each test report and will be used for a comparison with the DUT data and reference sound source data to determine the corrections for background noise. As per the 3743-2 standard, if the third octave background noise is less than four decibels below the reference sound source or the DUT, no data shall be reported without clearly stating that that the background noise requirements of the standard have not been met. This is not expected to be an issue for the roof bolter testing as the third octave roof bolter sound pressure levels are expected to greatly exceed the typical background noise levels. The corrections for background sound pressure levels and typical third octave background noise levels are given below in table 4.7 and typical background sound pressure noise levels are shown in table 4.8.

Table 4.7 Corrections for Background Sound Pressure Levels

Difference between sound pressure level measured with sound source operating and background sound pressure alone.	**Correction to be subtracted from sound pressure level measured with noise source operating to obtain sound pressure level due to noise source alone.**
4	2
5	2
6	1
7	1
8	1
9	0.5
10	0.5
> 10	0

Table 4.8 Typical Background Noise Sound Pressure Levels

Third Octave Band Frequency (Hz)	**Sound Pressure Level**		**Third Octave band Frequency (Hz)**	**Sound Pressure Level**	
	(dB)	**(dBA)**		**(dB)**	**(dBA)**
50	36.5	6.3	800	29.3	28.5
63	38.9	12.7	1,000	33.8	33.8
80	43.2	20.7	1,250	27.5	28.1
100	35.1	16.0	1,600	23.8	24.8
125	44.0	27.9	2,000	22.2	23.4
160	32.3	18.9	2,500	21.3	22.6
200	32.7	21.8	3,150	18.4	19.6
250	35.8	27.2	4,000	15.2	16.2
315	31.0	24.4	5,000	12.8	13.3
400	33.9	29.1	6,300	11.0	10.9
500	31.1	27.9	8,000	10.9	9.8
630	27.8	25.9	10,000	10.0	7.5

4.1.9 Calculation of Sound Power Levels

From the measured one-third octave band sound pressure levels and the calculated third octave band sound pressure levels for frequency bands of interest, the mean overall value, in decibels, shall be calculated by;

$$L_p = 10 * \text{Log}[\ (1/n) * (10^{\ 0.1Lp1} + 10^{\ 0.1Lp2} + \ldots + 10^{\ 0.1Lpn})\ ] \qquad (5)$$

where

L_{p1} is the third octave band level or A-weighted level for the first measurement (dB)

L_{pn} is the third octave band level or A-weighted level for the n^{th} measurement (dB)

n is the total number of measurements for a particular third octave band or with the A-weighted network inserted.

To conduct the comparison method for determining sound power, a Bruel & Kjaer 4204 reference noise source will be placed on the floor of the test room at least 1.5 meters from any wall. The mean sound pressure level in each third octave band will then be determined and any background noise corrections will be performed if necessary, using the calculation procedure provided earlier. Then, the sound power level produced by the DUT will then be determined, L_{we}, in decibels (reference: 1 pW) for each third octave band as follows. Subtract the band pressure level produced by the reference noise source, L_{pr} (after background noise corrections) from the know sound power level produced by the reference noise source and then add the difference to the band pressure level of the DUT, L_{pe}, (after corrections for background noise), i.e.;

$$L_{we} = L_{pe} + (L_{wr} - L_{pr}) \quad (6)$$

Where

L_{pe} is the mean band pressure level of the DUT (dB) (reference: 20 uPa)

L_{wr} is the band power level of the reference noise source (dB) (reference: 1 pW)

L_{pr} is the mean band pressure level of the reference noise source (dB) (reference: 20 uPa)

4.1.10 Information to be Reported for Each Test Condition

The report for each test will state whether or not the reported sound power levels have been obtained in full conformity with the requirements of the ISO 3743-2 standard as mentioned in previous sections. The report for each test will provide the sound power levels in decibels referenced to one pW (picowatt). Sound level exposure of mining machine operators is determined both by the sound power radiated by the machine and by the acoustic characteristics of the mine environment. The sound power is the quantity of most interest, because this information provides the sound radiated by the machine. Once the sound power is known, the sound pressure level that the operator would experience can be predicted or determined based on the acoustic characteristics of the environment. Sound power gives a direct comparison of noise for any machine tested under the same conditions. An example of this data (report summary) for each test to be conducted (testing plan) in the reverberation room for the roof bolter testing is shown below:

Table 4.9 Example of Reported Information for each Sound Power Test

SOUND POWER MEASUREMENT REPORT

SOUND POWER MEASUREMENT AS PER THE ISO 3743-2 (comparison method)

TEST SPECIFICATIONS		REFERENCE SOURCE SPECIFICATIONS	
DATE	3/20/03	MANUFACTURER	Bruel & Kjaer
LOCATION	PRL reverberation room, Bldg 154	TYPE	4204
OPERATOR	J. Shawn Peterson	TECHNICAL COMMENTS	Last calibrated 12/20/02, certificate number P101784-1
COMMENTS	none		
		SERIAL NUMBER	955307

SOURCE SPECIFICATIONS					
DEVICE	roof bolter		X	Y	Z
TECHNICAL COMMENTS	none				
MANUFACTURER	J. H. Fletcher	LOCATION(S) OF SOURCE	9.0	6.0	1.0
SERIAL NUMBER	93070/20000332				
YEAR OF MANUFACTURE	2002	LOCATION(S) OF REFERENCE SOURCE	12.0	4.0	0.0
OPERATION CONDITIONS	normal		LENGTH (M)	WIDTH (M)	HEIGHT (M)
MOUNTING CONDITIONS	N/A	SOURCE DIMENSIONS	9.0	4.0	1.5

ACOUSTICAL ENVIRONMENT							
	LENGTH (M)	WIDTH (M)	HEIGHT (M)		PRE-TEST		POST-TEST
CHAMBER DIMENSIONS	18.3	10.4	6.7	AIR TEMPERATURE ©	22.3		22.3
CHAMBER WALL SURFACES (METERS SQUARED)	RIGHT	123.2		AMBIENT PRESSURE (Pa)	978.0		978.0
	LEFT	133.0		RELATIVE HUMIDITY (%)	66.4		66.9
	FRONT	69.8					
	REAR	78.0					
	TOTAL	404.0					

INSTRUMENTATION			
MANUFACTURER	Bruel & Kjaer	CALIBRATION : DATE	8/9/02
NAME	Multi-channel Pulse	CALIBRATION : PLACE	Bruel & Kjaer
TYPE	3560E	CALIBRATION : METHOD	Calibration procedure 704823
SERIAL NUMBER	2361569		

TEST PARTICULARS			
TEST TYPE	dry	ROCK COMPRESSIVE STRENGTH (psi)	23,000
BIT MANUFACTURER	Brady	THRUST (lbs)	5,280
		ROTATION SPEED (rpm)	300
BIT TYPE	carbide	WATER PRESSURE (psi)	80
DRILL STEEL TYPE	hexagonal	WATER FLOW (gal / min)	1
DRILL STEEL SIZE (dia.)	1 inch	MIST WATER FLOW (qt / min)	1

Table 4.10. One-third octave sound power levels determined for a specific test (numeric)

OVERALL THIRD OCTAVE SOUND POWER LEVELS

Band (Hz)	100	125	160	200	250	315
Level (dB re 1 pW)	103.7	106.1	108.2	109.9	109.0	106.9

Band (Hz)	400	500	630	800	1000	1250
Level (dB re 1 pW)	109.0	110.7	110.2	110.9	109.6	109.8

Band (Hz)	1600	2000	2500	3150	4000	5000
Level (dB re 1 pW)	108.3	107.8	105.1	104.6	101.6	98.5

Band (Hz)	6300	8000	10000	A	L	
Level (dB re 1 pW)	98.5	92.9	89.2	118.9	120.7	

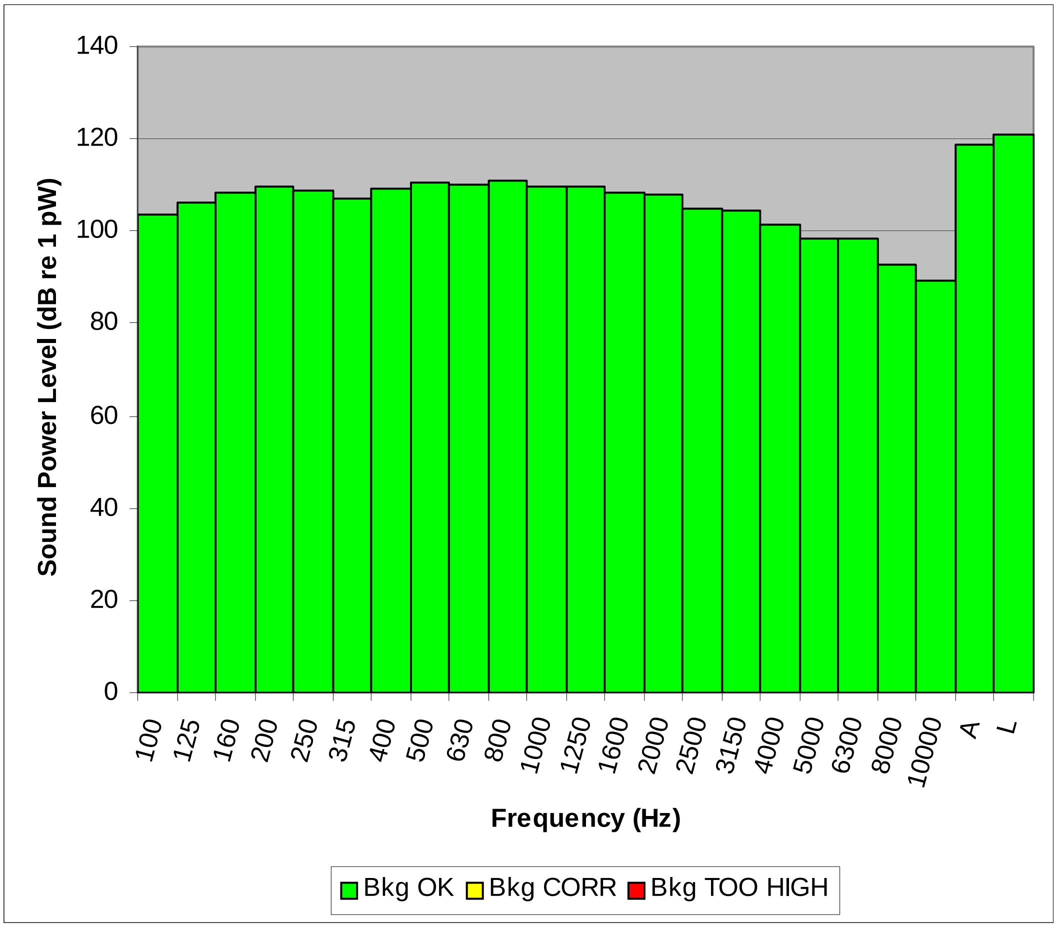

Figure 4.2 One-third Octave Sound Power Levels Determined for a Specific Control Test

4.2 Modification of Steel Test Fixture Used for Roof Bolter Testing in the Reverberation Room

4.2.1 Objective

The sound power levels radiated by a roof bolting machine were evaluated by drilling into high compressive strength rock media (>20,000 psi) in the reverberation chamber. The rock media was supported on a steel structure that is comprised of rectangular tubes as shown in figure 4.3.

Figure 4.3 Test Fixture in Reverberation Room.

It was necessary to insure that the test fixture did not make a significant contribution to the sound power radiated during actual testing. Initially, the tubes were hollow and the rock was placed directly on the rock support tubes and held in place by a tensioned chain. The objective of the tests performed was to assess the potential sound power radiated by the rock support during drilling as discussed below. Then, modifications to the structure were performed to reduce the sound power radiated by the rock support. The tests performed are described below.

4.2.2 Tests Performed to Assess Sound Power Radiated from Test Fixture

Two types of tests were performed to assess the performance of the rock support structure before any modifications to the fixture were performed (21). First, Frequency Response Function (FRF) measurements were performed at several locations on the test fixture. The rock was placed directly on the rock support tubes and held in place with a tensioned chain. An instrumented impact hammer was used to apply an input force to the structure and accelerometers were used at several locations to measure the vibratory response of the structure. The input was then randomly moved to each accelerometer location to measure FRFs in g/N. The accelerometers were located and oriented as follows:

1. Top Horizontal Tube at 34.5” from the end oriented to measure in the Y direction.
2. Top Horizontal Tube at 34.5” from the end oriented to measure in the Z direction (vertical).
3. Middle Horizontal Tube at 34.5” from the end oriented to measure in the Y direction.
4. Middle Horizontal Tube at 34.5” from the end oriented to measure in the Z direction (vertical).
5. Rock Support Tube #7 at 20.5” from the end oriented to measure in the X direction.
6. Rock Support Tube #7 at 20.5” from the end oriented to measure in the Z direction (vertical).
7. Vertical Support Tube at 20.5” from the top end oriented to measure in the X direction.

8. Vertical Support Tube at 20.5” from the top end oriented to measure in the Y direction.

Figure 4.4 below displays location of support tubes on the test fixture along with the specific accelerometer locations.

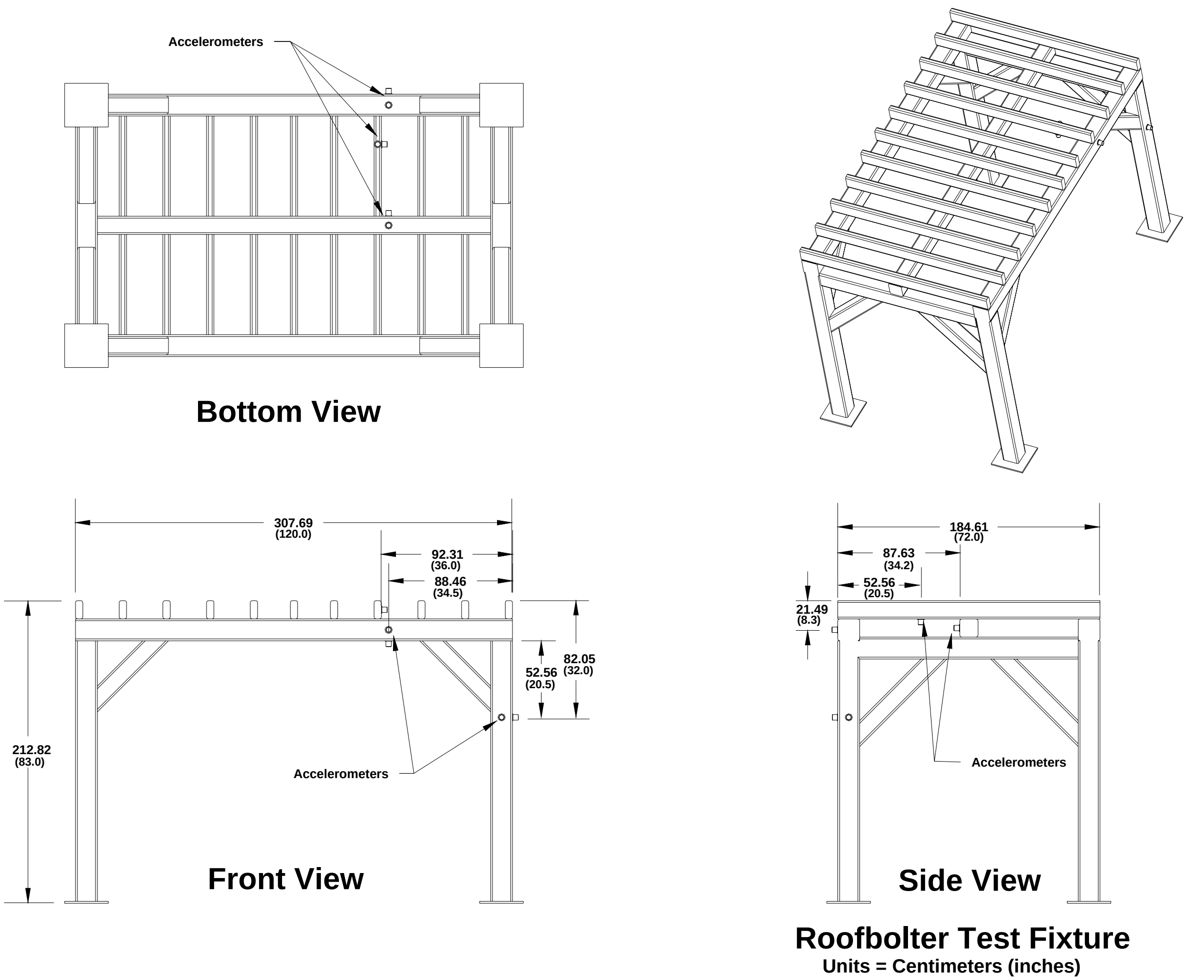

Figure 4.4 Location of Test Fixture Support Tubes and Accelerometers

The hollow tubes were then filled with sand, except for the diagonal tubes and the horizontal tubes along the short direction at the top of the structure. This was done for two reasons: convenience and to create an impedance mismatch in the structure to reduce vibration transmission. In addition to filling the tubes, two layers of a urethane material were bonded to the rock support tubes to break direct contact between the rock and the structure. Finally, a layer of urethane was placed between the rock and the chain.

After measuring the FRFs in g/N, software was used to integrate the FRFs to provide the data into units of velocity per unit force: mm/s/N. Velocity-based (mobility) FRFs are better suited to judging noise radiation because the sound power radiated by an object is related to the surface averaged mean square velocity. After measuring the velocity-based (mobility) FRFs, a hole was drilled and the accelerations were measured at each of the accelerometer locations. An A-weighting filter was applied to the digital data in the time domain and the signals were integrated to obtain the A-weighted vibration velocity at each accelerometer location.

Software was then used to compute the 1/3-octave spectra with slow time weighting and RMS averaging for each time history. Finally, the A-weighted sound power radiated by the test fixture while drilling was calculated based on the data before and after the modifications using ISO/CD 7849 (22). The A-weighted sound power was used instead of the linear sound power because A-weighting is the frequency weighting that closely approximates the frequency response of the human ear. The influences of low and high frequencies are reduced in comparison to midrange frequencies because people are most sensitive to midrange sounds. Therefore, the sound power can be calculated from:

$$L_w = \overline{L_v} + 10\log\left(\frac{S}{S_0}\right) \qquad (7)$$

where

$\overline{L_v}$ is the surface average velocity level with a reference of 50 nm/s

S is the surface area

S_0 is the reference surface area of $1m^2$.

The above equation was derived assuming a radiation efficiency of 1 and standard atmospheric conditions. It was unlikely that the radiation efficiency would be 1 at all frequencies, however, since the interest is the maximum sound power that can be radiated, this assumption would skew the estimate to the conservative side. Figure 4.5 shows the estimate of the sound power radiated by the test fixture before and after the modifications. The figure shows that the most significant sound power radiated by the fixture before the modifications is in the 1600 and 2000 Hz 1/3-Octave bands. The figure also shows that with the modifications, the highest 1/3-Octave A-weighted sound power level would be in the 1600 and 2000 Hz 1/3-Octave bands. However, the modifications reduced the sound power level radiated to under 60 dBA (30 dB) in all bands. Since it was likely that the drill will radiate much higher sound power levels, the fixture would not be a significant factor.

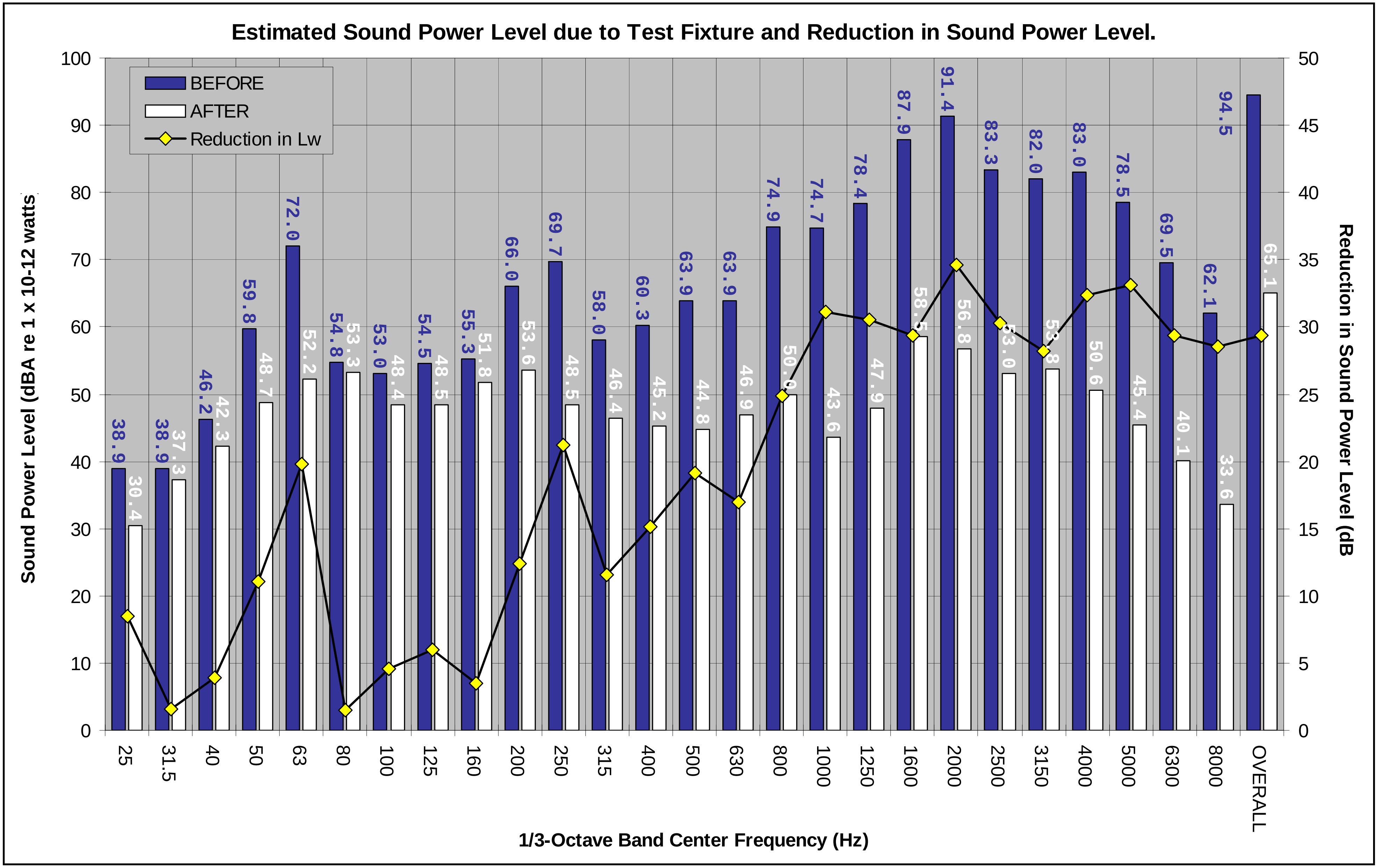

Figure 4.5 Estimated A-weighted Sound Power Level and Reduction in Estimated Sound Power Level Before and After Modification

4.2.3 Conclusions

Velocity based FRFs indicated that filling the test fixture with sand significantly increased the damping of the structure. Subsequent recordings of accelerations at several locations showed that the vibration was significantly reduced for drilling conditions due to the added sand and isolating the rock from the test fixture. The procedure for estimating the sound power radiated from a structure using vibration data was followed to estimate the sound power level radiated by the fixture during drilling before and after the modifications. Before the modifications, the estimated sound power level radiated by the fixture exceeded 90 dBA in the 2000 Hz 1/3-octave band. After the modifications, the estimated sound power level for all 1/3-octave bands was below 60 dBA. Since the sound power level radiated by the roof bolting machine was expected to be much higher (more than 20 dBA) than 60 dBA, the test fixture was no longer a significant contributor to the sound power determined in the reverberation room, therefore sound power levels determined, will only be attributed to the activity of the roof bolting machine.

4.3 Sound Power Level Testing in Reverberation Room

Sound power level testing was conducted in the reverberation room. Sound power level determination in a reverberant field is one of several methods available to calculate the noise emission of equipment and the reverberation room at the PRL has a unique facility which facilitates these measurements (figure 4.6).

Figure 4.6 Reverberation Room at PRL

Further, a state of the art data collection, analysis, and reporting system is in place and allows for high throughput, i.e., a significant amount of testing may be conducted, from data collection to a detailed test report, within a short period of time (figure 4.7).

Figure 4.7. Bruel & Kjaer Pulse Data Acquisition System

As mentioned previously, the sound power level data collected, will be related to differing drilling parameters (thrust, rotational speed, penetration rate, drill steel size and shape, drill bit size) and drilling methods (vacuum, wet or mist) associated with the roof bolting machine during drilling operations in high-compressive strength (>20,000 psi) rock media. The reverberation room was used to determine the sound power generated by the roof bolting machine in relation to the type of drilling procedure utilized for drilling a bolt hole. Numerous tests were performed to determine the effectiveness of each possible noise control related to the overall sound power generated for each testing condition. Table number 4.11 below demonstrates the different tests conducted (rotational speeds and thrust configurations) for dry, wet and mist system drilling methods in high compressive strength rock media (>20,000 psi), along with the specific data collected for each test configuration. Additionally, the following sections illustrate how the selected drilling parameters (thrust, rotational speed and penetration rate) were set and determined for the differing testing conditions.

Table 4.11 Test Data Collected During Sound Power Level Testing

Vacuum, Wet or Mist	Kennametal
Manual	Carbide
Granite	1 or 1.375

SET POINTS		AVERAGE		SOUND POWER LEVEL		PENETRATION	
(lbs)	(rpm)	(lbs)	(rpm)	(dB)	(dBA)	(in)	(in/sec)
setthrst	setspd	avthrust	avspeed	spdb	spdba	pendepth	penrate
2,121	200						
	300						
	400						
	500						
	600						
2,828	200						
	300						
	400						
	500						
	600						
3,535	200						
	300						
	400						
	500						
	600						
4,242	200						
	300						
	400						
	500						
	600						
4,949	200						
	300						
	400						
	500						
	600						
5,656	200						
	300						
	400						
	500						
	600						
6,363	200						
	300						
	400						
	500						
	600						

4.3.1 Setting of Thrust Configurations

The thrust setting on the bolting machine was set utilizing the following steps displayed below:

1) Verify the required thrust pressure required for the specific test configuration.

2) Determine the existing thrust setting.

   a. Push the enable button on the operator joystick (figure 4.8), then push the joystick forward, causing the drill head to move up and contact the center beam of the test fixture. The mast should be located in a position which will allow the drill head to fully contact the center beam of the test fixture (figure 4.9).

Figure 4.8 Joystick on Control Panel

Figure 4.9 Drill Mast of Roof Bolting Machine Raised to Test Stand

b. While continuing to push forward on the operator joystick, examine the thrust pressure gauge located to the left of the hydraulic controls. Note the pressure.

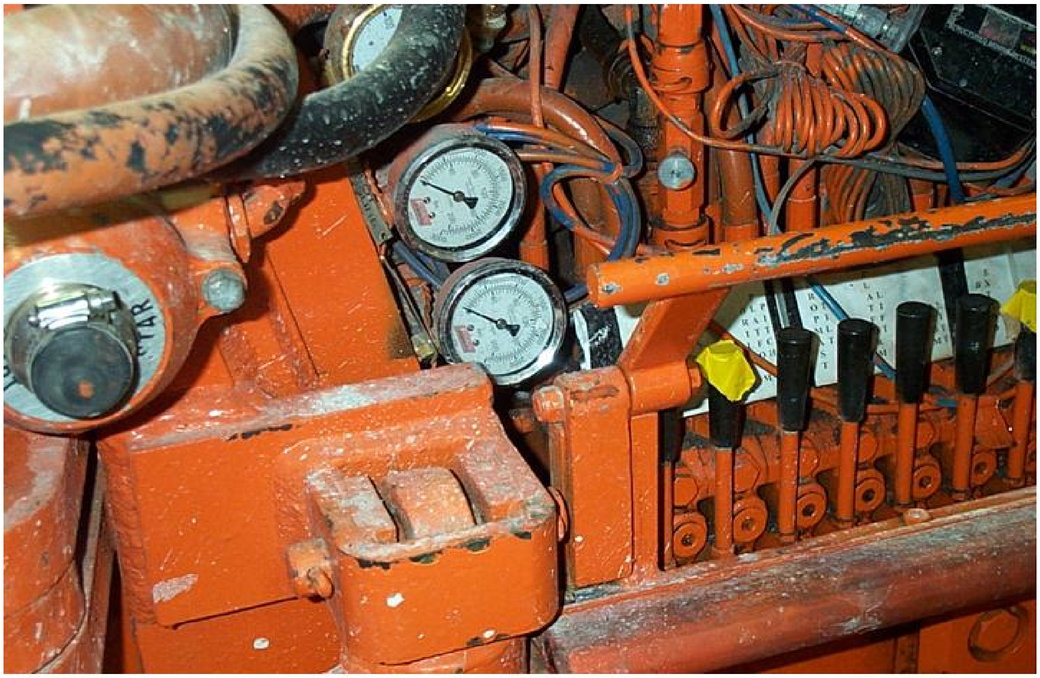

Figure 4.10 Location of Thrust Pressure Gauge

c. Determine direction to turn manual relief valve to reach desired thrust pressure (figure 4.11).

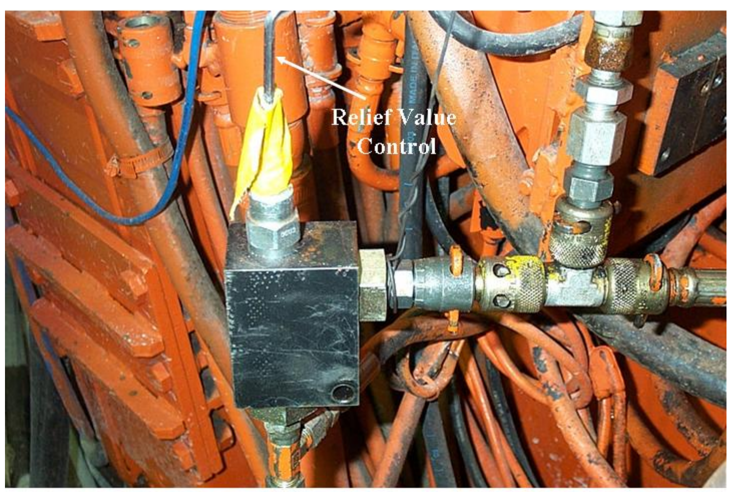

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Figure 4.11 Location of Relief Valve Control

d. If desired thrust pressure is lower than existing pressure, reduce the pressure by turning the allen-wrench in a counter-clockwise direction.

e. If desired thrust pressure is higher than existing pressure, increase pressure by turning allen-wrench in a clockwise direction.

f. Follow steps a and b mentioned above to verify new pressure setting.

g. If thrust setting does not match desired test pressure repeat steps above until desired setting is obtained.

4.3.2 Setting Rotational Speed Configurations

The rotational speed was measured utilizing a pulser disk, electro-sensors and a signal conditioner (figure 4.12.). The pulser disk mounts on the roof bolting machine chuck, therefore the drill steel passes through a hole in the disk. Embedded in the disk are magnets that are sensed when the drill chuck rotates. The sensor signal is then transmitted to the signal conditioner unit, which displays the rotation speed in Hz, or magnetic pulses per second. The signal conditioner has a 0-10 Vdc output, scaled to Hz. This dc output is fed into the Bruel and Kjaer Pulse system and scaled into engineering units, represented by rpm.

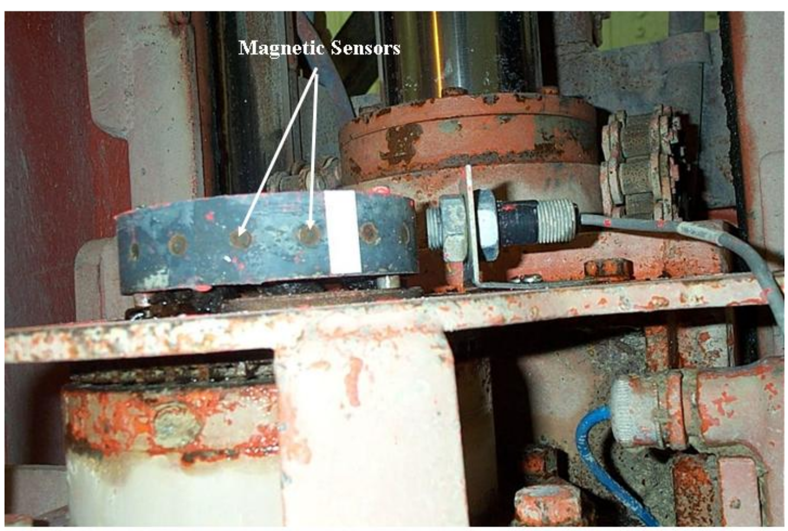


Figure 4.12 Pulser Disk and Electro-sensors Mounted on Drill Chuck

The scaling associated with the rotational speed system is shown below:

0 – 240 Hz = 0 – 1,800 rpm = 0 – 10 Vdc out or;

1 Hz = 7.5 rpm or;

1 rpm = 5.556 mVdc out

Thus, the Bruel and Kjaer Pulse system then scales 5.556 mVdc to 1 rpm.

4.3.3 Determining Penetration Rate or Displacement During Testing

To determine penetration rate during testing a string potentiometer was installed on the roof bolting machine (figure 4.13).

Figure 4.13 Location of String Potentiometer for Determination of Penetration Rate

The unit output voltage varied linearly with the distance the cable was displaced and was usable from two to eighty inches. The unit was installed on the bottom of the roof bolting machine with the cable attached to the chuck. The output voltage was then fed into the Bruel and Kjaer Pulse system per the calibration reports provided for the instrument.

4.3.4 Pulse System and Excel Data Collection Common to Speed and Displacement

Data acquisition in the pulse system was started via a Visual Basic code launched in Excel. Speed and displacement data was fed into the pulse system and were displayed in windows in engineering units. Information in the pulse system was dynamically linked to the Excel spreadsheet and updated once per second. Once data collection was initiated in Excel, Visual Basic code reviewed the Excel cells containing the most recently collected speed, displacement, and time data and then copied the results to a table in the Excel worksheet, and then moved down into the next row. One second later, the dynamically linked data was updated, and the process repeated itself, adding rows of time, speed, and displacement data. This was plotted in essentially real time in Excel. Once the test was completed, an average of the speed data was calculated and used for the test report. The change in displacement and time were calculated and used to calculate the penetration rate, again for the test report. An example of a test report for one specific test is displayed below (figure 4.14).

Test Report

Test Type **:** wet
Test Mode **:** manual
Material **:** granite
Compressive Strength (lbs) **:** 21,000

Bit Manufacturer **:** A
Bit Type **:** carbide
Bit Size (in) **:** 1

Drill Steel **:** round

Water Flow Rate (gal/min) **:** 3 g/m
Mist Flow Rate (qt/min) **:** N/A

Set Thrust (lbs) **:** 2,828
Average Thrust (lbs) **:** 3,113

Set Rotation Speed (rpm) **:** 500
Average Rotation Speed (rpm): 508

Penetration Rate (in/sec) **:** 0.434

Sound Power (dB) **:** 105.9
Sound Power (dBA) **:** 105.4
Time (sec) **:** 30.0

Figure 4.14 Example of a Test Report – Sound Power

4.4 Rock Media and Strength Property Testing of Drilling Media

4.4.1 Type of Rock Media

As mentioned earlier, for phase 1 of the research, differing drilling parameters were tested to determine sound power levels of the roof bolting machine during drilling into high compressive strength media (>20,000 psi). The type of material tested and utilized during phase 1 of the research study was Barre Gray Granite as shown in figure 4.15 below.

Figure 4.15 Barre Gray Granite – Rock Media Used for Testing in Phase 1

4.4.2   Obtaining Rock Cores of Drilling Media

The rock media, Barre Gray Granite, was core drilled at the laboratory to obtain rock samples for rock strength testing. The individual rock samples were then tested in the rock mechanics lab to determine significant rock properties, such as unconfined compressive strength, used during noise testing in the reverberation room. Figure 16 below displays several core samples obtained from the drilling of the Barre Gray Granite, rock media type used for phase 1 of the research study.

Figure 4.16 Sample of Core Collected from Barre Granite Rock Media

4.4.3 Unconfined Compressive Strength Testing of Rock Media

The rock cores obtained from the drilling procedure were then prepared and tested for rock strength properties (unconfined compressive strength). Dependent upon the size of samples available, the number of strength properties varied. The test procedures utilized adhered to the ASTM standards and were conducted on cores of 2-in in diameter. Results of the testing are shown in table 4.12 below.

Table 4.12 Unconfined Compressive Strength Results of Barre Gray Granite

Specimen Number	**Length (L), inches**	**Diameter (D), inches**	**L/D Ratio**	**Area (A) in^2**	**Load at Failure (P), pounds**	**Compressive Strength (C), psi**	**Corrected Compressive Strength (C∘), psi**
D1	4.006	1.990	2.013	3.109	71,900	23,126	23,144
D2	3.997	1.990	2.009	3.109	72,880	23,442	23,454
D3	4.001	1.992	2.009	3.117	75,920	24,360	24,373
AVERAGE					73,567	23,643	**23,657**

The average unconfined compressive strength of all cores tested was 23,657 psi, approximately 24,000 psi for the Barre Gray Granite rock media.

4.5 Testing of Differing Bits and Drill Steel

4.5.1 Drill Bits

A variety of types and sizes of drill bits are being utilized in the mining industry today during roof bolting operations (figure 4.17).

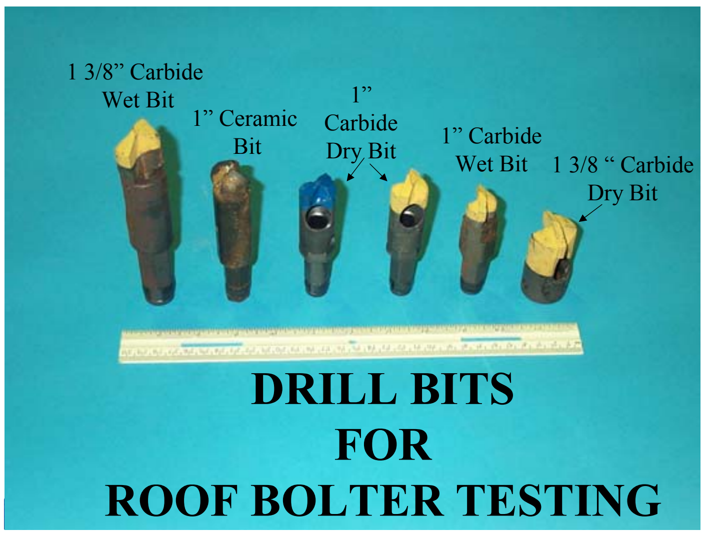


Figure 4.17 Types of Drill Bits Used During Roof Bolting Operations

Critical information related to the type and/or size of bits in relation to noise output is very limited in the mining industry today. Noise testing was performed in the reverberation room on a variety of differing types and sizes of drill bits. The different types of drill bits tested included:

- 1-inch and 1 3/8-inch carbide bit used during dry drilling operations (new bit used for each test).
- 1-inch and 1 3/8-inch carbide bit used during wet drilling operations (including mist-system technology) (new bit used for each test)

4.5.2 Drill Steel

The mining industry utilizes different types of drill rod during roof bolting operations. Significant information related to the type and/or size of drill steel in relation to noise output is unidentified in the mining industry today. Noise testing was performed in the reverberation room on a variety of differing types and sizes of drill steel. The different types of drill steel tested (figure 4.18) for noise generation included:

- 1 inch and 1 3/8 inch round drill steel
- 1 inch and 1 3/8 inch hex drill steel

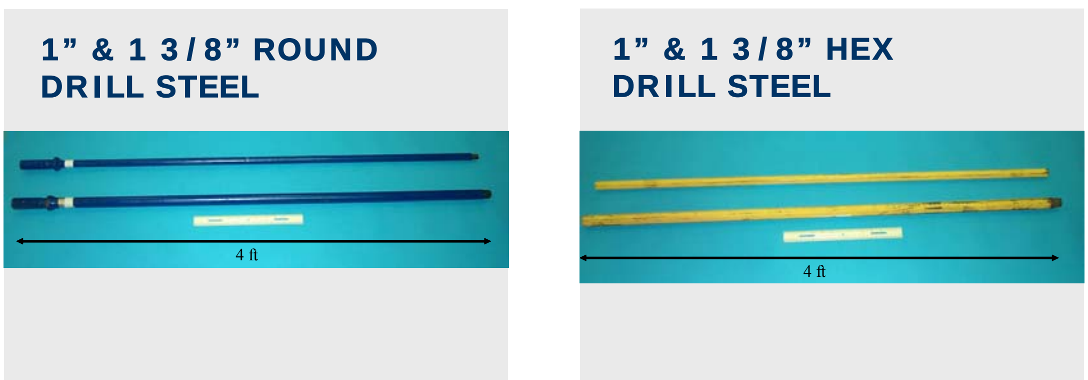


Figure 4.18 Types of Drill Steel Used During Roof Bolting Operations

4.6 Testing of Different Drilling Methods

4.6.1 Dry (Vacuum), Wet and "Mist" Systems

During roof bolting operations, drilling of the immediate roof occurs by drilling the bolt hole dry (vacuum) or using water as a drilling fluid. Tests were conducted in the reverberation room to determine if the use of water during the drilling technique of a roof bolting operation minimizes noise output associated with the procedure. Noise testing was performed during dry and wet drilling operations. During wet drilling operations, differing flow rates of water was tested for noise characteristics. Additionally, the use of a "mist" system was also incorporated in the wet drilling tests to minimize the flow of water to the bit. The "mist" system is designed to provide minimal flow (e.g. quart/minute of water) to the bit, reducing the potential hazard of extreme amounts of water affecting the roof bolter operator. The "mist" system utilized a system of compressed air and water input for providing minimal flow rate to the bit. Figure 4.19 displays a photograph of the "mist" system used during noise testing.

Figure 4.19 Photograph of "Mist" System Used During Noise Testing

4.7 Summary of Tests Conducted in the Reverberation Room

In summary, a total of approximately 500 noise tests (determination of sound power) were performed to characterize the differing noise controls associated with roof bolting operations in high compressive strength rock media (>20,000 psi). All tests were performed in the Pittsburgh Research Laboratory's Reverberation Room to determine sound power levels, during drilling operations, associated with the following characteristics:

- Vacuum (dry) Drilling
- Wet Drilling (3 gallons of water per minute to drilling bit)
- Mist System (3 quarts of water per minute to drilling bit)
- Round Drill Steel
- Hex Drill Steel
- Drill Bit Size (1-inch and 1 ⅜-inch)
- Manual Drilling (differing thrust, rotational speed and penetration rate drilling parameters)

Please note, sound levels experienced by a roof bolter operator are determined both by the sound power radiated by the drilling operation and by the acoustic characteristics of the mine environment. The sound power is the quantity of most interest, because this information provides the sound radiated by the drilling procedure related to any utilization of engineering noise controls. Because of all the variations both geometrically and acoustically in underground mines it would be difficult to achieve uniform test conditions in an underground mine setting. Additionally, it would be impossible to control the acoustic environment underground, which would make it difficult to evaluate the roof bolting machine and its components for noise levels. Therefore, testing was conducted in the Pittsburgh Research Lab (PRL) Reverberation Chamber for sound power levels generated from the roof bolting machine. Utilizing the reverberation chamber provided the determination of sound power radiating from the machine in a controlled acoustic environment and would be independent of the many differing variables associated with the underground mining environment. The determination of sound power in the reverberation room provided a direct comparison of noise for any engineering noise controls tested during each individual test. The preceding chapter, Chapter 5, displays the data collected for all sound power tests conducted in the reverberation room, along with the methods and the applications used in determining constructive results related to the assessment of noise control technologies related to drilling operations associated with the roof bolting machine.

As mentioned earlier, testing noise control technologies related to the roof bolting machine were conducted in the reverberation room due to the varying geometries and the acoustical characteristics associated with underground coal mines. Chapter 6 provides a methodology for characterizing the acoustical uniqueness of an underground coal mine and with the use of an acoustical model, provides the ability of the user to predict the sound pressure level the roof bolting machine operator would experience, given the measured sound power levels collected from the laboratory (reverberation room). The model provides the mining community with a state-of-the-art opportunity to examine and measure sound power in the laboratory (related to engineering noise controls) and then directly associate or correlate the measured value to a sound pressure level experienced by the operator of a specific mining machine, specifically, the roof bolting machine, in determining overexposure to noise.

CHAPTER 5

APPLICATIONS OF SOUND POWER LEVEL MEASUREMENTS CONDUCTED IN THE REVERBERATION ROOM

As mentioned in Chapter 4, a total of approximately 500 noise tests (determination of sound power) were performed to characterize the differing noise controls associated with roof bolting operations in high compressive strength rock media (>20,000 psi). All tests were performed in the Pittsburgh Research Laboratory's Reverberation Room to determine sound power levels of roof bolting operations associated with the following characteristics:

- Vacuum (dry) Drilling
- Wet Drilling (3 gallons of water per minute to drilling bit)
- Mist System (3 quarts of water per minute to drilling bit)
- Round Drill Steel
- Hex Drill Steel
- Drill Bit Size (1-inch and 1 ⅜-inch)
- Manual Drilling (differing thrust, rotational speed and penetration rate drilling parameters)

5.1 Drilling Components and Parameters Utilized for Testing

In formulating a conservative test plan, it was decided to use drilling components and parameters that were representative of industry usage. These are listed below in Table 5.1.

Table 5.1 Variables for Sound Power Level Testing

Item	Units	Values
Drilling type	-----	vacuum, mist @ 3 qt/min, wet @ 3 gal/min
Drill steel	-----	round, hexagonal
Drill bit size	in	one, one and three-eighths
Rotation speed	rpm	200, 300, 300, 400, 500, 600
Thrust	lbs	2,121, 2,828, 3,535, 4,242, 4,949, 5,656*, 6,363*

- * One and three-eighths inch (1 3/8”) bit size only, due to safety limitations.

Various combinations of these parameters are shown in table 5.1, in which, comprise the test configurations related to the testing of the high compressive strength rock media (>20,000 psi). Data was not obtained or collected for tests utilizing a 1-inch bit and 1-inch drill steel at thrust settings 5,656 and 6,363 lbs respectively due to safety concerns when drilling into the high compressive strength media and using a 1-inch drill steel. Additionally, several data points were not collected where thrust settings were low (2,121, 2,828 and 3535 lbs) and rotational speeds were high (500 and 600 rpm) due to ineffective performance of the drilling process. Additionally, the penetration depth (inches) was measured for each test and consequently the penetration rate (inches/second) for each test was determined or measured and displayed in the following tables listed below.

5.2 Data Collected for Sound Power Level Tests

Data collected for all sound power level tests conducted are shown in the following tables:

- Table 5.2 – Vacuum drilling method, 1-inch bit, round drill steel
- Table 5.3 – Vacuum drilling method, 1-inch bit, hex drill steel
- Table 5.4 – Vacuum drilling method, 1-3/8-inch bit, round drill steel
- Table 5.5 – Vacuum drilling method, 1-3/8-inch bit, hex drill steel
- Table 5.6 – Wet drilling method (3 gal/min), 1-inch bit, round drill steel
- Table 5.7 – Wet drilling method (3 gal/min), 1-inch bit, hex drill steel
- Table 5.8 – Wet drilling method (3 gal/min), 1-3/8-inch bit, round drill steel
- Table 5.9 – Wet drilling method (3 gal/min), 1-3/8-inch bit, hex drill steel
- Table 5.10 – Mist drilling method (3 qt/min), 1-inch bit, round drill steel
- Table 5.11 – Mist drilling method (3 qt/min), 1-inch bit, hex drill steel
- Table 5.12 – Mist drilling method (3 qt/min), 1-3/8-inch bit, round drill steel
- Table 5.13 – Mist drilling method (3 qt/min), 1-3/8-inch bit, hex drill steel

Tables 5.2 thru 5.13 are shown respectively on the following pages.

Table 5.2 Sound Power Level Testing – Vacuum Method, 1-inch bit, Round Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs)	SPEED (rpm)	THRUST (lbs)	SPEED (rpm)	LINEAR (dB)	A-WGT (dBA)	DEPTH (in)	RATE (in/sec)
setthrst	setspd	avthrust	avspeed	spdb	spdba	pendepth	penrate
2,121	200	2,239	209	106.8	106.6	3.42	0.125
2,121	200	2,228	210	107.1	107.1	3.14	0.114
2,121	300	2,282	306	108.2	108.3	3.49	0.128
2,121	300	2,272	305	107.4	107.4	4.09	0.149
2,121	400	2,324	400	108.3	108.4	3.85	0.141
2,121	400	2,280	402	108.5	108.6	3.79	0.139
2,121	500	2,220	514	109.3	109.5	4.38	0.168
2,121	600	2,241	609	108.7	108.8	3.53	0.134
2,828	200	2,711	208	108.0	107.8	5.11	0.187
2,828	300	2,696	305	109.8	109.9	5.21	0.190
2,828	300	2,705	306	109.4	109.4	5.64	0.205
2,828	400	2,701	402	109.8	109.9	4.82	0.177
2,828	500	2,865	509	109.9	110.1	5.82	0.226
2,828	600	2,892	602	110.0	110.1	5.20	0.201
3,535	200	3,435	215	110.1	110.2	7.12	0.260
3,535	300	3,451	304	110.7	110.9	7.18	0.262
3,535	300	3,620	311	109.5	109.6	9.97	0.390
3,535	400	3,487	405	111.1	111.5	6.28	0.229
3,535	400	3,483	404	111.4	111.6	6.28	0.229
3,535	500	3,628	510	110.3	110.5	6.26	0.239
3,535	600	3,653	607	110.9	111.1	6.17	0.237
4,242	200	4,085	208	111.0	111.2	9.67	0.353
4,242	300	4,097	305	111.3	111.6	9.76	0.358
4,242	400	4,111	404	111.5	111.5	8.39	0.305
4,242	400	4,283	406	111.2	111.4	10.03	0.385
4,242	500	4,291	509	110.7	110.9	8.09	0.311
4,242	600	4,314	604	110.7	110.9	7.24	0.279
4,949	200	4,744	221	110.4	110.4	8.63	0.313
4,949	200	4,778	223	110.4	110.6	10.41	0.394
4,949	300	4,769	308	111.9	112.3	10.94	0.387
4,949	400	4,800	404	112.3	112.6	11.90	0.432
4,949	400	4,821	406	110.3	110.4	10.93	0.422
4,949	500	4,870	507	111.1	111.4	8.22	0.311
4,949	600	4,822	607	110.4	110.7	5.78	0.222

Table 5.3 Sound Power Level Testing – Vacuum Method, 1-inch bit, Hex Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs)	SPEED (rpm)	THRUST (lbs)	SPEED (rpm)	LINEAR (dB)	A-WGT (dBA)	DEPTH (in)	RATE (in/sec)
setthrst	setspd	avthrust	avspeed	spdb	spdba	pendepth	penrate
2,121	200	2,334	206	108.9	109.0	4.6	0.165
	300	2,333	303	110.0	110.2	3.9	0.141
	400	2,344	404	110.8	111.0	2.9	0.107
	500	2,226	508	109.9	110.2	3.9	0.150
	600	2,241	602	112.4	112.8	4.2	0.163
2,828	200	2,919	208	111.2	111.3	5.4	0.194
	300	2,933	305	112.5	112.7	7.6	0.219
	400	2,955	401	112.0	112.3	6.1	0.210
		2,849	406	110.2	110.5	4.8	0.187
	500	2,877	508	110.8	111.1	5.5	0.212
	600	2,890	606	112.2	112.5	2.3	0.089
3,535	200	3,587	207	112.5	112.7	8.0	0.287
		3,588	209	111.3	111.6	8.5	0.330
	300	3,622	307	112.5	112.8	8.7	0.334
		3,607	307	113.0	113.4	8.9	0.340
	400	3,642	400	112.9	113.2	8.1	0.288
		3,660	398	113.0	113.4	8.8	0.314
	500	3,622	508	113.1	113.6	4.4	0.212
	600	3,651	606	112.5	112.9	4.5	0.173
4,242	200	4,294	218	112.2	112.5	11.6	0.452
		4,238	208	110.9	110.8	7.0	0.249
	300	4,254	305	113.0	113.3	10.7	0.382
	400	4,258	402	112.4	112.7	10.1	0.361
	500	4,344	508	113.5	114.0	7.2	0.290
	600	4,362	607	112.4	112.9	4.4	0.165
4,949	200	4,818	209	111.9	112.3	11.2	0.395
		4,916	211	112.6	113.0	11.3	0.495
	300	4,869	306	112.8	113.2	13.8	0.475
	400	4,898	407	113.0	113.3	12.5	0.445
	500	4,979	510	113.9	114.3	13.0	0.509
	600	4,995	607	112.6	113.0	4.6	0.172

Table 5.4 Sound Power Level Testing – Vacuum Method, 1-3/8-inch bit, Round Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs) setthrst	SPEED (rpm) setspd	THRUST (lbs) avthrust	SPEED (rpm) avspeed	LINEAR (dB) spdb	A-WGT (dBA) spdba	DEPTH (in) pendepth	RATE (in/sec) penrate
2,121	200	2,268	203	105.7	105.5	2.12	0.087
	300	2,285	306	106.5	106.1	1.91	0.078
	400	2,293	402	108.8	108.6	1.84	0.076
2,828	200	2,915	211	108.5	108.8	3.12	0.128
		2,908	215	108.2	108.5	2.96	0.121
	300	2,925	308	108.3	108.5	3.56	0.146
		2,923	311	108.1	108.3	2.94	0.120
	400	2,952	404	109.2	109.6	3.42	0.139
3,535	200	3,527	211	108.3	108.5	3.92	0.161
		3,522	213	108.1	108.3	4.30	0.176
	300	3,545	306	109.2	109.6	4.96	0.204
		3,545	305	108.6	108.9	4.40	0.181
	400	3,580	402	109.7	110.1	5.41	0.220
		3,567	402	109.8	110.2	4.43	0.182
4,242	200	4,183	208	111.3	111.8	5.95	0.205
	300	4,181	306	112.4	113.0	5.72	0.197
		4,228	309	111.3	111.7	5.53	0.212
	400	4,239	403	112.5	113.0	4.51	0.173
		4,360	405	112.1	112.5	2.61	0.093
	500	4,303	511	111.1	111.3	1.66	0.059
	600	4,405	606	109.9	110.0	1.32	0.047
4,949	200	4,842	210	111.6	112.1	7.27	0.251
	300	4,865	307	111.7	112.3	6.32	0.218
		4,923	314	112.2	112.7	7.17	0.279
	400	4,886	405	113.6	114.2	6.85	0.237
	500	5,082	509	110.8	111.0	1.83	0.065
	600	5,090	604	109.8	109.8	1.53	0.005
5,656	200	5,415	215	113.1	113.6	8.33	0.287
	300	5,438	307	111.9	112.5	7.87	0.271
	400	5,446	403	112.5	113.1	7.25	0.250
	500	5,677	510	106.9	106.8	1.61	0.056
	600	5,684	604	108.7	108.7	1.47	0.052
6,363	200	6,195	207	112.9	113.4	9.48	0.339
		6,242	212	112.3	112.7	10.74	0.381
	300	6,234	312	113.7	114.3	9.92	0.354
		6,218	310	112.7	113.1	9.90	0.353
	400	6,167	402	114.1	114.8	8.35	0.288
		6,237	402	113.6	114.1	5.84	0.208
	500	6,261	505	109.5	109.8	2.29	0.081
	600	6,283	602	106.5	106.1	1.40	0.049

Table 5.5 Sound Power Level Testing – Vacuum Method, 1-3/8-inch bit, Hex Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs)	SPEED (rpm)	THRUST (lbs)	SPEED (rpm)	LINEAR (dB)	A-WGT (dBA)	DEPTH (in)	RATE (in/sec)
setthrst	setspd	avthrust	avspeed	spdb	spdba	pendepth	penrate
2,121	200	2,283	212	106.1	106.3	1.6	0.067
	300	2,302	309	109.0	109.5	1.9	0.078
	400	2,326	402	110.0	110.4	2.1	0.084
2,828	200	2,892	209	109.3	109.7	2.8	0.115
	300	2,914	308	109.9	110.4	3.6	0.134
	400	2,943	405	112.2	113.0	3.5	0.145
3,535	200	3,559	208	109.2	109.6	4.4	0.180
	300	3,575	304	111.3	111.9	5.0	0.205
		3,715	313	111.9	112.5	3.9	0.150
	400	3,591	402	112.2	112.8	4.9	0.200
		3741	405	112.7	113.3	4.3	0.167
4,242	200	4,321	214	112.3	112.8	6.5	0.225
	300	4,316	309	113.4	114.1	5.7	0.195
		4,342	313	112.6	113.3	4.9	0.187
	400	4,330	402	113.9	114.6	5.9	0.202
		4,357	403	113.8	114.6	3.8	0.150
	500	4,407	505	113.9	114.7	3.1	0.115
	600	4,420	604	113.4	114.1	1.6	0.059
4,949	200	4,979	212	113.2	113.8	7.3	0.253
	300	5,001	310	113.1	113.8	8.3	0.285
		4,958	309	113.1	113.7	6.7	0.247
	400	5,047	405	114.8	115.5	5.8	0.200
		4,973	409	113.6	114.3	4.4	0.161
	500	4,982	511	114.0	114.7	2.8	0.104
	600	4,992	604	113.2	113.9	1.2	0.044
5,656	200	5,558	211	113.5	114.1	8.7	0.301
		5,485	218	112.7	113.3	8.7	0.324
	300	5,497	313	113.7	114.4	7.3	0.271
		5,502	310	113.7	114.3	8.4	0.312
	400	5,576	405	115.3	116.1	6.1	0.211
		5,510	408	114.5	115.2	4.6	0.167
	500	5,523	511	113.9	114.7	2.9	0.103
	600	5,544	600	112.8	113.4	2.5	0.089
6,363	200	6,342	212	113.5	114.1	9.8	0.337
		6,224	211	114.0	114.6	10.2	0.361
	300	6,360	311	114.5	115.2	10.5	0.361
		6,234	309	115.1	115.7	9.8	0.347
	400	6,382	404	115.5	116.2	6.6	0.227
		6,244	402	114.5	115.3	5.8	0.206
	500	6,256	506	113.7	114.3	2.8	0.099
	600	6,205	603	112.6	113.2	1.8	0.065

Table 5.6 Sound Power Level Testing – Wet Drilling Method (3 gal/min), 1-inch bit, Round Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs)	SPEED (rpm)	THRUST (lbs)	SPEED (rpm)	LINEAR (dB)	A-WGT (dBA)	DEPTH (in)	RATE (in/sec)
setthrst	setspd	avthrust	avspeed	spdb	spdba	pendepth	penrate
2,121	200	2,313	207	103.3	102.1	5.4	0.224
2,121	200	2,306	211	102.9	102.0	5.2	0.213
2,121	300	2,321	309	103.4	102.2	4.1	0.168
2,121	300	2,318	308	104.8	104.0	5.8	0.237
2,121	400	2,335	402	103.8	102.9	4.2	0.169
2,121	400	2,329	405	106.2	105.5	6.4	0.262
2,121	500	2,448	503	103.6	102.4	5.7	0.222
2,121	600	2,461	605	104.6	103.6	5.6	0.218
2,828	200	2,909	205	104.0	103.5	4.2	0.340
2,828	300	3,084	311	105.3	104.3	8.9	0.347
2,828	300	3,005	312	105.0	104.4	4.5	0.367
2,828	400	2,978	402	104.9	103.9	7.3	0.298
2,828	400	3,098	403	104.4	103.2	7.8	0.301
2,828	500	3,113	508	105.9	105.4	11.4	0.434
2,828	500	3,012	507	103.7	102.5	9.3	0.357
2,828	600	3,129	605	106.4	105.7	9.8	0.377
3,535	200	3,591	201	104.9	104.4	5.7	0.463
3,535	300	3,605	308	106.5	106.3	6.6	0.540
3,535	300	3,601	314	106.0	105.8	6.3	0.519
3,535	400	3,617	401	107.1	106.8	7.5	0.681
3,535	500	3,815	511	106.2	105.9	11.2	0.540
3,535	600	3,820	604	107.7	107.7	15.1	0.586
4,242	200	4,275	210	106.4	105.8	6.2	0.616
4,242	200	4,272	213	106.3	105.7	5.2	0.511
4,242	300	4,285	309	107.4	107.0	6.7	0.654
4,242	300	4,285	315	106.9	106.5	6.5	0.642
4,242	400	4,288	411	107.6	107.3	7.0	0.680
4,242	400	4,296	411	108.8	108.6	8.0	0.799
4,242	500	4,411	508	106.3	105.8	15.6	0.594
4,242	600	4,434	595	106.9	106.7	15.4	0.598
4,949	200	4,888	206	106.7	106.2	5.6	0.681
4,949	200	4,899	205	106.8	106.3	5.1	0.626
4,949	300	4,898	302	107.8	107.6	6.8	0.843
4,949	300	4,916	307	108.3	108.2	6.3	0.770
4,949	400	4,927	412	108.2	108.1	7.7	0.955
4,949	400	4,912	412	109.0	108.9	7.5	0.928
4,949	500	4,876	510	107.5	107.1	18.7	0.723
4,949	600	4,902	607	106.6	106.2	17.2	0.672

Table 5.7 Sound Power Level Testing – Wet Drilling Method (3 gal/min), 1-inch bit, Hex Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs)	SPEED (rpm)	THRUST (lbs)	SPEED (rpm)	LINEAR (dB)	A-WGT (dBA)	DEPTH (in)	RATE (in/sec)
setthrst	**setspd**	**avthrust**	**avspeed**	**spdb**	**spdba**	**pendepth**	**penrate**
2,121	200	2,314	207	102.1	100.6	1.8	0.196
	300	2,332	315	101.6	100.5	2.4	0.255
	400	2,347	404	104.0	103.8	2.3	0.249
	500	2,295	508	105.7	105.6	4.3	0.175
	600	2,306	607	106.0	105.9	4.3	0.176
2,828	200	2,924	214	103.1	101.5	2.9	0.320
		2,932	198	105.1	104.2	3.2	0.317
	300	2,939	306	103.9	102.8	3.6	0.386
	400	2,957	406	105.2	104.8	3.5	0.458
		3,121	403	105.8	105.7	7.8	0.309
	500	3,135	507	107.4	107.7	8.3	0.342
	600	3,147	602	107.2	107.2	9.5	0.389
3,535	200	3,670	215	104.4	103.8	3.8	0.416
		3,665	204	104.7	103.9	3.8	0.428
	300	3,715	316	106.0	105.3	8.5	0.344
		3,720	304	106.1	105.9	6.5	0.537
	400	3,578	409	108.0	108.2	4.6	0.457
		3,581	402	108.0	107.9	4.9	0.576
	500	3,741	517	107.6	107.5	11.2	0.451
		3,644	504	108.0	108.3	10.5	0.435
	600	3,755	606	108.2	108.3	11.1	0.443
		3,657	605	106.8	106.9	8.8	0.353
4,242	200	4,273	202	103.0	101.7	6.3	0.680
		4,349	216	105.7	105.2	11.4	0.463
	300	4,272	310	104.6	103.8	6.6	0.719
	400	4,297	412	106.6	106.1	7.4	0.810
		4,296	398	105.2	104.8	7.5	0.805
	500	4,382	511	108.0	108.1	14.6	0.597
	600	4,392	614	108.5	108.4	14.8	0.600
4,949	200	4,793	215	105.8	105.1	12.9	0.529
		4,930	209	104.8	104.7	6.1	0.762
	300	4,940	306	105.8	105.6	9.4	1.025
		4,806	314	106.0	105.5	12.7	0.518
	400	4,944	414	106.4	105.7	8.9	0.965
	500	4,831	509	108.0	108.1	14.6	0.598
	600	4,850	578	108.0	108.3	14.4	0.556

Table 5.8 Sound Power Level Testing – Wet Drilling Method (3 gal/min), 1-3/8-inch bit, Round Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs)	SPEED (rpm)	THRUST (lbs)	SPEED (rpm)	LINEAR (dB)	A-WGT (dBA)	DEPTH (in)	RATE (in/sec)
setthrst	setspd	avthrust	avspeed	spdb	spdba	pendepth	penrate
2,121	200	2,335	210	105.8	104.9	1.0	0.094
		2,337	208	105.1	103.9	1.0	0.094
	300	2,340	310	105.1	104.3	2.6	0.107
		2,337	311	105.6	105.0	3.0	0.123
	400	2,351	406	106.9	106.6	2.7	0.113
		2,347	407	105.8	105.5	2.9	0.120
2,828	200	2,916	211	104.3	103.5	3.0	0.122
		2,915	209	104.3	103.6	3.4	0.141
	300	2,937	305	105.2	104.9	4.5	0.188
		2,935	305	105.0	104.5	4.4	0.181
	400	2,959	411	106.3	106.1	4.6	0.189
		2,955	411	106.8	106.7	4.5	0.185
3,535	200	3,611	218	106.2	105.9	5.0	0.203
		3,609	214	105.6	105.3	6.0	0.246
	300	3,623	313	105.5	105.1	6.5	0.266
		3,621	311	106.3	106.0	6.3	0.261
	400	3,709	408	108.4	108.0	5.9	0.366
		3,701	411	108.7	108.5	6.4	0.394
4,242	200	4,187	217	107.2	106.8	5.1	0.320
		4,188	215	106.6	106.0	4.6	0.285
	300	4,210	313	108.3	108.1	6.0	0.368
		4,202	307	107.9	107.6	5.4	0.335
	400	4,233	408	109.0	108.8	8.1	0.429
		4,230	407	109.1	108.9	6.9	0.424
	500	4,456	510	108.7	108.9	8.4	0.321
	600	4,485	603	109.0	109.2	9.5	0.365
4,949	200	4,833	211	107.0	106.5	6.4	0.393
		4,808	217	106.9	106.3	7.0	0.428
	300	4,816	309	108.7	108.5	7.5	0.464
		4,826	310	107.8	107.4	7.7	0.466
		4,840	403	108.5	108.3	8.0	0.489
	500	5,110	506	109.6	109.8	11.0	0.409
	600	5,136	604	110.6	110.8	10.2	0.386
5,656	200	5,649	210	108.2	108.0	5.5	0.447
		5,644	212	107.5	107.3	5.1	0.411
	300	5,662	311	109.3	109.2	6.8	0.558
		5,512	310	108.5	108.6	7.3	0.604
	400	5,669	411	110.3	110.2	7.9	0.650
		5,666	401	109.0	108.7	7.0	0.573
	500	5,740	507	110.1	110.3	12.1	0.436
	600	5,755	604	110.1	110.4	11.6	0.429
6,363	200	6,298	206	108.3	108.0	6.2	0.511
	300	6,307	308	109.8	109.7	6.8	0.560
	400	6,320	407	109.7	109.6	7.6	0.628
		6,148	402	109.2	109.3	15.4	0.594
	500	6,161	504	108.4	108.4	11.9	0.452
	600	6,369	601	109.6	109.4	18.2	0.688

Table 5.9 Sound Power Level Testing – Wet Drilling Method (3 gal/min), 1-3/8-inch bit, Hex Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs)	SPEED (rpm)	THRUST (lbs)	SPEED (rpm)	LINEAR (dB)	A-WGT (dBA)	DEPTH (in)	RATE (in/sec)
setthrst	setspd	avthrust	avspeed	spdb	spdba	pendepth	penrate
2,121	200	2,338	209	104.5	104.2	1.3	0.055
	300	2,360	311	105.0	105.0	2.1	0.086
	400	2,378	403	106.3	106.1	2.4	0.099
2,828	200	2,915	213	104.5	104.2	2.3	0.094
	300	2,937	309	106.2	106.3	3.3	0.134
	400	2,961	402	107.0	107.0	3.9	0.160
3,535	200	3,593	209	105.0	104.9	4.7	0.190
	300	3,606	312	105.1	105.0	5.7	0.234
	400	3,622	400	106.1	106.1	5.9	0.246
4,242	200	4,402	212	105.7	104.9	5.9	0.223
		4,207	208	105.8	105.7	2.6	0.285
	300	4,227	302	106.7	106.8	3.3	0.358
		4,277	309	106.4	106.4	6.8	0.278
	400	4,258	411	107.4	107.5	4.5	0.484
		4,286	398	107.5	107.6	8.5	0.348
	500	4,454	505	107.9	108.0	9.2	0.338
	600	4,478	604	108.9	109.2	9.4	0.357
4,949	200	4,848	207	106.6	106.4	4.5	0.372
		4,846	206	106.7	106.4	3.9	0.320
	300	4,859	315	107.9	107.9	4.9	0.406
		4,852	313	107.5	107.5	4.8	0.390
	400	4,867	407	110.3	110.5	5.5	0.601
		5,000	401	107.4	107.2	9.6	0.365
	500	5,014	506	108.1	108.0	9.7	0.353
	600	5,027	602	109.1	109.1	9.4	0.356
5,656	200	5,435	201	107.4	107.5	3.8	0.408
		5,595	216	107.1	106.9	9.5	0.361
	300	5,539	315	109.1	109.3	6.0	0.488
		5,539	308	108.5	108.6	6.0	0.497
	400	5,561	413	108.8	108.8	7.5	0.610
		5,586	424	109.2	109.2	5.6	0.550
	500	5,642	510	109.0	109.0	10.8	0.411
	600	5,664	604	108.8	108.9	11.9	0.422
6,363	200	6,200	204	108.5	108.6	4.8	0.523
		6,155	196	107.7	107.7	5.8	0.567
	300	6,197	316	108.7	108.8	5.7	0.616
		6,137	304	109.1	109.1	6.0	0.598
	400	6,219	405	110.7	110.8	6.5	0.710
		6,213	408	109.8	110.0	5.7	0.618
	500	6,334	508	109.4	109.4	17.9	0.675
	600	6,323	598	110.2	110.2	17.1	0.657
		6,346	604	110.7	110.7	14.0	0.529

Table 5.10 Sound Power Level Testing – Mist Drilling Method (3 qt/min), 1-inch bit, Round Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs)	SPEED (rpm)	THRUST (lbs)	SPEED (rpm)	LINEAR (dB)	A-WGT (dBA)	DEPTH (in)	RATE (in/sec)
setthrst	setspd	avthrust	avspeed	spdb	spdba	pendepth	penrate
2,121	200	2,418	214	105.3	104.6	4.05	0.1580
	300	2,432	307	106.5	105.8	4.84	0.1910
	400	2,445	402	107.4	106.7	5.53	0.2180
	500	2,458	507	107.5	107.4	6.60	0.2600
	600	2,472	593	107.7	107.7	5.58	0.2220
2,828	200	2,978	216	105.0	104.5	6.93	0.2730
	300	2,993	301	107.4	107.1	8.85	0.3510
	400	3,004	408	108.4	107.9	8.99	0.3590
	500	3,004	510	108.7	108.5	8.05	0.3190
	600	3,012	605	109.4	109.2	8.45	0.3280
3,535	200	3,685	213	106.5	106.3	9.16	0.3610
	300	3,700	306	108.6	108.5	9.93	0.3920
	400	3,716	404	109.1	109.1	12.06	0.4690
	500	3,734	509	109.9	109.7	11.36	0.4520
	600	3,758	607	110.1	110.1	11.70	0.4600
4,242	200	4,335	216	100.2	107.9	10.85	0.4270
	300	4,350	305	109.3	109.2	13.96	0.5410
	400	4,364	407	110.5	110.5	14.83	0.5910
	500	4,381	508	110.9	111.1	14.22	0.5610
	600	4,397	606	111.1	111.2	14.94	0.5770
4,949	200	4,928	210	109.1	108.9	14.11	0.5640
	300	4,947	307	110.2	110.2	16.39	0.6440
	400	4,966	405	110.8	110.9	17.50	0.6900
	500	4,994	502	112.0	112.2	16.66	0.7300
	600	4,825	584	112.4	112.5	23.19	0.9200

Table 5.11 Sound Power Level Testing – Mist Drilling Method (3 qt/min), 1-inch bit, Hex Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs)	SPEED (rpm)	THRUST (lbs)	SPEED (rpm)	LINEAR (dB)	A-WGT (dBA)	DEPTH (in)	RATE (in/sec)
setthrst	setspd	avthrust	avspeed	spdb	spdba	pendepth	penrate
2,121	200	2,347	216	105.4	104.6	3.77	0.1520
	300	2,357	307	106.8	106.5	4.93	0.1950
	400	2,370	405	107.8	107.9	4.72	0.1910
	500	2,387	508	108.0	108.1	4.73	0.1950
	600	2,404	607	108.2	108.5	4.56	0.1850
2,828	200	2,989	216	106.4	105.9	6.14	0.2460
	300	2,999	308	108.0	107.8	7.02	0.2840
	400	3,008	406	109.7	109.8	6.40	0.2800
	500	3,022	505	109.3	109.6	6.80	0.2730
	600	3,036	606	110.0	110.3	5.50	0.2230
3,535	200	3,686	218	107.1	106.7	8.53	0.3430
	300	3,699	302	108.6	108.5	10.11	0.4070
	400	3,709	404	110.9	110.9	9.66	0.3880
	500	3,723	501	111.0	111.3	9.28	0.3740
	600	3,738	604	112.0	112.4	9.37	0.3790
4,242	200	4,239	204	108.1	107.8	10.04	0.4170
	300	4,247	309	110.2	110.1	13.07	0.5380
	400	4,257	404	111.4	111.7	12.05	0.4880
	500	4,269	508	111.9	112.3	11.25	0.4650
	600	4,278	606	111.8	112.2	12.60	0.5190
4,949	200	4,899	212	109.3	109.3	11.52	0.4750
	300	4,916	310	111.2	111.4	12.21	0.4920
	400	4,909	403	111.3	111.6	13.21	0.5400
	500	4,929	506	113.4	113.9	12.39	0.5180
	600	4,955	608	113.1	113.6	13.31	0.5440

Table 5.12 Sound Power Level Testing – Mist Drilling Method (3 qt/min), 1-3/8-inch bit, Round Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs) setthrst	**SPEED (rpm) setspd**	**THRUST (lbs) avthrust**	**SPEED (rpm) avspeed**	**LINEAR (dB) spdb**	**A-WGT (dBA) spdba**	**DEPTH (in) pendepth**	**RATE (in/sec) penrate**
3,535	200	3,748	219	108.6	108.4	4.51	0.2050
	300	3,752	310	109.6	109.7	5.73	0.2190
	400	3,756	402	110.8	111.1	6.12	0.2360
	500	3,779	510	111.4	111.8	5.94	0.2310
	600	3,789	606	112.1	112.6	5.78	0.2240
4,242	200	4,352	214	110.8	110.9	6.66	0.2580
	300	4,361	311	111.7	112.0	7.03	0.2730
	400	4,371	406	112.2	112.5	7.88	0.3060
	500	4,383	510	112.3	112.7	8.09	0.3140
	600	4,396	609	112.6	113.1	6.94	0.2700
4,949	200	4,953	218	111.3	111.5	7.62	0.2910
	300	4,965	309	111.2	111.3	9.33	0.3580
	400	4,967	401	111.7	112.1	7.93	0.3050
	500	4,986	512	112.2	112.6	8.83	0.3350
	600	5,007	607	112.9	113.4	8.26	0.3140
5,656	200	5,523	216	111.6	111.8	9.14	0.3580
	300	5,528	312	110.3	110.4	9.91	0.3820
	400	5,942	403	113.3	113.6	10.88	0.4160
	500	5,558	510	113.1	113.6	10.60	0.4120
	600	5,569	608	114.5	114.8	9.93	0.3760
6,363	200	6,244	218	109.9	109.8	10.17	0.3970
	300	6,256	309	111.1	111.2	12.39	0.4850
	400	6,275	401	112.6	112.9	13.91	0.5370
	500	6,294	509	113.8	114.3	13.58	0.5240
	600	6,317	608	113.0	113.4	12.44	0.4830

Table 5.13 Sound Power Level Testing – Mist Drilling Method (3 qt/min), 1-3/8-inch bit, Hex Drill Steel

SET POINTS		AVERAGE		SOUND POWER		PENETRATION	
THRUST (lbs) setthrst	SPEED (rpm) setspd	THRUST (lbs) avthrust	SPEED (rpm) avspeed	LINEAR (dB) spdb	A-WGT (dBA) spdba	DEPTH (in) pendepth	RATE (in/sec) penrate
3,535	200	3,680	213	107.9	107.9	4.64	0.2110
	300	3,692	305	110.1	109.9	5.43	0.2500
	400	3,717	403	111.2	111.7	4.05	0.1850
	500	3,736	509	112.5	112.9	3.84	0.1730
	600	3,752	606	113.2	113.3	4.14	0.1880
4,242	200	4,298	213	108.5	108.7	4.98	0.2290
	300	4,310	314	111.2	111.6	5.78	0.2640
	400	4,326	402	112.0	112.5	5.95	0.2740
	500	4,338	508	113.4	114.0	4.76	0.2160
	600	4,357	607	114.2	114.8	4.88	0.2720
4,949	200	4,977	212	107.3	107.3	6.34	0.2910
	300	4,998	303	108.0	108.0	7.12	0.3270
	400	5,013	398	111.8	112.3	6.56	0.3000
	500	5,037	511	113.7	114.2	5.13	0.2370
	600	5,060	606	115.6	116.2	5.78	0.2670
5,656	200	5,617	211	110.3	110.5	7.87	0.3990
	300	5,632	306	112.7	113.1	9.10	0.4110
	400	5,646	404	113.2	113.6	8.92	0.4020
	500	5,671	512	116.3	117.0	8.09	0.3660
	600	5,686	595	115.5	116.1	8.20	0.3740
6,363	200	6,260	212	111.7	111.9	9.36	0.4320
	300	6,287	312	113.2	113.6	10.41	0.4810
	400	6,317	404	114.5	114.9	10.00	0.4620
	500	6,347	507	115.4	115.9	11.78	0.5380
	600	6,306	598	116.3	116.9	9.05	0.4030

Nomenclature within tables 5.2 thru 5.13 include:

SET POINTS – these represent the settings for thrust and rotational speed prior to the drilling procedure

- Thrust (lbs) – setthrst – thrust setting prior to drilling
- Speed (rpm) – setspd – rotational speed setting prior to drilling

AVERAGE – represents the average thrust and speed measured during the drilling portion of the test

- Thrust (lbs) – avthrust – average thrust during the test

- Speed (rpm) – avspeed – average rotational speed during the test

SOUND POWER – represents the total noise energy emitted from machine during the test

- Linear (dB) – spdb – linear sound power determined for test
- A-WGT (dBA) – spdba – a-weighted sound power determined for test

PENETRATION – the length of run the drill bit encountered during a test

- Depth (in) – pendepth – The depth, in inches, the bit penetrated the rock media during a test
- Rate (in/sec) – penrate – The rate, in inches per second, the bit traveled thru the rock media during the test.

5.3 Experimental Test Results – Sound Power Levels

The data, represented graphically, listed in the following discussion are the average sound power levels (L_{wA}) expressed in A-weighted decibels (dBA) and the penetration rates (in/sec) monitored at a given test configuration. Furthermore, all similar tests (e.g., same steel shape and bit size) were averaged for a given thrust or rotation speed. This approach facilitated the illustrating of trends showing the affects of thrusts or rotation speeds on the data. As a result, relationships were determined for sound power, penetration rate, thrust and rotational speed related to the different types of drilling methods (vacuum, wet and mist). The laboratory data was characterized and plotted for each test configuration as shown below.

5.3.1 Round Drill Steel Compared to Hexagonal Drill Steel (Penetration Rate and Sound Power)

Figure 5.1 below represents plots of thrust vs. penetration rate for one-inch round and one-inch hex drill steel given differing rotational speeds.

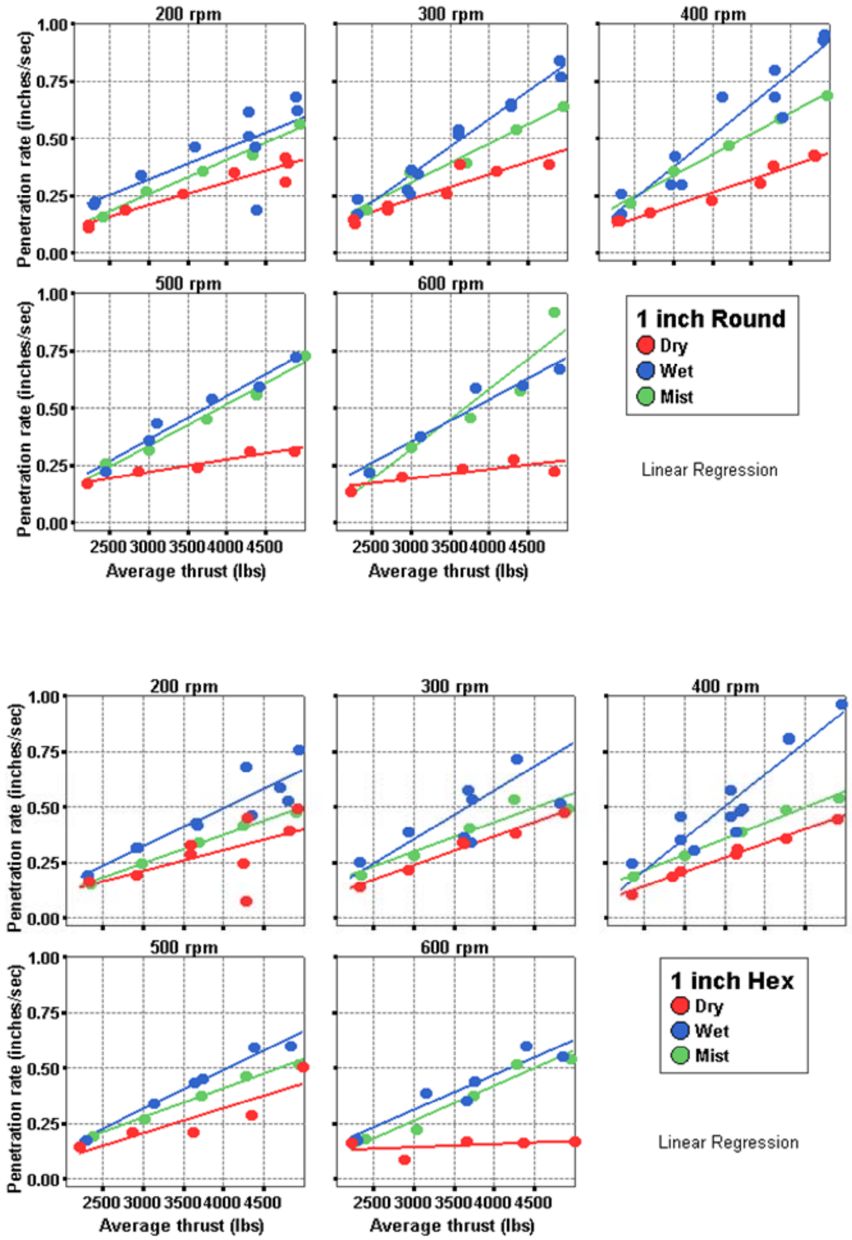


Figure 5.1 Drill Steels - Round and Hex (1-inch) – Thrust vs. Penetration Rate

In most cases, for both the one-inch round and hex drill steel, the data represents higher penetration rates when utilizing a wet, mist and dry drilling system respectively.   However, for the one-inch round drill steel, penetration rates were higher using a mist system of drilling as compared to a wet system when the rotational speed was higher, specifically at 600 rpm. The data also shows that penetration rates did increase as the thrust was increased for both the one-inch round and hex drill steel with the exception of the one-inch hex drill steel at the higher rotational speed of 600 rpm. The penetration rate for this remained fairly constant as the thrust was increased.

Figure 5.2 represents plots of penetration rates vs. sound power for one-inch round and one-inch hex drill steel given differing rotational speeds.

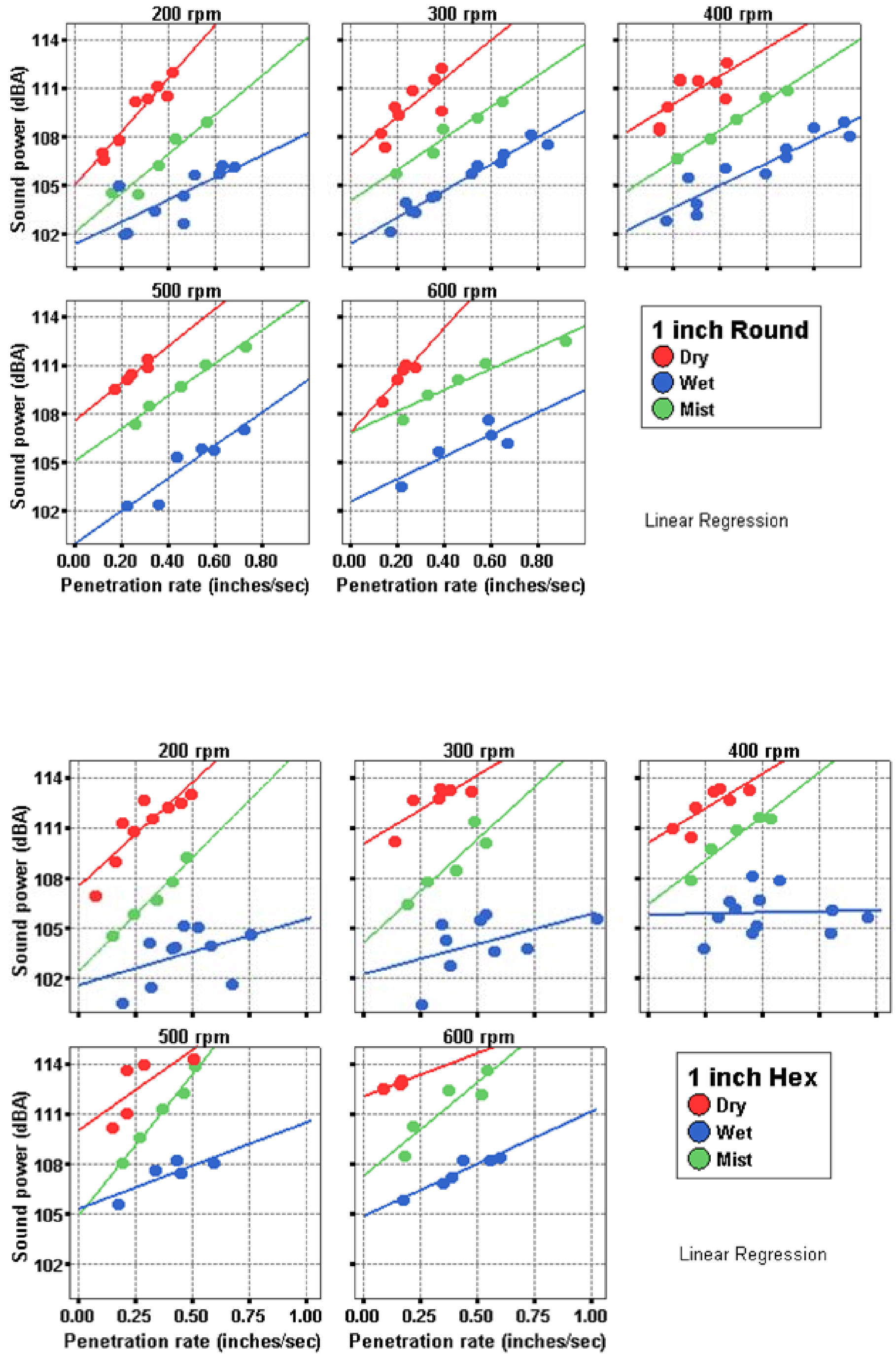
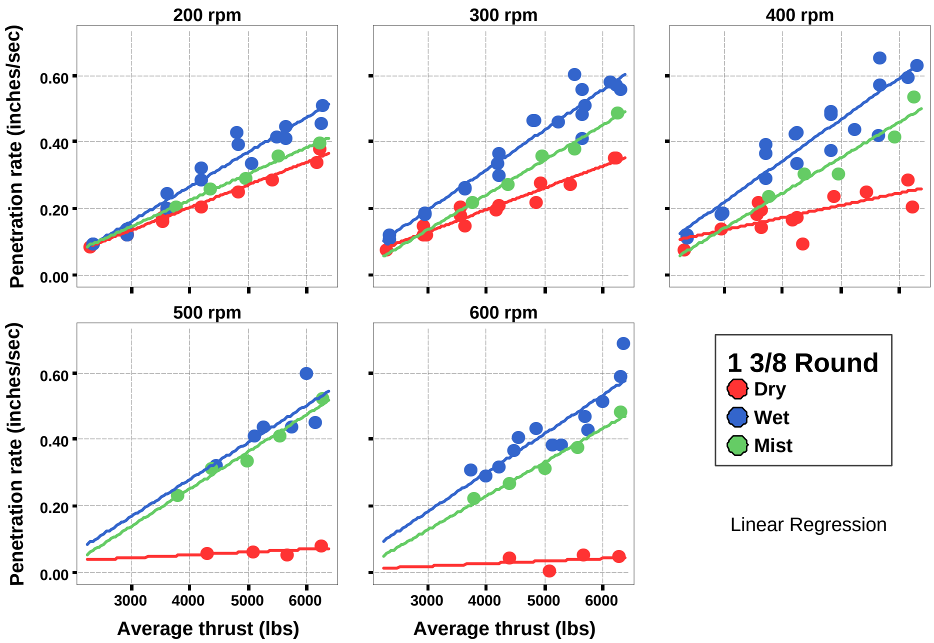


Figure 5.2 Drill Steels - Round and Hex (1-inch) – Penetration Rate vs. Sound Power

For all cases, sound power levels were highest during vacuum or dry drilling tests and the levels decreased during mist and wet system type of drilling respectively as shown in figure 5.2. In general, for all configurations, as the penetration rate increased, the sound power level increased as well. Additionally, sound power levels for the round drill steel were lower than compared to the hex type drill steel. Figure 5.3 below represents plots of thrust vs. penetration rate for 1.375-inch round and hex drill steel given differing rotational speeds.



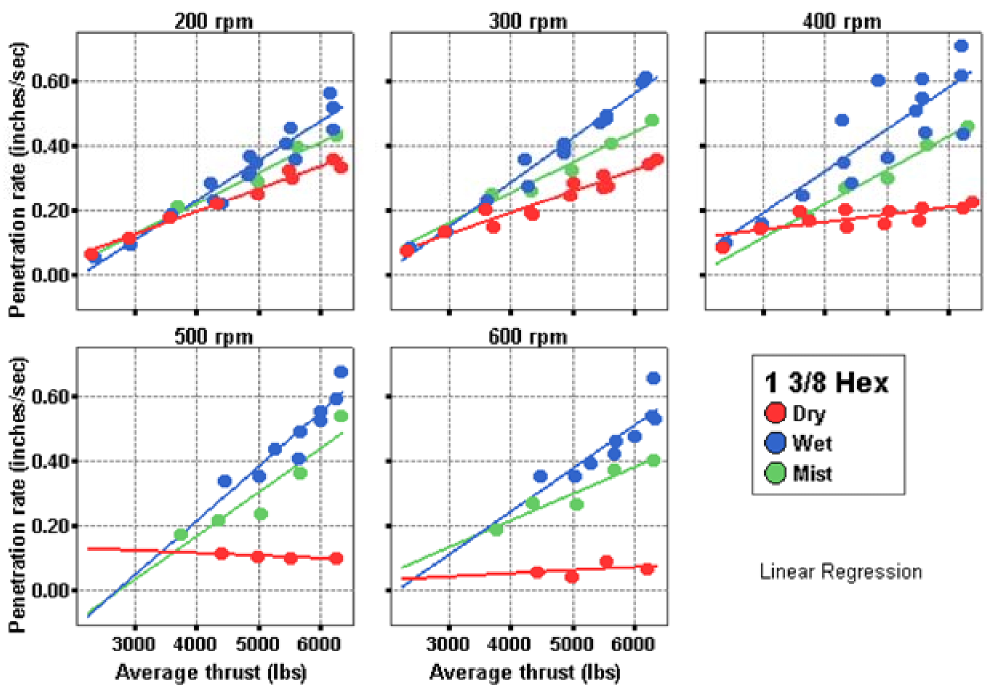


Figure 5.3 Drill Steels - Round and Hex (1.375-inch) – Thrust vs. Penetration Rate

As seen earlier with the one-inch round and hex drill steel in figure 5.1, the data represented for the 1.375-inch round and hex drill steel also presents higher penetration rates when using a wet, mist and dry drilling system respectively. However, penetration rates are significantly decreased when utilizing a dry or vacuum drilling system and operating at higher rotational speeds, specifically, 400 thru 600 rpm. Additionally, penetration rates did increase as the thrust was increased for both the 1.375-inch round and hex drill steel until a vacuum type of drilling system was used and rotational speeds were higher. Figure 5.4 displays plots of penetration rates vs. sound power for 1.375-inch round and hex drill steel given differing rotational speeds.

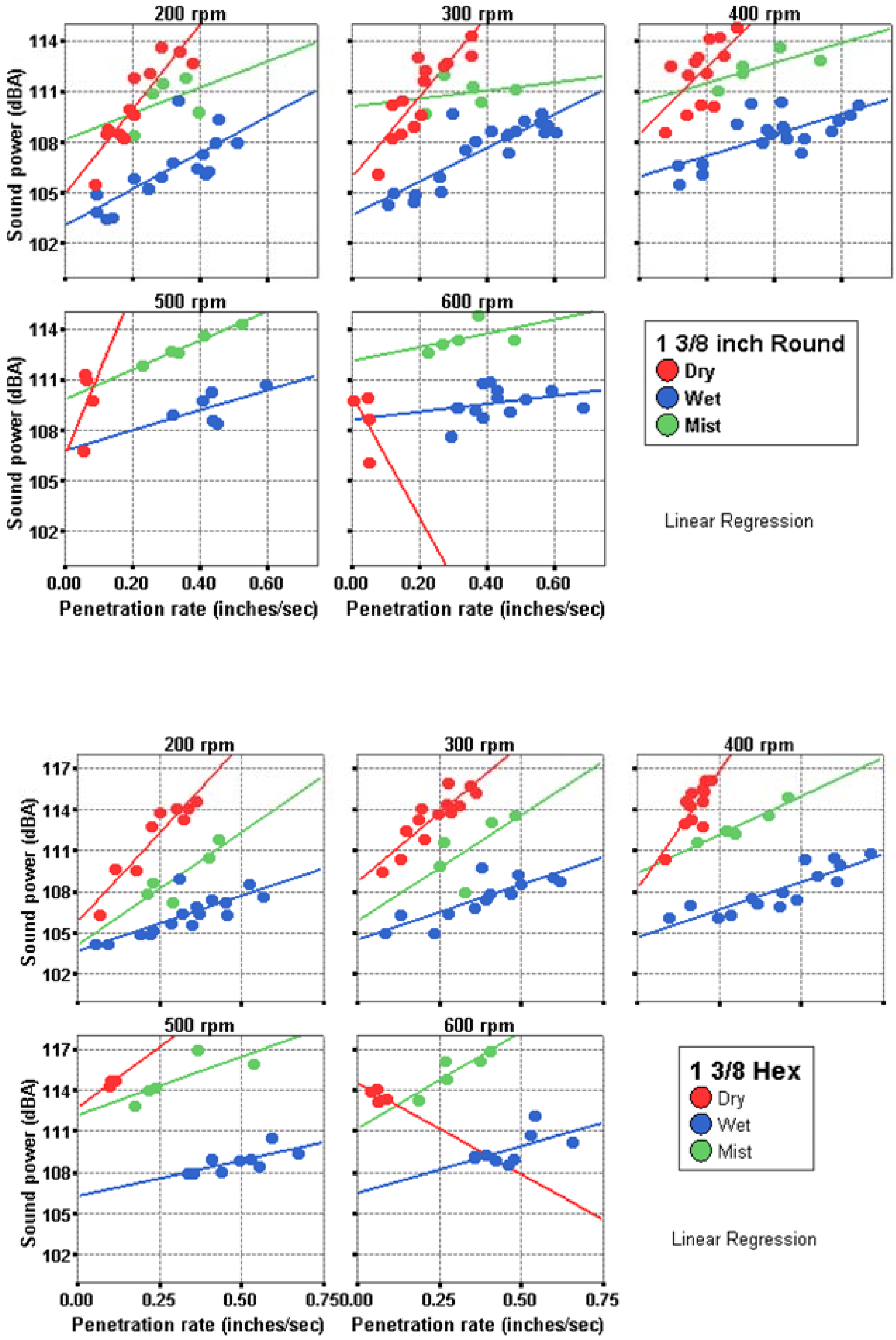


Figure 5.4 Drill Steels - Round and Hex (1.375-inch) – Penetration Rate vs. Sound Power

In general, sound power levels were lowest during wet drilling tests and highest when utilizing a vacuum or dry method of drilling. Additionally, the penetration rates for the vacuum drilling method were much lower as compared to the mist or wet systems of drilling. Minimal penetration rates were observed at higher rotational speeds utilizing the dry or vacuum method of drilling and sound power levels were higher utilizing the 1.375-inch hex drill steel as compared to the round steel and the one-inch hex results showed sound power levels less than one-inch round at lower rotational speeds but the advantage disappears at 500 and 600 rpm.

5.3.2 One-Inch Diameter Compared to One and Three-Eighths Inch Diameter Drill Bits

Figure 5.5 represents plots of penetration rates vs. thrust for comparing one-inch to 1.375-inch round and hex drill steel given differing rotational speeds.

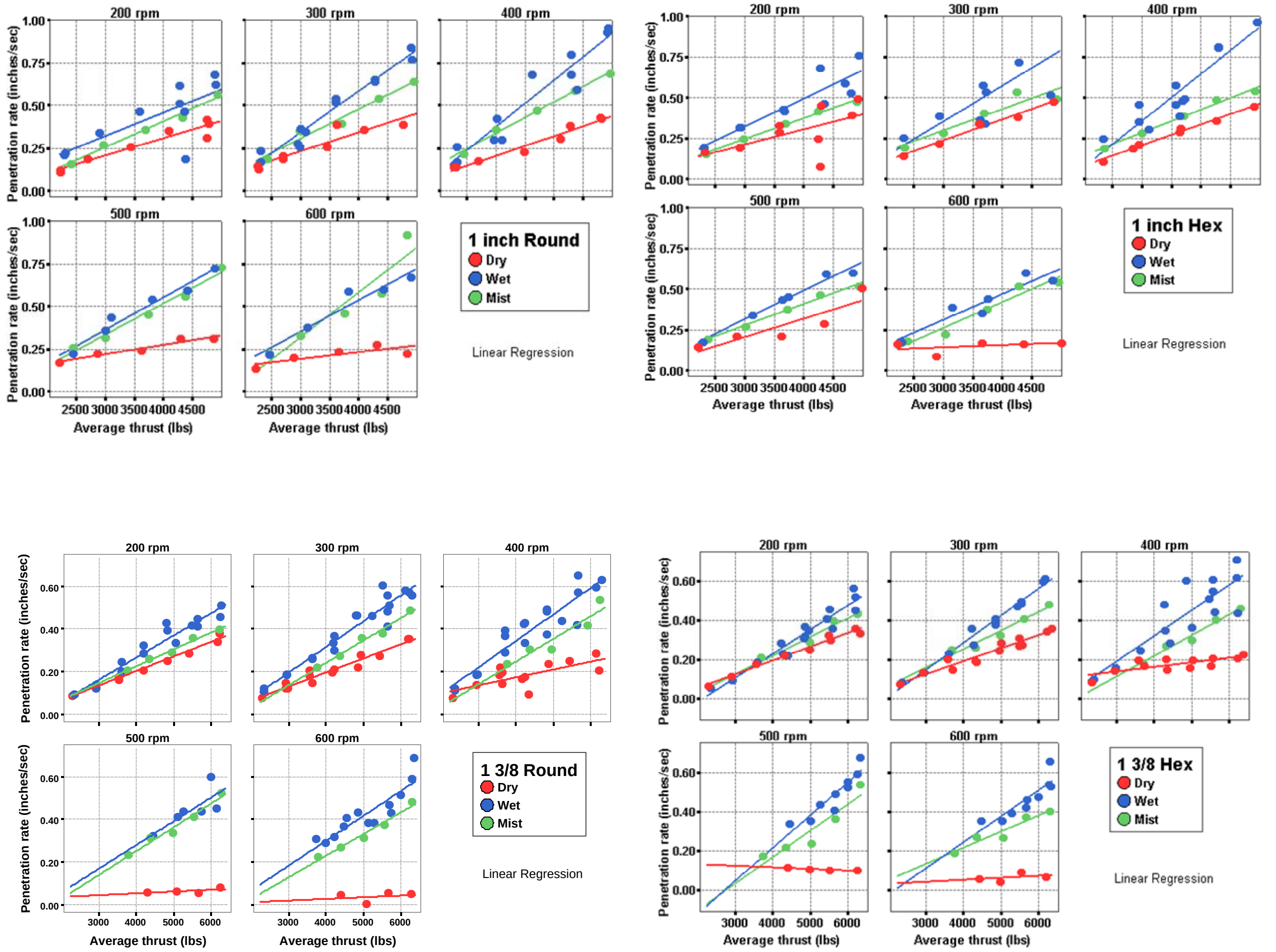


Figure 5.5 One-inch vs. 1.375-inch Drill Bit (Penetration Rate vs. Thrust)

As shown in figure 5.5 above, the thrust has a significant affect on the penetration rate for most cases. The one-inch drill bit performance was on the order of two to three times that of the 1.375-inch drill bit. However, the thrust had minimal influence relative to using a dry method of drilling at the higher rotational speeds, specifically, 500 and 600 rpm. The one-inch drill bit performed significantly better than the 1.375-inch drill bit relative to rotational speed. Figure 5.6 displays plots of penetration rates vs. sound power levels for comparing one-inch to 1.375-inch round and hex drill bits given differing rotational speeds.

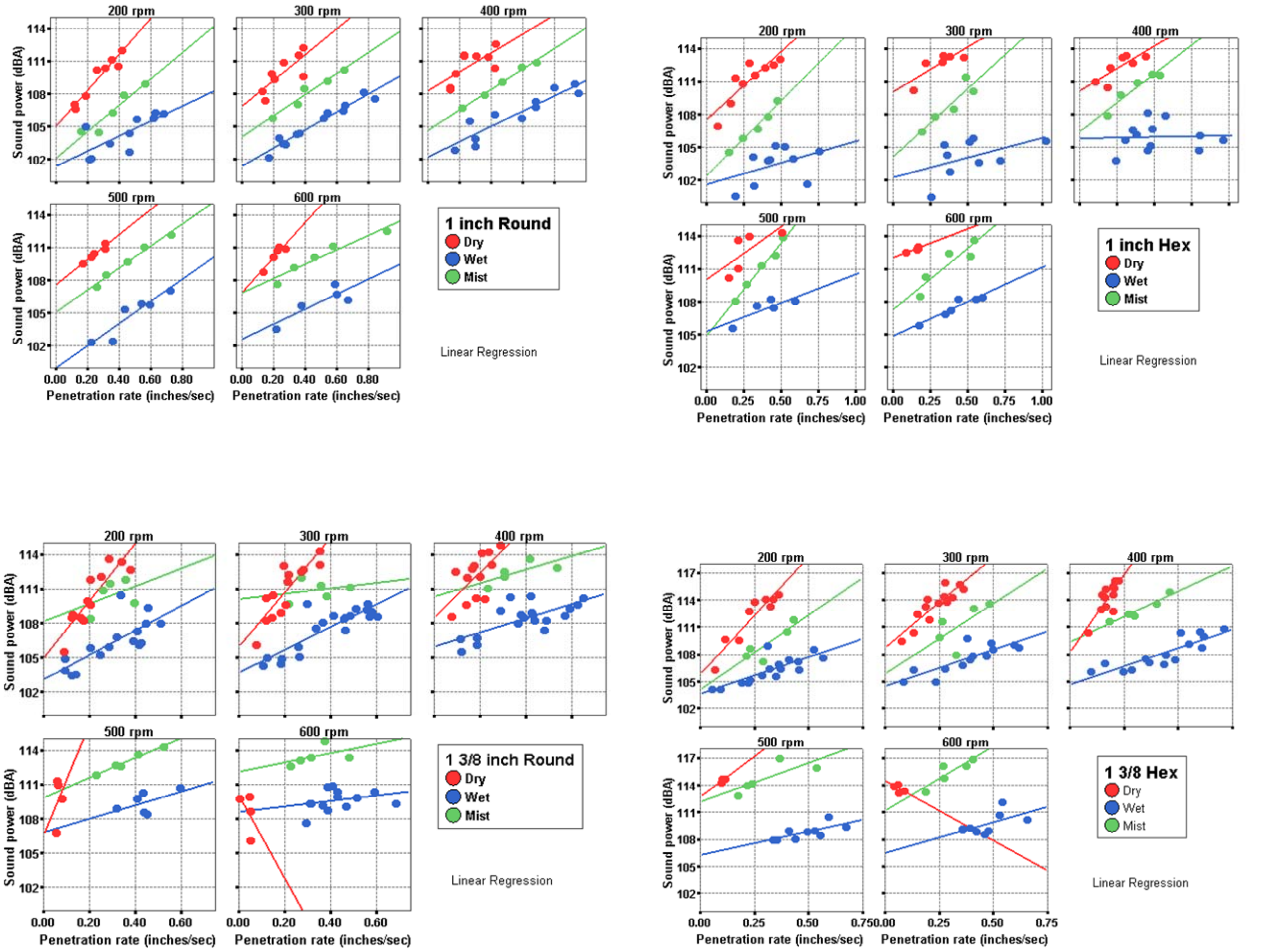


Figure 5.6 One-inch vs. 1.375-inch Drill Bit (Penetration Rate vs. Sound Power Level)

Sound power levels experienced with the 1.375-inch diameter bit were observed to be higher than experienced with the one-inch diameter bit, varying approximately by 2.5 dBA. Additionally, sound power levels for either a one-inch or 1.375-inch diameter bit were lowest during the wet drilling method. Penetration rates using a one-inch diameter bit were typically higher than when using a 1.375-inch diameter bit independent upon the type of drilling method used. As was the case with thrust, when using rotation speed as a comparative basis, the vacuum round drill steel results indicate a lower sound power than similar hex drill steel tests. For wet testing, there is no difference between the one-inch and 1.375-inch round and hex results.

5.3.3 General Conclusions Regarding Data Collection

When comparing round and hex drill steel, round drill steel should be used when utilizing the vacuum type of drilling method and hex drill steels when performing the wet or mist type of drilling method. While increasing the thrust does yield an increased sound power level for both of the round and hex drill steel, the differences are negligible. When comparing rotational speed affect relative to round or hex drill steel, the round drill steel, during vacuum type drilling, provides a lower sound power level than similar hex drill steel tests. For wet or mist system type of drilling, their appears to be no difference between the one-inch and 1.375-inch round and hex drill steel. Upon comparing penetration rates relative to round or hex drill steel in relation to thrust or rotational speed, their appears to be minimal affect attributed to thrust or rotational speeds.

When comparing the one-inch diameter bits to the 1.375-inch diameter bits, the one-inch diameter drill bits are slightly quieter than the 1.375-inch diameter drill bits. The penetration rates relative to the one-inch drill bits are noticeably higher than the 1.375-inch bits, on an order of two to three times higher. When comparing the 1-inch bit to the 1.375-inch bit relative to rotational speed, the one-inch bit performed significantly better than the 1.375-inch bit. For optimal performance and lower sound power levels, rotational speeds in the range of 200-400 rpm performed better and were quieter.

When comparing the different types of drilling methods, specifically vacuum, mist or wet, wet and mist drilling, penetration rates utilizing a wet or mist system drilling technique were much higher than using a dry or vacuum type drilling method. Additionally, utilizing a wet or mist system proved to emit less noise than similar tests conducted under vacuum or dry conditions. Much of the difference is attributable to the lubricating affect of the water or mist, which attenuates higher frequency noise. An example of this effect is given in figure 5.7 (17,22). Here, one-inch round data tested at a thrust of 4,949 pounds and a rotation speed of 200 rpm is given for testing under both vacuum and wet drilling system conditions. For all one-third octave band frequencies of 1,000 Hz and greater, it is clearly shown that the sound power levels are greater for vacuum drilling. Four examples of this are listed in table 5.14. For each case, the sound power level contributions for the one-third octave bands from 50 through 800 Hz are essentially the same for vacuum and wet drilling, e.g., for the one-inch round case they are 95 dBA and 96 dBA respectively. There is a significantly larger difference in the frequency range 1 kHz through 10 kHz. For the one-inch round example, there is a 5 dBA difference. Similar results are listed for the other three cases.

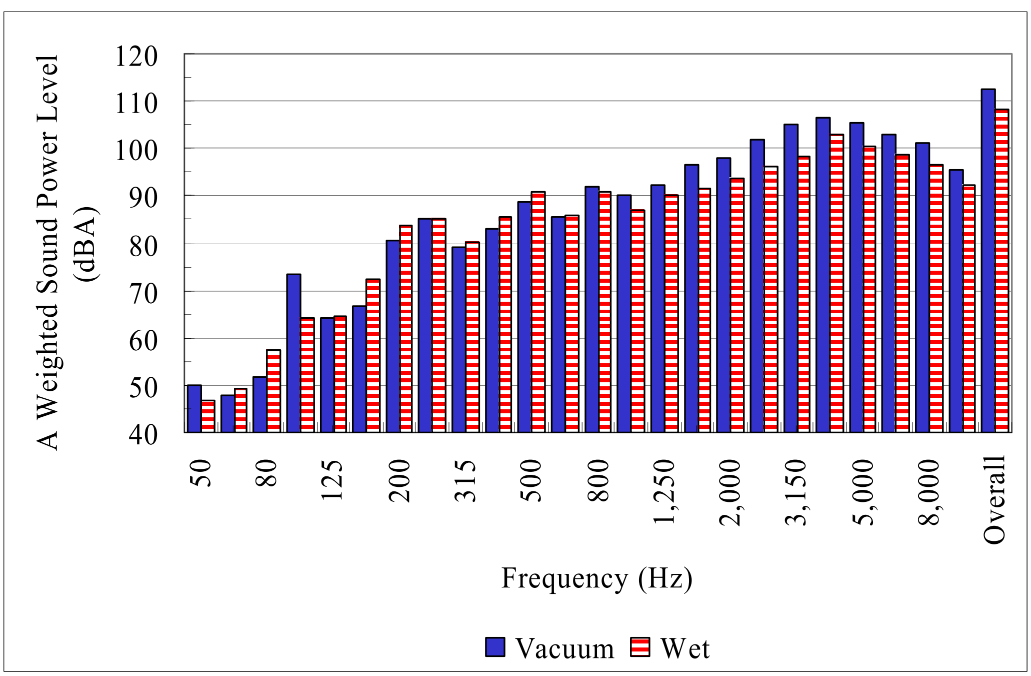


Figure 5.7 One-inch Round Drill Steel - Vacuum and Wet – Sound Power Levels - 4,949 lbs Thrust, 200 rpm Rotational Speed

Table 5.14 - Sound Power Level Contributions of Two Frequency Bands

Size & Shape	Thrust (lbs) Speed (rpm)	Frequency Band (Hz)	Vacuum L_{wA}	Wet L_{wA}
1-inch round	4,949 400	50 through 800	95	96
		1 k through 10 k	113	108
1-3/8 inch round	6,363 400	50 through 800	96	96
		1 k through 10 k	115	109
1-inch hex	4,949 400	50 through 800	93	96
		1 k through 10 k	112	105
1-3/8 inch hex	5,656 200	50 through 800	97	95
		1 k through 10 k	114	107

Further analysis indicated another key point. The overall A-weighted sound power levels are essentially unaffected by the sound power generated in the one-third octave bands below 1 kHz. For each example given, the overall A-weighted sound power level is the same as the 1 kHz through 10 kHz contributions, given rounding the sound power levels to the nearest dBA.

5.4 Development of a Statistical Model for Determining Sound Power Levels

5.4.1 Introduction

The next step of the research was to compile, summarize and statistically correlate all of the data collected (approximately 500 tests) for drilling into a high-compressive strength media (>20,000 psi) by developing one equation, which, would be used to determine sound power levels given any drilling method (vacuum, wet or mist) and utilizing differing drilling parameters or configurations related to thrust, rotational speed, bit size and type of drill steel used. A commercially available, statistical software package, SPSS was used to correlate all of the data.

In order to statistically correlate the data into one useful equation, the data from each test had to be organized into a useful form. The laboratory data is shown in table 5.15. Each individual test supplied the following independent data: 1) bit size; 2) drill steel type; 3) thrust utilized; 4) rotational speed and 5) type of drilling method (vacuum, mist or wet). The dependent information derived from the statistical approach was the sound power level generated from each test configuration. As shown in table 5.15, the independent variables utilized for the model were:

Water	=	0 gpm for the vacuum drilling method
		0.75 gpm for the mist drilling method
		3 gpm for the wet drilling method
Thrust	=	average thrust level used for the individual test, in lbs.
Speed	=	average rotational speed used for the individual test, in rpm
Bit Size	=	1 for 1-inch and 1.375 for 1.375-inch
Drill Steel	=	0 for hex drill steel and 1 for round drill steel

It was determined the penetration rate measured for each test was not to be included as a specific independent variable when developing the one equation for predicting sound power. The penetration rates measured for each test were directly affected by all of the independent variables listed above. Therefore, a direct correlation between the dependent variable, sound power and the penetration rate cannot exist due to the contribution required by all of the independent variables (drilling method, thrust, speed, bit size and type of drill steel) in determining the penetration rate.

Table 5.15 Laboratory Data Utilized for Input into the Statistical Model

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
106.60	209.00	2239.00	.00	1.000	1.000
107.10	210.00	2228.00	.00	1.000	1.000
108.30	306.00	2282.00	.00	1.000	1.000
107.40	305.00	2272.00	.00	1.000	1.000
108.40	400.00	2324.00	.00	1.000	1.000
108.60	402.00	2280.00	.00	1.000	1.000
109.50	514.00	2220.00	.00	1.000	1.000
108.80	609.00	2241.00	.00	1.000	1.000
107.80	208.00	2711.00	.00	1.000	1.000
109.90	305.00	2696.00	.00	1.000	1.000
109.40	306.00	2705.00	.00	1.000	1.000
109.90	402.00	2701.00	.00	1.000	1.000
110.10	509.00	2865.00	.00	1.000	1.000
110.10	602.00	2882.00	.00	1.000	1.000
110.20	215.00	3435.00	.00	1.000	1.000
110.90	304.00	3451.00	.00	1.000	1.000
109.60	311.00	3620.00	.00	1.000	1.000
111.50	405.00	3487.00	.00	1.000	1.000
111.60	404.00	3483.00	.00	1.000	1.000
110.50	510.00	3628.00	.00	1.000	1.000
111.10	607.00	3653.00	.00	1.000	1.000
111.20	208.00	4085.00	.00	1.000	1.000
111.60	305.00	4097.00	.00	1.000	1.000
111.50	404.00	4111.00	.00	1.000	1.000
111.40	406.00	4283.00	.00	1.000	1.000
110.90	509.00	4291.00	.00	1.000	1.000
110.90	604.00	4314.00	.00	1.000	1.000
110.40	221.00	4744.00	.00	1.000	1.000
110.60	223.00	4778.00	.00	1.000	1.000
112.30	308.00	4769.00	.00	1.000	1.000
112.60	404.00	4800.00	.00	1.000	1.000
110.40	406.00	4821.00	.00	1.000	1.000
111.40	507.00	4870.00	.00	1.000	1.000
110.70	607.00	4822.00	.00	1.000	1.000
112.00	211.00	4745.00	.00	1.000	1.000
105.50	203.00	2268.00	.00	1.375	1.000
106.10	306.00	2285.00	.00	1.375	1.000
108.60	402.00	2293.00	.00	1.375	1.000
108.80	211.00	2915.00	.00	1.375	1.000
108.50	215.00	2908.00	.00	1.375	1.000
108.50	308.00	2925.00	.00	1.375	1.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
108.30	311.00	2923.00	.00	1.375	1.000
109.60	404.00	2952.00	.00	1.375	1.000
108.50	211.00	3527.00	.00	1.375	1.000
108.30	213.00	3522.00	.00	1.375	1.000
109.60	306.00	3545.00	.00	1.375	1.000
108.90	305.00	3545.00	.00	1.375	1.000
110.10	402.00	3580.00	.00	1.375	1.000
110.20	402.00	3567.00	.00	1.375	1.000
111.80	208.00	4183.00	.00	1.375	1.000
113.00	306.00	4181.00	.00	1.375	1.000
111.70	309.00	4228.00	.00	1.375	1.000
113.00	403.00	4239.00	.00	1.375	1.000
112.50	405.00	4360.00	.00	1.375	1.000
111.30	511.00	4303.00	.00	1.375	1.000
110.00	606.00	4405.00	.00	1.375	1.000
112.10	210.00	4842.00	.00	1.375	1.000
112.30	307.00	4865.00	.00	1.375	1.000
112.70	314.00	4923.00	.00	1.375	1.000
114.20	405.00	4886.00	.00	1.375	1.000
111.00	509.00	5082.00	.00	1.375	1.000
113.60	215.00	5415.00	.00	1.375	1.000
112.50	307.00	5438.00	.00	1.375	1.000
113.10	403.00	5446.00	.00	1.375	1.000
113.40	207.00	6195.00	.00	1.375	1.000
112.70	212.00	6242.00	.00	1.375	1.000
114.30	312.00	6234.00	.00	1.375	1.000
113.10	310.00	6218.00	.00	1.375	1.000
114.80	402.00	6167.00	.00	1.375	1.000
114.10	402.00	6237.00	.00	1.375	1.000
111.40	155.00	6225.00	.00	1.375	1.000
112.80	402.00	4180.00	.00	1.375	1.000
110.20	318.00	2979.00	.00	1.375	1.000
110.00	223.00	3609.00	.00	1.375	1.000
112.10	411.00	3625.00	.00	1.375	1.000
112.00	405.00	3628.00	.00	1.375	1.000
110.50	312.00	3623.00	.00	1.375	1.000
109.60	221.00	3615.00	.00	1.375	1.000
109.00	206.00	2334.00	.00	1.000	.000
110.20	303.00	2333.00	.00	1.000	.000
111.00	404.00	2344.00	.00	1.000	.000
110.20	506.00	2226.00	.00	1.000	.000
112.80	602.00	2241.00	.00	1.000	.000
111.30	208.00	2919.00	.00	1.000	.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
112.70	305.00	2933.00	.00	1.000	.000
112.30	401.00	2955.00	.00	1.000	.000
110.50	406.00	2840.00	.00	1.000	.000
111.10	508.00	2877.00	.00	1.000	.000
112.50	606.00	2890.00	.00	1.000	.000
112.70	207.00	3587.00	.00	1.000	.000
111.60	209.00	3588.00	.00	1.000	.000
112.80	307.00	3622.00	.00	1.000	.000
113.40	307.00	3607.00	.00	1.000	.000
113.20	400.00	3642.00	.00	1.000	.000
113.40	398.00	3660.00	.00	1.000	.000
113.60	508.00	3622.00	.00	1.000	.000
112.90	606.00	3651.00	.00	1.000	.000
112.50	218.00	4294.00	.00	1.000	.000
110.80	208.00	4238.00	.00	1.000	.000
113.30	305.00	4254.00	.00	1.000	.000
112.70	402.00	4258.00	.00	1.000	.000
114.00	508.00	4344.00	.00	1.000	.000
112.90	607.00	4362.00	.00	1.000	.000
112.30	209.00	4818.00	.00	1.000	.000
113.00	211.00	4916.00	.00	1.000	.000
113.20	306.00	4869.00	.00	1.000	.000
113.30	407.00	4898.00	.00	1.000	.000
114.30	510.00	4979.00	.00	1.000	.000
113.00	607.00	4995.00	.00	1.000	.000
106.30	212.00	2283.00	.00	1.375	.000
109.50	309.00	2302.00	.00	1.375	.000
110.40	402.00	2326.00	.00	1.375	.000
109.70	209.00	2892.00	.00	1.375	.000
110.40	308.00	2914.00	.00	1.375	.000
113.00	405.00	2943.00	.00	1.375	.000
109.60	208.00	3559.00	.00	1.375	.000
111.90	304.00	3575.00	.00	1.375	.000
112.50	313.00	3715.00	.00	1.375	.000
112.80	402.00	3591.00	.00	1.375	.000
113.30	405.00	3741.00	.00	1.375	.000
112.80	214.00	4321.00	.00	1.375	.000
114.10	309.00	4316.00	.00	1.375	.000
113.30	313.00	4342.00	.00	1.375	.000
114.60	402.00	4330.00	.00	1.375	.000
114.60	403.00	4357.00	.00	1.375	.000
114.70	505.00	4407.00	.00	1.375	.000
114.10	604.00	4420.00	.00	1.375	.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
113.80	212.00	4979.00	.00	1.375	.000
113.80	310.00	5001.00	.00	1.375	.000
113.70	309.00	4958.00	.00	1.375	.000
115.50	405.00	5047.00	.00	1.375	.000
114.30	409.00	4973.00	.00	1.375	.000
114.70	511.00	4982.00	.00	1.375	.000
113.90	604.00	4992.00	.00	1.375	.000
114.10	211.00	5558.00	.00	1.375	.000
113.30	218.00	5485.00	.00	1.375	.000
114.40	313.00	5497.00	.00	1.375	.000
114.30	310.00	5502.00	.00	1.375	.000
116.10	405.00	5576.00	.00	1.375	.000
115.20	408.00	5510.00	.00	1.375	.000
114.70	511.00	5523.00	.00	1.375	.000
113.40	600.00	5544.00	.00	1.375	.000
114.10	212.00	6342.00	.00	1.375	.000
114.60	211.00	6224.00	.00	1.375	.000
115.20	311.00	6360.00	.00	1.375	.000
115.70	309.00	6234.00	.00	1.375	.000
116.20	404.00	6382.00	.00	1.375	.000
115.30	402.00	6244.00	.00	1.375	.000
114.30	506.00	6256.00	.00	1.375	.000
113.20	603.00	6205.00	.00	1.375	.000
102.10	207.00	2313.00	3.00	1.000	1.000
102.00	211.00	2306.00	3.00	1.000	1.000
102.20	309.00	2321.00	3.00	1.000	1.000
104.00	308.00	2318.00	3.00	1.000	1.000
102.90	402.00	2335.00	3.00	1.000	1.000
105.50	405.00	2329.00	3.00	1.000	1.000
102.40	503.00	2448.00	3.00	1.000	1.000
103.60	605.00	2461.00	3.00	1.000	1.000
103.50	205.00	2909.00	3.00	1.000	1.000
104.30	311.00	3084.00	3.00	1.000	1.000
104.40	312.00	3005.00	3.00	1.000	1.000
103.90	402.00	2978.00	3.00	1.000	1.000
103.20	403.00	3098.00	3.00	1.000	1.000
105.40	508.00	3113.00	3.00	1.000	1.000
102.50	507.00	3012.00	3.00	1.000	1.000
105.70	605.00	3129.00	3.00	1.000	1.000
104.40	201.00	3591.00	3.00	1.000	1.000
106.30	308.00	3605.00	3.00	1.000	1.000
105.80	314.00	3601.00	3.00	1.000	1.000
106.80	401.00	3617.00	3.00	1.000	1.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
105.90	511.00	3815.00	3.00	1.000	1.000
107.70	604.00	3820.00	3.00	1.000	1.000
105.80	210.00	4275.00	3.00	1.000	1.000
105.70	213.00	4272.00	3.00	1.000	1.000
107.00	309.00	4285.00	3.00	1.000	1.000
106.50	315.00	4285.00	3.00	1.000	1.000
107.30	411.00	4288.00	3.00	1.000	1.000
108.60	411.00	4296.00	3.00	1.000	1.000
105.80	508.00	4411.00	3.00	1.000	1.000
106.70	595.00	4434.00	3.00	1.000	1.000
106.20	206.00	4888.00	3.00	1.000	1.000
106.30	205.00	4899.00	3.00	1.000	1.000
107.60	302.00	4898.00	3.00	1.000	1.000
108.20	307.00	4916.00	3.00	1.000	1.000
108.10	412.00	4927.00	3.00	1.000	1.000
108.90	412.00	4912.00	3.00	1.000	1.000
107.10	510.00	4876.00	3.00	1.000	1.000
106.20	607.00	4902.00	3.00	1.000	1.000
105.80	407.00	4398.00	3.00	1.000	1.000
105.00	212.00	4371.00	3.00	1.000	1.000
106.10	400.00	3028.00	3.00	1.000	1.000
103.40	304.00	2953.00	3.00	1.000	1.000
102.70	215.00	4368.00	3.00	1.000	1.000
103.50	305.00	2985.00	3.00	1.000	1.000
104.90	210.00	2335.00	3.00	1.375	1.000
103.90	208.00	2337.00	3.00	1.375	1.000
104.30	310.00	2340.00	3.00	1.375	1.000
105.00	311.00	2337.00	3.00	1.375	1.000
106.60	406.00	2351.00	3.00	1.375	1.000
105.50	407.00	2347.00	3.00	1.375	1.000
103.50	211.00	2916.00	3.00	1.375	1.000
103.60	209.00	2915.00	3.00	1.375	1.000
104.90	305.00	2937.00	3.00	1.375	1.000
104.50	305.00	2935.00	3.00	1.375	1.000
106.10	411.00	2959.00	3.00	1.375	1.000
106.70	411.00	2955.00	3.00	1.375	1.000
105.90	218.00	3611.00	3.00	1.375	1.000
105.30	214.00	3609.00	3.00	1.375	1.000
105.10	313.00	3623.00	3.00	1.375	1.000
106.00	311.00	3621.00	3.00	1.375	1.000
108.00	408.00	3709.00	3.00	1.375	1.000
108.50	411.00	3701.00	3.00	1.375	1.000
106.80	217.00	4187.00	3.00	1.375	1.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
106.00	215.00	4188.00	3.00	1.375	1.000
108.10	313.00	4210.00	3.00	1.375	1.000
107.60	307.00	4202.00	3.00	1.375	1.000
108.80	408.00	4233.00	3.00	1.375	1.000
108.90	407.00	4230.00	3.00	1.375	1.000
108.90	510.00	4456.00	3.00	1.375	1.000
109.20	603.00	4485.00	3.00	1.375	1.000
106.50	211.00	4833.00	3.00	1.375	1.000
106.30	217.00	4808.00	3.00	1.375	1.000
108.50	309.00	4816.00	3.00	1.375	1.000
107.40	310.00	4826.00	3.00	1.375	1.000
107.40	403.00	4839.00	3.00	1.375	1.000
108.30	403.00	4840.00	3.00	1.375	1.000
109.80	506.00	5110.00	3.00	1.375	1.000
110.80	604.00	5136.00	3.00	1.375	1.000
108.00	210.00	5649.00	3.00	1.375	1.000
107.30	212.00	5644.00	3.00	1.375	1.000
109.20	311.00	5662.00	3.00	1.375	1.000
108.60	310.00	5512.00	3.00	1.375	1.000
110.20	411.00	5669.00	3.00	1.375	1.000
108.70	401.00	5666.00	3.00	1.375	1.000
110.30	507.00	5740.00	3.00	1.375	1.000
110.40	604.00	5755.00	3.00	1.375	1.000
108.00	206.00	6298.00	3.00	1.375	1.000
109.40	178.00	6270.00	3.00	1.375	1.000
109.70	308.00	6307.00	3.00	1.375	1.000
109.00	307.00	6143.00	3.00	1.375	1.000
109.60	407.00	6320.00	3.00	1.375	1.000
109.30	402.00	6148.00	3.00	1.375	1.000
108.40	504.00	6161.00	3.00	1.375	1.000
109.40	601.00	6369.00	3.00	1.375	1.000
110.40	578.00	6311.00	3.00	1.375	1.000
108.60	310.00	6230.00	3.00	1.375	1.000
110.70	506.00	6009.00	3.00	1.375	1.000
109.90	562.00	6018.00	3.00	1.375	1.000
109.10	565.00	5692.00	3.00	1.375	1.000
108.80	571.00	5286.00	3.00	1.375	1.000
108.60	472.00	5270.00	3.00	1.375	1.000
108.30	415.00	5249.00	3.00	1.375	1.000
108.40	332.00	5229.00	3.00	1.375	1.000
110.00	544.00	4868.00	3.00	1.375	1.000
110.90	577.00	4554.00	3.00	1.375	1.000
109.40	579.00	4223.00	3.00	1.375	1.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
107.70	572.00	3987.00	3.00	1.375	1.000
109.40	582.00	3734.00	3.00	1.375	1.000
108.60	577.00	4892.00	3.00	1.375	1.000
109.10	408.00	3703.00	3.00	1.375	1.000
109.70	313.00	4210.00	3.00	1.375	1.000
110.30	413.00	4233.00	3.00	1.375	1.000
108.80	405.00	4841.00	3.00	1.375	1.000
106.10	214.00	5496.00	3.00	1.375	1.000
108.70	301.00	5653.00	3.00	1.375	1.000
108.70	310.00	5653.00	3.00	1.375	1.000
110.40	409.00	5661.00	3.00	1.375	1.000
109.30	300.00	5711.00	3.00	1.375	1.000
110.50	202.00	5057.00	3.00	1.375	1.000
100.60	207.00	2314.00	3.00	1.000	.000
100.50	315.00	2332.00	3.00	1.000	.000
103.80	404.00	2347.00	3.00	1.000	.000
105.60	508.00	2295.00	3.00	1.000	.000
105.90	607.00	2306.00	3.00	1.000	.000
101.50	214.00	2924.00	3.00	1.000	.000
104.20	198.00	2932.00	3.00	1.000	.000
102.80	306.00	2939.00	3.00	1.000	.000
104.80	406.00	2957.00	3.00	1.000	.000
105.70	403.00	3121.00	3.00	1.000	.000
107.70	507.00	3135.00	3.00	1.000	.000
107.20	602.00	3147.00	3.00	1.000	.000
103.80	215.00	3670.00	3.00	1.000	.000
103.90	204.00	3665.00	3.00	1.000	.000
105.30	316.00	3715.00	3.00	1.000	.000
105.90	304.00	3720.00	3.00	1.000	.000
108.20	409.00	3578.00	3.00	1.000	.000
107.90	402.00	3581.00	3.00	1.000	.000
107.50	517.00	3741.00	3.00	1.000	.000
108.30	504.00	3644.00	3.00	1.000	.000
108.30	606.00	3755.00	3.00	1.000	.000
106.90	605.00	3657.00	3.00	1.000	.000
101.70	202.00	4273.00	3.00	1.000	.000
105.20	216.00	4349.00	3.00	1.000	.000
103.80	310.00	4272.00	3.00	1.000	.000
106.10	412.00	4297.00	3.00	1.000	.000
104.80	398.00	4296.00	3.00	1.000	.000
108.10	511.00	4382.00	3.00	1.000	.000
108.40	614.00	4392.00	3.00	1.000	.000
105.10	215.00	4793.00	3.00	1.000	.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
104.70	209.00	4930.00	3.00	1.000	.000
105.60	306.00	4940.00	3.00	1.000	.000
105.50	314.00	4806.00	3.00	1.000	.000
105.70	414.00	4944.00	3.00	1.000	.000
108.10	509.00	4831.00	3.00	1.000	.000
108.30	578.00	4850.00	3.00	1.000	.000
105.20	409.00	3696.00	3.00	1.000	.000
104.00	201.00	4694.00	3.00	1.000	.000
106.70	401.00	3726.00	3.00	1.000	.000
103.70	319.00	3682.00	3.00	1.000	.000
106.60	403.00	2957.00	3.00	1.000	.000
104.30	307.00	3618.00	3.00	1.000	.000
106.20	400.00	3635.00	3.00	1.000	.000
104.20	209.00	2338.00	3.00	1.375	.000
105.00	311.00	2360.00	3.00	1.375	.000
106.10	403.00	2378.00	3.00	1.375	.000
104.20	213.00	2915.00	3.00	1.375	.000
106.30	309.00	2937.00	3.00	1.375	.000
107.00	402.00	2961.00	3.00	1.375	.000
104.90	209.00	3593.00	3.00	1.375	.000
105.00	312.00	3606.00	3.00	1.375	.000
106.10	400.00	3622.00	3.00	1.375	.000
104.90	212.00	4402.00	3.00	1.375	.000
105.70	208.00	4207.00	3.00	1.375	.000
106.80	302.00	4227.00	3.00	1.375	.000
106.40	309.00	4277.00	3.00	1.375	.000
107.50	411.00	4258.00	3.00	1.375	.000
107.60	398.00	4286.00	3.00	1.375	.000
108.00	505.00	4454.00	3.00	1.375	.000
109.20	604.00	4478.00	3.00	1.375	.000
106.40	207.00	4848.00	3.00	1.375	.000
106.40	206.00	4846.00	3.00	1.375	.000
107.90	315.00	4859.00	3.00	1.375	.000
107.50	313.00	4852.00	3.00	1.375	.000
110.50	407.00	4867.00	3.00	1.375	.000
107.20	401.00	5000.00	3.00	1.375	.000
108.00	506.00	5014.00	3.00	1.375	.000
109.10	602.00	5027.00	3.00	1.375	.000
107.50	201.00	5435.00	3.00	1.375	.000
106.90	216.00	5595.00	3.00	1.375	.000
109.30	315.00	5539.00	3.00	1.375	.000
108.60	308.00	5539.00	3.00	1.375	.000
108.80	413.00	5561.00	3.00	1.375	.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
109.20	424.00	5586.00	3.00	1.375	.000
109.00	510.00	5642.00	3.00	1.375	.000
108.90	604.00	5664.00	3.00	1.375	.000
108.60	204.00	6200.00	3.00	1.375	.000
107.70	196.00	6155.00	3.00	1.375	.000
108.80	316.00	6197.00	3.00	1.375	.000
109.10	304.00	6137.00	3.00	1.375	.000
110.80	405.00	6219.00	3.00	1.375	.000
110.00	408.00	6213.00	3.00	1.375	.000
109.40	508.00	6334.00	3.00	1.375	.000
110.20	598.00	6323.00	3.00	1.375	.000
110.70	604.00	6346.00	3.00	1.375	.000
112.20	556.00	6299.00	3.00	1.375	.000
110.50	453.00	6274.00	3.00	1.375	.000
108.50	436.00	6007.00	3.00	1.375	.000
109.00	561.00	6020.00	3.00	1.375	.000
108.60	543.00	5694.00	3.00	1.375	.000
108.90	428.00	5668.00	3.00	1.375	.000
108.10	428.00	5266.00	3.00	1.375	.000
109.30	579.00	5280.00	3.00	1.375	.000
109.00	453.00	6004.00	3.00	1.375	.000
108.40	596.00	4993.00	3.00	1.375	.000
108.10	481.00	4969.00	3.00	1.375	.000
107.50	401.00	4933.00	3.00	1.375	.000
107.30	403.00	4610.00	3.00	1.375	.000
107.70	484.00	4622.00	3.00	1.375	.000
109.00	590.00	4636.00	3.00	1.375	.000
108.50	586.00	4348.00	3.00	1.375	.000
110.20	473.00	4216.00	3.00	1.375	.000
106.10	376.00	4179.00	3.00	1.375	.000
107.90	475.00	3714.00	3.00	1.375	.000
110.10	555.00	3728.00	3.00	1.375	.000
109.60	510.00	3709.00	3.00	1.375	.000
109.00	213.00	4836.00	3.00	1.375	.000
109.80	304.00	4853.00	3.00	1.375	.000
107.90	304.00	5453.00	3.00	1.375	.000
110.40	405.00	5468.00	3.00	1.375	.000
106.30	403.00	4432.00	3.00	1.375	.000
105.20	205.00	4265.00	3.00	1.375	.000
105.60	213.00	4971.00	3.00	1.375	.000
106.30	210.00	5523.00	3.00	1.375	.000
108.00	401.00	5624.00	3.00	1.375	.000
106.90	405.00	6231.00	3.00	1.375	.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
107.30	218.00	6210.00	3.00	1.375	.000
104.60	214.00	2418.00	.75	1.000	1.000
105.80	307.00	2432.00	.75	1.000	1.000
106.70	402.00	2445.00	.75	1.000	1.000
107.40	507.00	2458.00	.75	1.000	1.000
107.70	593.00	2472.00	.75	1.000	1.000
104.50	216.00	2978.00	.75	1.000	1.000
107.10	301.00	2993.00	.75	1.000	1.000
107.90	408.00	3004.00	.75	1.000	1.000
108.50	510.00	3004.00	.75	1.000	1.000
109.20	605.00	3012.00	.75	1.000	1.000
106.30	213.00	3685.00	.75	1.000	1.000
108.50	306.00	3700.00	.75	1.000	1.000
109.10	404.00	3716.00	.75	1.000	1.000
109.70	509.00	3734.00	.75	1.000	1.000
110.10	607.00	3758.00	.75	1.000	1.000
107.90	216.00	4335.00	.75	1.000	1.000
109.20	305.00	4350.00	.75	1.000	1.000
110.50	407.00	4364.00	.75	1.000	1.000
111.10	508.00	4381.00	.75	1.000	1.000
111.20	606.00	4397.00	.75	1.000	1.000
108.90	210.00	4928.00	.75	1.000	1.000
110.20	307.00	4947.00	.75	1.000	1.000
110.90	405.00	4966.00	.75	1.000	1.000
112.20	502.00	4994.00	.75	1.000	1.000
112.50	584.00	4825.00	.75	1.000	1.000
108.40	219.00	3748.00	.75	1.375	1.000
109.70	310.00	3752.00	.75	1.375	1.000
111.10	402.00	3756.00	.75	1.375	1.000
111.80	510.00	3779.00	.75	1.375	1.000
112.60	606.00	3789.00	.75	1.375	1.000
110.90	214.00	4352.00	.75	1.375	1.000
112.00	311.00	4361.00	.75	1.375	1.000
112.50	406.00	4371.00	.75	1.375	1.000
112.70	510.00	4383.00	.75	1.375	1.000
113.10	609.00	4396.00	.75	1.375	1.000
111.50	218.00	4953.00	.75	1.375	1.000
111.30	309.00	4965.00	.75	1.375	1.000
112.10	401.00	4967.00	.75	1.375	1.000
112.60	512.00	4986.00	.75	1.375	1.000
113.40	607.00	5007.00	.75	1.375	1.000
111.80	216.00	5523.00	.75	1.375	1.000
110.40	312.00	5528.00	.75	1.375	1.000

Sound Power dBA	**Speed rpm**	**Thrust lbs**	**Water gpm**	**Bit Size in.**	**Drill Steel (hex/round)**
113.60	403.00	5942.00	.75	1.375	1.000
113.60	510.00	5558.00	.75	1.375	1.000
114.80	608.00	5569.00	.75	1.375	1.000
109.80	218.00	6244.00	.75	1.375	1.000
111.20	309.00	6256.00	.75	1.375	1.000
112.90	401.00	6275.00	.75	1.375	1.000
114.30	509.00	6294.00	.75	1.375	1.000
113.40	608.00	6317.00	.75	1.375	1.000
107.20	216.00	2347.00	.75	1.000	.000
108.09	307.00	2357.00	.75	1.000	.000
109.04	405.00	2370.00	.75	1.000	.000
110.04	508.00	2387.00	.75	1.000	.000
111.00	607.00	2404.00	.75	1.000	.000
108.07	216.00	2989.00	.75	1.000	.000
108.86	308.00	2999.00	.75	1.000	.000
109.69	406.00	3008.00	.75	1.000	.000
110.54	505.00	3022.00	.75	1.000	.000
111.39	606.00	3036.00	.75	1.000	.000
109.02	218.00	3686.00	.75	1.000	.000
109.64	302.00	3699.00	.75	1.000	.000
110.38	404.00	3709.00	.75	1.000	.000
111.09	501.00	3723.00	.75	1.000	.000
111.83	604.00	3738.00	.75	1.000	.000
109.68	204.00	4239.00	.75	1.000	.000
110.34	309.00	4247.00	.75	1.000	.000
110.93	404.00	4257.00	.75	1.000	.000
111.58	508.00	4269.00	.75	1.000	.000
112.19	606.00	4278.00	.75	1.000	.000
110.63	212.00	4899.00	.75	1.000	.000
111.14	310.00	4916.00	.75	1.000	.000
111.59	403.00	4909.00	.75	1.000	.000
112.11	506.00	4929.00	.75	1.000	.000
112.63	608.00	4955.00	.75	1.000	.000
107.90	213.00	3680.00	.75	1.375	.000
109.90	305.00	3692.00	.75	1.375	.000
111.70	403.00	3717.00	.75	1.375	.000
112.90	509.00	3736.00	.75	1.375	.000
113.30	606.00	3752.00	.75	1.375	.000
108.70	213.00	4298.00	.75	1.375	.000
111.60	314.00	4310.00	.75	1.375	.000
112.50	402.00	4326.00	.75	1.375	.000
114.00	508.00	4338.00	.75	1.375	.000
114.80	607.00	4357.00	.75	1.375	.000

Sound Power dBA	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)
107.30	212.00	4977.00	.75	1.375	.000
108.00	303.00	4998.00	.75	1.375	.000
112.30	398.00	5013.00	.75	1.375	.000
114.20	511.00	5037.00	.75	1.375	.000
116.20	606.00	5060.00	.75	1.375	.000
110.50	211.00	5617.00	.75	1.375	.000
113.10	306.00	5632.00	.75	1.375	.000
113.60	404.00	5646.00	.75	1.375	.000
117.00	512.00	5671.00	.75	1.375	.000
116.10	595.00	5686.00	.75	1.375	.000
111.90	212.00	6260.00	.75	1.375	.000
113.60	312.00	6287.00	.75	1.375	.000
114.90	404.00	6317.00	.75	1.375	.000
115.90	507.00	6347.00	.75	1.375	.000
116.90	598.00	6306.00	.75	1.375	.000

Utilizing the sound power level as the dependent variable and the rotational speed, thrust, drilling method, bit size and drill steel type as the independent variables, a statistical approach utilizing a multiple linear regression analysis, was performed to fit the data and to provide an accurate representation for obtaining one equation to determine the sound power level given any drilling method or drilling configuration used. Table 5.16 represents the regression coefficients determined from the statistical model run.

Table 5.16 Regression Coefficients Determined from the Statistical Model

(Constant)	101.708
Water	-1.766
Thrust	.001
Speed	.007
Bit Size	2.568
Drill Steel	-.640

5.4.2 Statistical Accuracy of the Model

The statistical accuracy of the data fit is shown in the histogram below (figure 5.8) and tabulated in table 5.17. Additionally, R^2, the coefficient of determination, or the measure of the goodness of fit of a linear model, was equal to .849, indicating the model to be a good fit or representation of the data set.

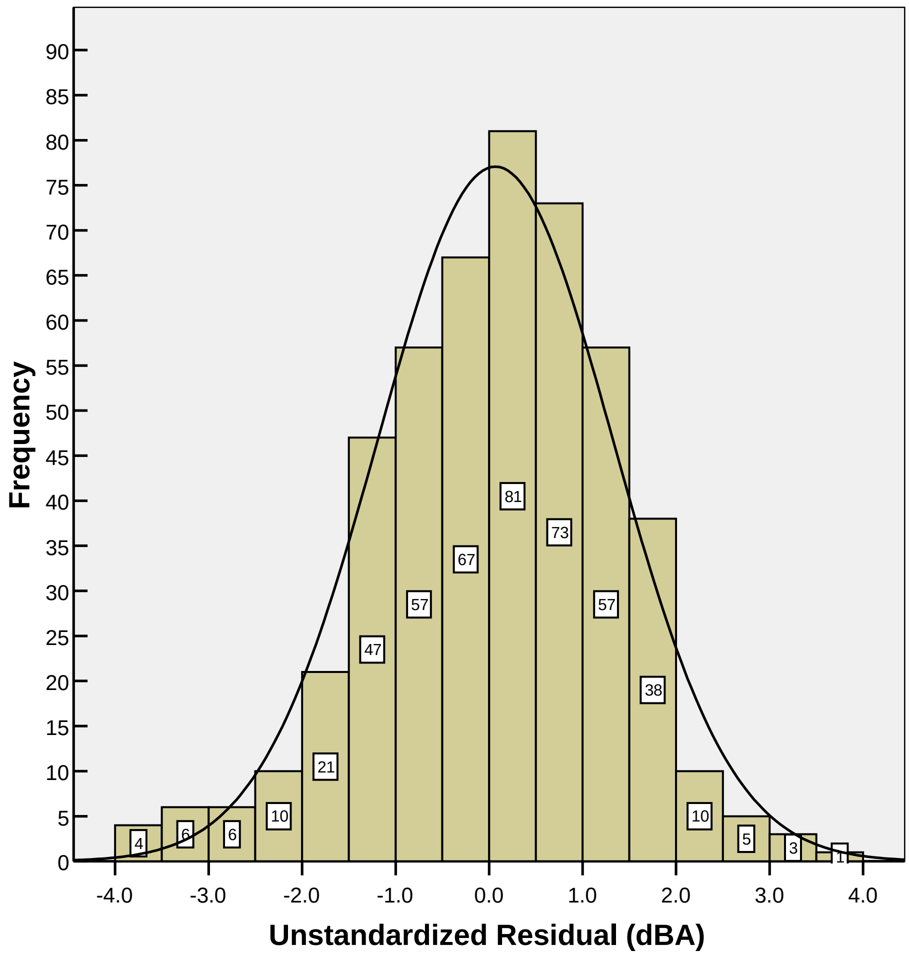


Figure 5.8 Histogram Representing the Fit Accuracy of Statistical Run of Model

As shown in figure 5.8, the data follows a nice "bell-shaped" curve, indicating the data set is normally distributed. Also, figure 5.8 displays, graphically, the residuals (laboratory minus model values of sound power) from the data set. As shown, five residuals were determined to be plus or minus 3.5 to 4.0 dBA and nine residuals at plus or minus 3.0 to 3.5 dBA. The remaining 472 residuals all fell within plus or minus 0 to 3.0 dBA. Therefore, 97% of the data fell within a residual of 0 to 3.0 dBA and would be well received within the acoustical community, particularly during prediction exercises.

Table 5.17 Comparing Laboratory Results to Model Results (Sound Power Level)

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
106.60	209.00	2239.00	.00	1.000	1.000	107.75978	-1.15978
107.10	210.00	2228.00	.00	1.000	1.000	107.75385	-.65385
108.30	306.00	2282.00	.00	1.000	1.000	108.40316	-.10316
107.40	305.00	2272.00	.00	1.000	1.000	108.38604	-.98604
108.40	400.00	2324.00	.00	1.000	1.000	109.02700	-.62700
108.60	402.00	2280.00	.00	1.000	1.000	108.99101	-.39101
109.50	514.00	2220.00	.00	1.000	1.000	109.61354	-.11354
108.80	609.00	2241.00	.00	1.000	1.000	110.22048	-1.42048
107.80	208.00	2711.00	.00	1.000	1.000	108.27164	-.47164
109.90	305.00	2696.00	.00	1.000	1.000	108.85136	1.04864
109.40	306.00	2705.00	.00	1.000	1.000	108.86739	.53261
109.90	402.00	2701.00	.00	1.000	1.000	109.45304	.44696
110.10	509.00	2865.00	.00	1.000	1.000	110.29067	-.19067
110.10	602.00	2882.00	.00	1.000	1.000	110.88093	-.78093
110.20	215.00	3435.00	.00	1.000	1.000	109.10923	1.09077
110.90	304.00	3451.00	.00	1.000	1.000	109.67380	1.22620
109.60	311.00	3620.00	.00	1.000	1.000	109.90230	-.30230
111.50	405.00	3487.00	.00	1.000	1.000	110.33409	1.16591
111.60	404.00	3483.00	.00	1.000	1.000	110.32355	1.27645
110.50	510.00	3628.00	.00	1.000	1.000	111.13419	-.63419
111.10	607.00	3653.00	.00	1.000	1.000	111.75781	-.65781
111.20	208.00	4085.00	.00	1.000	1.000	109.77955	1.42045
111.60	305.00	4097.00	.00	1.000	1.000	110.38891	1.21109
111.50	404.00	4111.00	.00	1.000	1.000	111.01276	.48724
111.40	406.00	4283.00	.00	1.000	1.000	111.21381	.18619
110.90	509.00	4291.00	.00	1.000	1.000	111.85566	-.95566
110.90	604.00	4314.00	.00	1.000	1.000	112.46480	-1.56480
110.40	221.00	4744.00	.00	1.000	1.000	110.58269	-.18269
110.60	223.00	4778.00	.00	1.000	1.000	110.63229	-.03229
112.30	308.00	4769.00	.00	1.000	1.000	111.14485	1.15515
112.60	404.00	4800.00	.00	1.000	1.000	111.76891	.83109
110.40	406.00	4821.00	.00	1.000	1.000	111.80425	-1.40425
111.40	507.00	4870.00	.00	1.000	1.000	112.47880	-1.07880
110.70	607.00	4822.00	.00	1.000	1.000	113.04075	-2.34075
112.00	211.00	4745.00	.00	1.000	1.000	110.52232	1.47768
105.50	203.00	2268.00	.00	1.375	1.000	108.65847	-3.15847

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
106.10	306.00	2285.00	.00	1.375	1.000	109.31019	-3.21019
108.60	402.00	2293.00	.00	1.375	1.000	109.90901	-1.30901
108.80	211.00	2915.00	.00	1.375	1.000	109.41770	-.61770
108.50	215.00	2908.00	.00	1.375	1.000	109.43460	-.93460
108.50	308.00	2925.00	.00	1.375	1.000	110.02486	-1.52486
108.30	311.00	2923.00	.00	1.375	1.000	110.04110	-1.74110
109.60	404.00	2952.00	.00	1.375	1.000	110.64453	-1.04453
108.50	211.00	3527.00	.00	1.375	1.000	110.08935	-1.58935
108.30	213.00	3522.00	.00	1.375	1.000	110.09615	-1.79615
109.60	306.00	3545.00	.00	1.375	1.000	110.69300	-1.09300
108.90	305.00	3545.00	.00	1.375	1.000	110.68685	-1.78685
110.10	402.00	3580.00	.00	1.375	1.000	111.32145	-1.22145
110.20	402.00	3567.00	.00	1.375	1.000	111.30718	-1.10718
111.80	208.00	4183.00	.00	1.375	1.000	110.79084	1.00916
113.00	306.00	4181.00	.00	1.375	1.000	111.39098	1.60902
111.70	309.00	4228.00	.00	1.375	1.000	111.46100	.23900
113.00	403.00	4239.00	.00	1.375	1.000	112.05082	.94918
112.50	405.00	4360.00	.00	1.375	1.000	112.19591	.30409
111.30	511.00	4303.00	.00	1.375	1.000	112.78486	-1.48486
110.00	606.00	4405.00	.00	1.375	1.000	113.48070	-3.48070
112.10	210.00	4842.00	.00	1.375	1.000	111.52637	.57363
112.30	307.00	4865.00	.00	1.375	1.000	112.14780	.15220
112.70	314.00	4923.00	.00	1.375	1.000	112.25447	.44553
114.20	405.00	4886.00	.00	1.375	1.000	112.77318	1.42682
111.00	509.00	5082.00	.00	1.375	1.000	113.62749	-2.62749
113.60	215.00	5415.00	.00	1.375	1.000	112.18594	1.41406
112.50	307.00	5438.00	.00	1.375	1.000	112.77664	-.27664
113.10	403.00	5446.00	.00	1.375	1.000	113.37546	-.27546
113.40	207.00	6195.00	.00	1.375	1.000	112.99280	.40720
112.70	212.00	6242.00	.00	1.375	1.000	113.07511	-.37511
114.30	312.00	6234.00	.00	1.375	1.000	113.68096	.61904
113.10	310.00	6218.00	.00	1.375	1.000	113.65110	-.55110
114.80	402.00	6167.00	.00	1.375	1.000	114.16059	.63941
114.10	402.00	6237.00	.00	1.375	1.000	114.23741	-.13741
111.40	155.00	6225.00	.00	1.375	1.000	112.70612	-1.30612
112.80	402.00	4180.00	.00	1.375	1.000	111.97993	.82007
110.20	318.00	2979.00	.00	1.375	1.000	110.14559	.05441
110.00	223.00	3609.00	.00	1.375	1.000	110.25309	-.25309
112.10	411.00	3625.00	.00	1.375	1.000	111.42615	.67385
112.00	405.00	3628.00	.00	1.375	1.000	111.39257	.60743
110.50	312.00	3623.00	.00	1.375	1.000	110.81548	-.31548

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
109.60	221.00	3615.00	.00	1.375	1.000	110.24738	-.64738
109.00	206.00	2334.00	.00	1.000	.000	108.64027	.35973
110.20	303.00	2333.00	.00	1.000	.000	109.23536	.96464
111.00	404.00	2344.00	.00	1.000	.000	109.86820	1.13180
110.20	506.00	2226.00	.00	1.000	.000	110.36562	-.16562
112.80	602.00	2241.00	.00	1.000	.000	110.97212	1.82788
111.30	208.00	2919.00	.00	1.000	.000	109.29458	2.00542
112.70	305.00	2933.00	.00	1.000	.000	109.90613	2.79387
112.30	401.00	2955.00	.00	1.000	.000	110.52031	1.77969
110.50	406.00	2840.00	.00	1.000	.000	110.42484	.07516
111.10	508.00	2877.00	.00	1.000	.000	111.09236	.00764
112.50	606.00	2890.00	.00	1.000	.000	111.70896	.79104
112.70	207.00	3587.00	.00	1.000	.000	110.02154	2.67846
111.60	209.00	3588.00	.00	1.000	.000	110.03493	1.56507
112.80	307.00	3622.00	.00	1.000	.000	110.67457	2.12543
113.40	307.00	3607.00	.00	1.000	.000	110.65811	2.74189
113.20	400.00	3642.00	.00	1.000	.000	111.26813	1.93187
113.40	398.00	3660.00	.00	1.000	.000	111.27559	2.12441
113.60	508.00	3622.00	.00	1.000	.000	111.90997	1.69003
112.90	606.00	3651.00	.00	1.000	.000	112.54414	.35586
112.50	218.00	4294.00	.00	1.000	.000	110.86505	1.63495
110.80	208.00	4238.00	.00	1.000	.000	110.74213	.05787
113.30	305.00	4254.00	.00	1.000	.000	111.35588	1.94412
112.70	402.00	4258.00	.00	1.000	.000	111.95646	.74354
114.00	508.00	4344.00	.00	1.000	.000	112.70234	1.29766
112.90	607.00	4362.00	.00	1.000	.000	113.33058	-.43058
112.30	209.00	4818.00	.00	1.000	.000	111.38481	.91519
113.00	211.00	4916.00	.00	1.000	.000	111.50465	1.49535
113.20	306.00	4869.00	.00	1.000	.000	112.03697	1.16303
113.30	407.00	4898.00	.00	1.000	.000	112.68957	.61043
114.30	510.00	4979.00	.00	1.000	.000	113.41153	.88847
113.00	607.00	4995.00	.00	1.000	.000	114.02528	-1.02528
106.30	212.00	2283.00	.00	1.375	.000	109.52491	-3.22491
109.50	309.00	2302.00	.00	1.375	.000	110.14195	-.64195
110.40	402.00	2326.00	.00	1.375	.000	110.73989	-.33989
109.70	209.00	2892.00	.00	1.375	.000	110.17483	-.47483
110.40	308.00	2914.00	.00	1.375	.000	110.80745	-.40745
113.00	405.00	2943.00	.00	1.375	.000	111.43547	1.56453
109.60	208.00	3559.00	.00	1.375	.000	110.90069	-1.30069
111.90	304.00	3575.00	.00	1.375	.000	111.50829	.39171
112.50	313.00	3715.00	.00	1.375	.000	111.71725	.78275
112.80	402.00	3591.00	.00	1.375	.000	112.12819	.67181

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
113.30	405.00	3741.00	.00	1.375	.000	112.31124	.98876
112.80	214.00	4321.00	.00	1.375	.000	111.77384	1.02616
114.10	309.00	4316.00	.00	1.375	.000	112.35225	1.74775
113.30	313.00	4342.00	.00	1.375	.000	112.40536	.89464
114.60	402.00	4330.00	.00	1.375	.000	112.93921	1.66079
114.60	403.00	4357.00	.00	1.375	.000	112.97499	1.62501
114.70	505.00	4407.00	.00	1.375	.000	113.65678	1.04322
114.10	604.00	4420.00	.00	1.375	.000	114.27953	-.17953
113.80	212.00	4979.00	.00	1.375	.000	112.48368	1.31632
113.80	310.00	5001.00	.00	1.375	.000	113.11016	.68984
113.70	309.00	4958.00	.00	1.375	.000	113.05682	.64318
115.50	405.00	5047.00	.00	1.375	.000	113.74453	1.75547
114.30	409.00	4973.00	.00	1.375	.000	113.68791	.61209
114.70	511.00	4982.00	.00	1.375	.000	114.32470	.37530
113.90	604.00	4992.00	.00	1.375	.000	114.90728	-1.00728
114.10	211.00	5558.00	.00	1.375	.000	113.11296	.98704
113.30	218.00	5485.00	.00	1.375	.000	113.07587	.22413
114.40	313.00	5497.00	.00	1.375	.000	113.67294	.72706
114.30	310.00	5502.00	.00	1.375	.000	113.65999	.64001
116.10	405.00	5576.00	.00	1.375	.000	114.32509	1.77491
115.20	408.00	5510.00	.00	1.375	.000	114.27110	.92890
114.70	511.00	5523.00	.00	1.375	.000	114.91843	-.21843
113.40	600.00	5544.00	.00	1.375	.000	115.48850	-2.08850
114.10	212.00	6342.00	.00	1.375	.000	113.97952	.12048
114.60	211.00	6224.00	.00	1.375	.000	113.84387	.75613
115.20	311.00	6360.00	.00	1.375	.000	114.60776	.59224
115.70	309.00	6234.00	.00	1.375	.000	114.45718	1.24282
116.20	404.00	6382.00	.00	1.375	.000	115.20350	.99650
115.30	402.00	6244.00	.00	1.375	.000	115.03976	.26024
114.30	506.00	6256.00	.00	1.375	.000	115.69214	-1.39214
113.20	603.00	6205.00	.00	1.375	.000	116.23236	-3.03236
102.10	207.00	2313.00	3.00	1.000	1.000	102.73010	-.63010
102.00	211.00	2306.00	3.00	1.000	1.000	102.74700	-.74700
102.20	309.00	2321.00	3.00	1.000	1.000	103.36580	-1.16580
104.00	308.00	2318.00	3.00	1.000	1.000	103.35636	.64364
102.90	402.00	2335.00	3.00	1.000	1.000	103.95277	-1.05277
105.50	405.00	2329.00	3.00	1.000	1.000	103.96462	1.53538
102.40	503.00	2448.00	3.00	1.000	1.000	104.69755	-2.29755
103.60	605.00	2461.00	3.00	1.000	1.000	105.33874	-1.73874
103.50	205.00	2909.00	3.00	1.000	1.000	103.37190	.12810
104.30	311.00	3084.00	3.00	1.000	1.000	104.21546	.08454
104.40	312.00	3005.00	3.00	1.000	1.000	104.13490	.26510

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
103.90	402.00	2978.00	3.00	1.000	1.000	104.65844	-.75844
103.20	403.00	3098.00	3.00	1.000	1.000	104.79628	-1.59628
105.40	508.00	3113.00	3.00	1.000	1.000	105.45810	-.05810
102.50	507.00	3012.00	3.00	1.000	1.000	105.34111	-2.84111
105.70	605.00	3129.00	3.00	1.000	1.000	106.07185	-.37185
104.40	201.00	3591.00	3.00	1.000	1.000	104.09578	.30422
106.30	308.00	3605.00	3.00	1.000	1.000	104.76880	1.53120
105.80	314.00	3601.00	3.00	1.000	1.000	104.80128	.99872
106.80	401.00	3617.00	3.00	1.000	1.000	105.35357	1.44643
107.70	604.00	3820.00	3.00	1.000	1.000	106.82405	.87595
105.80	210.00	4275.00	3.00	1.000	1.000	104.90176	.89824
105.70	213.00	4272.00	3.00	1.000	1.000	104.91691	.78309
107.00	309.00	4285.00	3.00	1.000	1.000	105.52122	1.47878
106.50	315.00	4285.00	3.00	1.000	1.000	105.55810	.94190
107.30	411.00	4288.00	3.00	1.000	1.000	106.15143	1.14857
108.60	411.00	4296.00	3.00	1.000	1.000	106.16021	2.43979
105.80	508.00	4411.00	3.00	1.000	1.000	106.88261	-1.08261
106.70	595.00	4434.00	3.00	1.000	1.000	107.44257	-.74257
106.20	206.00	4888.00	3.00	1.000	1.000	105.54993	.65007
106.30	205.00	4899.00	3.00	1.000	1.000	105.55585	.74415
107.60	302.00	4898.00	3.00	1.000	1.000	106.15094	1.44906
108.20	307.00	4916.00	3.00	1.000	1.000	106.20143	1.99857
108.10	412.00	4927.00	3.00	1.000	1.000	106.85886	1.24114
108.90	412.00	4912.00	3.00	1.000	1.000	106.84240	2.05760
107.10	510.00	4876.00	3.00	1.000	1.000	107.40522	-.30522
106.20	607.00	4902.00	3.00	1.000	1.000	108.02994	-1.82994
105.80	407.00	4398.00	3.00	1.000	1.000	106.24757	-.44757
105.00	212.00	4371.00	3.00	1.000	1.000	105.01941	-.01941
106.10	400.00	3028.00	3.00	1.000	1.000	104.70102	1.39898
103.40	304.00	2953.00	3.00	1.000	1.000	104.02866	-.62866
102.70	215.00	4368.00	3.00	1.000	1.000	105.03456	-2.33456
103.50	305.00	2985.00	3.00	1.000	1.000	104.06993	-.56993
104.90	210.00	2335.00	3.00	1.375	1.000	103.67642	1.22358
103.90	208.00	2337.00	3.00	1.375	1.000	103.66632	.23368
104.30	310.00	2340.00	3.00	1.375	1.000	104.29653	.00347
105.00	311.00	2337.00	3.00	1.375	1.000	104.29939	.70061
106.60	406.00	2351.00	3.00	1.375	1.000	104.89865	1.70135
105.50	407.00	2347.00	3.00	1.375	1.000	104.90040	.59960
103.50	211.00	2916.00	3.00	1.375	1.000	104.32019	-.82019
103.60	209.00	2915.00	3.00	1.375	1.000	104.30680	-.70680
104.90	305.00	2937.00	3.00	1.375	1.000	104.92099	-.02099
104.50	305.00	2935.00	3.00	1.375	1.000	104.91879	-.41879

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
106.10	411.00	2959.00	3.00	1.375	1.000	105.59664	.50336
106.70	411.00	2955.00	3.00	1.375	1.000	105.59225	1.10775
105.90	218.00	3611.00	3.00	1.375	1.000	105.12595	.77405
105.30	214.00	3609.00	3.00	1.375	1.000	105.09917	.20083
105.10	313.00	3623.00	3.00	1.375	1.000	105.72302	-.62302
106.00	311.00	3621.00	3.00	1.375	1.000	105.70853	.29147
108.00	408.00	3709.00	3.00	1.375	1.000	106.40130	1.59870
108.50	411.00	3701.00	3.00	1.375	1.000	106.41096	2.08904
106.80	217.00	4187.00	3.00	1.375	1.000	105.75195	1.04805
106.00	215.00	4188.00	3.00	1.375	1.000	105.74075	.25925
108.10	313.00	4210.00	3.00	1.375	1.000	106.36723	1.73277
107.60	307.00	4202.00	3.00	1.375	1.000	106.32157	1.27843
108.80	408.00	4233.00	3.00	1.375	1.000	106.97637	1.82363
108.90	407.00	4230.00	3.00	1.375	1.000	106.96693	1.93307
108.90	510.00	4456.00	3.00	1.375	1.000	107.84802	1.05198
109.20	603.00	4485.00	3.00	1.375	1.000	108.45145	.74855
106.50	211.00	4833.00	3.00	1.375	1.000	106.42403	.07597
106.30	217.00	4808.00	3.00	1.375	1.000	106.43347	-.13347
108.50	309.00	4816.00	3.00	1.375	1.000	107.00771	1.49229
107.40	310.00	4826.00	3.00	1.375	1.000	107.02483	.37517
107.40	403.00	4839.00	3.00	1.375	1.000	107.61070	-.21070
108.30	403.00	4840.00	3.00	1.375	1.000	107.61180	.68820
109.80	506.00	5110.00	3.00	1.375	1.000	108.54118	1.25882
110.80	604.00	5136.00	3.00	1.375	1.000	109.17205	1.62795
108.00	210.00	5649.00	3.00	1.375	1.000	107.31342	.68658
107.30	212.00	5644.00	3.00	1.375	1.000	107.32022	-.02022
109.20	311.00	5662.00	3.00	1.375	1.000	107.94846	1.25154
108.60	310.00	5512.00	3.00	1.375	1.000	107.77769	.82231
110.20	411.00	5669.00	3.00	1.375	1.000	108.57077	1.62923
108.70	401.00	5666.00	3.00	1.375	1.000	108.50601	.19399
110.30	507.00	5740.00	3.00	1.375	1.000	109.23873	1.06127
110.40	604.00	5755.00	3.00	1.375	1.000	109.85138	.54862
108.00	206.00	6298.00	3.00	1.375	1.000	108.00109	-.00109
109.40	178.00	6270.00	3.00	1.375	1.000	107.79826	1.60174
109.70	308.00	6307.00	3.00	1.375	1.000	108.63789	1.06211
109.00	307.00	6143.00	3.00	1.375	1.000	108.45175	.54825
109.60	407.00	6320.00	3.00	1.375	1.000	109.26063	.33937
109.30	402.00	6148.00	3.00	1.375	1.000	109.04114	.25886
108.40	504.00	6161.00	3.00	1.375	1.000	109.68232	-1.28232
109.40	601.00	6369.00	3.00	1.375	1.000	110.50679	-1.10679
110.40	578.00	6311.00	3.00	1.375	1.000	110.30177	.09823
108.60	310.00	6230.00	3.00	1.375	1.000	108.56567	.03433

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
110.70	506.00	6009.00	3.00	1.375	1.000	109.52780	1.17220
109.90	562.00	6018.00	3.00	1.375	1.000	109.88187	.01813
109.10	565.00	5692.00	3.00	1.375	1.000	109.54254	-.44254
108.80	571.00	5286.00	3.00	1.375	1.000	109.13384	-.33384
108.60	472.00	5270.00	3.00	1.375	1.000	108.50780	.09220
108.30	415.00	5249.00	3.00	1.375	1.000	108.13442	.16558
108.40	332.00	5229.00	3.00	1.375	1.000	107.60233	.79767
110.00	544.00	4868.00	3.00	1.375	1.000	108.50915	1.49085
110.90	577.00	4554.00	3.00	1.375	1.000	108.36738	2.53262
109.40	579.00	4223.00	3.00	1.375	1.000	108.01641	1.38359
107.70	572.00	3987.00	3.00	1.375	1.000	107.71438	-.01438
109.40	582.00	3734.00	3.00	1.375	1.000	107.49819	1.90181
108.60	577.00	4892.00	3.00	1.375	1.000	108.73832	-.13832
109.10	408.00	3703.00	3.00	1.375	1.000	106.39471	2.70529
109.70	313.00	4210.00	3.00	1.375	1.000	106.36723	3.33277
110.30	413.00	4233.00	3.00	1.375	1.000	107.00710	3.29290
108.80	405.00	4841.00	3.00	1.375	1.000	107.62519	1.17481
106.10	214.00	5496.00	3.00	1.375	1.000	107.17009	-1.07009
108.70	301.00	5653.00	3.00	1.375	1.000	107.87712	.82288
108.70	310.00	5653.00	3.00	1.375	1.000	107.93244	.76756
110.40	409.00	5661.00	3.00	1.375	1.000	108.54970	1.85030
109.30	300.00	5711.00	3.00	1.375	1.000	107.93463	1.36537
110.50	202.00	5057.00	3.00	1.375	1.000	106.61455	3.88545
100.60	207.00	2314.00	3.00	1.000	.000	103.52586	-2.92586
100.50	315.00	2332.00	3.00	1.000	.000	104.20941	-3.70941
103.80	404.00	2347.00	3.00	1.000	.000	104.77289	-.97289
105.60	508.00	2295.00	3.00	1.000	.000	105.35504	.24496
105.90	607.00	2306.00	3.00	1.000	.000	105.97559	-.07559
101.50	214.00	2924.00	3.00	1.000	.000	104.23834	-2.73834
104.20	198.00	2932.00	3.00	1.000	.000	104.14878	.05122
102.80	306.00	2939.00	3.00	1.000	.000	104.82026	-2.02026
104.80	406.00	2957.00	3.00	1.000	.000	105.45464	-.65464
105.70	403.00	3121.00	3.00	1.000	.000	105.61619	.08381
107.70	507.00	3135.00	3.00	1.000	.000	106.27076	1.42924
107.20	602.00	3147.00	3.00	1.000	.000	106.86783	.33217
103.80	215.00	3670.00	3.00	1.000	.000	105.06319	-1.26319
103.90	204.00	3665.00	3.00	1.000	.000	104.99010	-1.09010
105.30	316.00	3715.00	3.00	1.000	.000	105.73335	-.43335
105.90	304.00	3720.00	3.00	1.000	.000	105.66509	.23491
108.20	409.00	3578.00	3.00	1.000	.000	106.15460	2.04540
107.90	402.00	3581.00	3.00	1.000	.000	106.11487	1.78513
107.50	517.00	3741.00	3.00	1.000	.000	106.99729	.50271

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
108.30	504.00	3644.00	3.00	1.000	.000	106.81093	1.48907
108.30	606.00	3755.00	3.00	1.000	.000	107.55967	.74033
106.90	605.00	3657.00	3.00	1.000	.000	107.44597	-.54597
101.70	202.00	4273.00	3.00	1.000	.000	105.64506	-3.94506
105.20	216.00	4349.00	3.00	1.000	.000	105.81452	-.61452
103.80	310.00	4272.00	3.00	1.000	.000	106.30776	-2.50776
106.10	412.00	4297.00	3.00	1.000	.000	106.96212	-.86212
104.80	398.00	4296.00	3.00	1.000	.000	106.87498	-2.07498
108.10	511.00	4382.00	3.00	1.000	.000	107.66389	.43611
108.40	614.00	4392.00	3.00	1.000	.000	108.30793	.09207
105.10	215.00	4793.00	3.00	1.000	.000	106.29565	-1.19565
104.70	209.00	4930.00	3.00	1.000	.000	106.40912	-1.70912
105.60	306.00	4940.00	3.00	1.000	.000	107.01629	-1.41629
105.50	314.00	4806.00	3.00	1.000	.000	106.91840	-1.41840
105.70	414.00	4944.00	3.00	1.000	.000	107.68447	-1.98447
108.10	509.00	4831.00	3.00	1.000	.000	108.14436	-.04436
108.30	578.00	4850.00	3.00	1.000	.000	108.58930	-.28930
105.20	409.00	3696.00	3.00	1.000	.000	106.28411	-1.08411
104.00	201.00	4694.00	3.00	1.000	.000	106.10095	-2.10095
106.70	401.00	3726.00	3.00	1.000	.000	106.26786	.43214
103.70	319.00	3682.00	3.00	1.000	.000	105.71558	-2.01558
106.60	403.00	2957.00	3.00	1.000	.000	105.43620	1.16380
104.30	307.00	3618.00	3.00	1.000	.000	105.57158	-1.27158
106.20	400.00	3635.00	3.00	1.000	.000	106.16184	.03816
104.20	209.00	2338.00	3.00	1.375	.000	104.46823	-.26823
105.00	311.00	2360.00	3.00	1.375	.000	105.11929	-.11929
106.10	403.00	2378.00	3.00	1.375	.000	105.70451	.39549
104.20	213.00	2915.00	3.00	1.375	.000	105.12605	-.92605
106.30	309.00	2937.00	3.00	1.375	.000	105.74024	.55976
107.00	402.00	2961.00	3.00	1.375	.000	106.33818	.66182
104.90	209.00	3593.00	3.00	1.375	.000	105.84555	-.94555
105.00	312.00	3606.00	3.00	1.375	.000	106.49288	-1.49288
106.10	400.00	3622.00	3.00	1.375	.000	107.05131	-.95131
104.90	212.00	4402.00	3.00	1.375	.000	106.75184	-1.85184
105.70	208.00	4207.00	3.00	1.375	.000	106.51325	-.81325
106.80	302.00	4227.00	3.00	1.375	.000	107.11295	-.31295
106.40	309.00	4277.00	3.00	1.375	.000	107.21084	-.81084
107.50	411.00	4258.00	3.00	1.375	.000	107.81691	-.31691
107.60	398.00	4286.00	3.00	1.375	.000	107.76774	-.16774
108.00	505.00	4454.00	3.00	1.375	.000	108.60976	-.60976
109.20	604.00	4478.00	3.00	1.375	.000	109.24458	-.04458
106.40	207.00	4848.00	3.00	1.375	.000	107.21058	-.81058

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
106.40	206.00	4846.00	3.00	1.375	.000	107.20224	-.80224
107.90	315.00	4859.00	3.00	1.375	.000	107.88645	.01355
107.50	313.00	4852.00	3.00	1.375	.000	107.86647	-.36647
110.50	407.00	4867.00	3.00	1.375	.000	108.46068	2.03932
107.20	401.00	5000.00	3.00	1.375	.000	108.56977	-1.36977
108.00	506.00	5014.00	3.00	1.375	.000	109.23049	-1.23049
109.10	602.00	5027.00	3.00	1.375	.000	109.83480	-.73480
107.50	201.00	5435.00	3.00	1.375	.000	107.81791	-.31791
106.90	216.00	5595.00	3.00	1.375	.000	108.08570	-1.18570
109.30	315.00	5539.00	3.00	1.375	.000	108.63272	.66728
108.60	308.00	5539.00	3.00	1.375	.000	108.58970	.01030
108.80	413.00	5561.00	3.00	1.375	.000	109.25920	-.45920
109.20	424.00	5586.00	3.00	1.375	.000	109.35425	-.15425
109.00	510.00	5642.00	3.00	1.375	.000	109.94428	-.94428
108.90	604.00	5664.00	3.00	1.375	.000	110.54618	-1.64618
108.60	204.00	6200.00	3.00	1.375	.000	108.67591	-.07591
107.70	196.00	6155.00	3.00	1.375	.000	108.57735	-.87735
108.80	316.00	6197.00	3.00	1.375	.000	109.36100	-.56100
109.10	304.00	6137.00	3.00	1.375	.000	109.22140	-.12140
110.80	405.00	6219.00	3.00	1.375	.000	109.93216	.86784
110.00	408.00	6213.00	3.00	1.375	.000	109.94402	.05598
109.40	508.00	6334.00	3.00	1.375	.000	110.69144	-1.29144
110.20	598.00	6323.00	3.00	1.375	.000	111.23253	-1.03253
110.70	604.00	6346.00	3.00	1.375	.000	111.29465	-.59465
112.20	556.00	6299.00	3.00	1.375	.000	110.94805	1.25195
110.50	453.00	6274.00	3.00	1.375	.000	110.28754	.21246
108.50	436.00	6007.00	3.00	1.375	.000	109.89003	-1.39003
109.00	561.00	6020.00	3.00	1.375	.000	110.67258	-1.67258
108.60	543.00	5694.00	3.00	1.375	.000	110.20418	-1.60418
108.90	428.00	5668.00	3.00	1.375	.000	109.46882	-.56882
108.10	428.00	5266.00	3.00	1.375	.000	109.02764	-.92764
109.30	579.00	5280.00	3.00	1.375	.000	109.97109	-.67109
109.00	453.00	6004.00	3.00	1.375	.000	109.99123	-.99123
108.40	596.00	4993.00	3.00	1.375	.000	109.76061	-1.36061
108.10	481.00	4969.00	3.00	1.375	.000	109.02745	-.92745
107.50	401.00	4933.00	3.00	1.375	.000	108.49624	-.99624
107.30	403.00	4610.00	3.00	1.375	.000	108.15405	-.85405
107.70	484.00	4622.00	3.00	1.375	.000	108.66507	-.96507
109.00	590.00	4636.00	3.00	1.375	.000	109.33193	-.33193
108.50	586.00	4348.00	3.00	1.375	.000	108.99128	-.49128
110.20	473.00	4216.00	3.00	1.375	.000	108.15189	2.04811
106.10	376.00	4179.00	3.00	1.375	.000	107.51509	-1.41509

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
107.90	475.00	3714.00	3.00	1.375	.000	107.61325	.28675
110.10	555.00	3728.00	3.00	1.375	.000	108.12032	1.97968
109.60	510.00	3709.00	3.00	1.375	.000	107.82288	1.77712
109.00	213.00	4836.00	3.00	1.375	.000	107.23428	1.76572
109.80	304.00	4853.00	3.00	1.375	.000	107.81225	1.98775
107.90	304.00	5453.00	3.00	1.375	.000	108.47073	-.57073
110.40	405.00	5468.00	3.00	1.375	.000	109.10797	1.29203
106.30	403.00	4432.00	3.00	1.375	.000	107.95870	-1.65870
105.20	205.00	4265.00	3.00	1.375	.000	106.55846	-1.35846
105.60	213.00	4971.00	3.00	1.375	.000	107.38244	-1.78244
106.30	210.00	5523.00	3.00	1.375	.000	107.96980	-1.66980
108.00	401.00	5624.00	3.00	1.375	.000	109.25459	-1.25459
106.90	405.00	6231.00	3.00	1.375	.000	109.94533	-3.04533
107.30	218.00	6210.00	3.00	1.375	.000	108.77293	-1.47293
104.60	214.00	2418.00	.75	1.000	1.000	106.71231	-2.11231
105.80	307.00	2432.00	.75	1.000	1.000	107.29927	-1.49927
106.70	402.00	2445.00	.75	1.000	1.000	107.89744	-1.19744
107.40	507.00	2458.00	.75	1.000	1.000	108.55706	-1.15706
107.70	593.00	2472.00	.75	1.000	1.000	109.10101	-1.40101
104.50	216.00	2978.00	.75	1.000	1.000	107.33918	-2.83918
107.10	301.00	2993.00	.75	1.000	1.000	107.87808	-.77808
107.90	408.00	3004.00	.75	1.000	1.000	108.54780	-.64780
108.50	510.00	3004.00	.75	1.000	1.000	109.17472	-.67472
109.20	605.00	3012.00	.75	1.000	1.000	109.76739	-.56739
106.30	213.00	3685.00	.75	1.000	1.000	108.09665	-1.79665
108.50	306.00	3700.00	.75	1.000	1.000	108.68471	-.18471
109.10	404.00	3716.00	.75	1.000	1.000	109.30461	-.20461
109.70	509.00	3734.00	.75	1.000	1.000	109.96972	-.26972
110.10	607.00	3758.00	.75	1.000	1.000	110.59839	-.49839
107.90	216.00	4335.00	.75	1.000	1.000	108.82844	-.92844
109.20	305.00	4350.00	.75	1.000	1.000	109.39192	-.19192
110.50	407.00	4364.00	.75	1.000	1.000	110.03420	.46580
111.10	508.00	4381.00	.75	1.000	1.000	110.67363	.42637
111.20	606.00	4397.00	.75	1.000	1.000	111.29353	-.09353
108.90	210.00	4928.00	.75	1.000	1.000	109.44236	-.54236
110.20	307.00	4947.00	.75	1.000	1.000	110.05940	.14060
110.90	405.00	4966.00	.75	1.000	1.000	110.68259	.21741
112.20	502.00	4994.00	.75	1.000	1.000	111.30950	.89050
112.50	584.00	4825.00	.75	1.000	1.000	111.62803	.87197
108.40	219.00	3748.00	.75	1.375	1.000	109.10640	-.70640
109.70	310.00	3752.00	.75	1.375	1.000	109.67011	.02989
111.10	402.00	3756.00	.75	1.375	1.000	110.23995	.86005

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
111.80	510.00	3779.00	.75	1.375	1.000	110.92899	.87101
112.60	606.00	3789.00	.75	1.375	1.000	111.53001	1.06999
110.90	214.00	4352.00	.75	1.375	1.000	109.73854	1.16146
112.00	311.00	4361.00	.75	1.375	1.000	110.34461	1.65539
112.50	406.00	4371.00	.75	1.375	1.000	110.93948	1.56052
112.70	510.00	4383.00	.75	1.375	1.000	111.59186	1.10814
113.10	609.00	4396.00	.75	1.375	1.000	112.21461	.88539
111.50	218.00	4953.00	.75	1.375	1.000	110.42270	1.07730
111.30	309.00	4965.00	.75	1.375	1.000	110.99518	.30482
112.10	401.00	4967.00	.75	1.375	1.000	111.56284	.53716
112.60	512.00	4986.00	.75	1.375	1.000	112.26592	.33408
113.40	607.00	5007.00	.75	1.375	1.000	112.87287	.52713
111.80	216.00	5523.00	.75	1.375	1.000	111.03597	.76403
110.40	312.00	5528.00	.75	1.375	1.000	111.63150	-1.23150
113.60	403.00	5942.00	.75	1.375	1.000	112.64516	.95484
113.60	510.00	5558.00	.75	1.375	1.000	112.88138	.71862
114.80	608.00	5569.00	.75	1.375	1.000	113.49579	1.30421
109.80	218.00	6244.00	.75	1.375	1.000	111.83953	-2.03953
111.20	309.00	6256.00	.75	1.375	1.000	112.41201	-1.21201
112.90	401.00	6275.00	.75	1.375	1.000	112.99832	-.09832
114.30	509.00	6294.00	.75	1.375	1.000	113.68297	.61703
113.40	608.00	6317.00	.75	1.375	1.000	114.31669	-.91669
107.20	216.00	2347.00	.75	1.000	.000	107.44135	-.24214
108.09	307.00	2357.00	.75	1.000	.000	108.01163	.07535
109.04	405.00	2370.00	.75	1.000	.000	108.62823	.41334
110.04	508.00	2387.00	.75	1.000	.000	109.27995	.76261
111.00	607.00	2404.00	.75	1.000	.000	109.90709	1.09197
108.07	216.00	2989.00	.75	1.000	.000	108.14592	-.07862
108.86	308.00	2999.00	.75	1.000	.000	108.72235	.13419
109.69	406.00	3008.00	.75	1.000	.000	109.33456	.35732
110.54	505.00	3022.00	.75	1.000	.000	109.95841	.57811
111.39	606.00	3036.00	.75	1.000	.000	110.59454	.79825
109.02	218.00	3686.00	.75	1.000	.000	108.92314	.10098
109.64	302.00	3699.00	.75	1.000	.000	109.45370	.18855
110.38	404.00	3709.00	.75	1.000	.000	110.09159	.29003
111.09	501.00	3723.00	.75	1.000	.000	110.70314	.38187
111.83	604.00	3738.00	.75	1.000	.000	111.35267	.47389
109.68	204.00	4239.00	.75	1.000	.000	109.44399	.23960
110.34	309.00	4247.00	.75	1.000	.000	110.09813	.24184
110.93	404.00	4257.00	.75	1.000	.000	110.69300	.24097
111.58	508.00	4269.00	.75	1.000	.000	111.34538	.23574
112.19	606.00	4278.00	.75	1.000	.000	111.95760	.22768

Sound Power dBA Laboratory	Speed rpm	Thrust lbs	Water gpm	Bit Size in.	Drill Steel (hex/round)	Sound Power dBA Model	Sound Power dBA Difference
110.63	212.00	4899.00	.75	1.000	.000	110.21749	.41267
111.14	310.00	4916.00	.75	1.000	.000	110.83848	.29710
111.59	403.00	4909.00	.75	1.000	.000	111.40240	.18382
112.11	506.00	4929.00	.75	1.000	.000	112.05742	.05347
112.63	608.00	4955.00	.75	1.000	.000	112.71287	-.08592
107.90	213.00	3680.00	.75	1.375	.000	109.78957	-1.88957
109.90	305.00	3692.00	.75	1.375	.000	110.36819	-.46819
111.70	403.00	3717.00	.75	1.375	.000	110.99796	.70204
112.90	509.00	3736.00	.75	1.375	.000	111.67032	1.22968
113.30	606.00	3752.00	.75	1.375	.000	112.28407	1.01593
108.70	213.00	4298.00	.75	1.375	.000	110.46780	-1.76780
111.60	314.00	4310.00	.75	1.375	.000	111.10174	.49826
112.50	402.00	4326.00	.75	1.375	.000	111.66017	.83983
114.00	508.00	4338.00	.75	1.375	.000	112.32485	1.67515
114.80	607.00	4357.00	.75	1.375	.000	112.95418	1.84582
107.30	212.00	4977.00	.75	1.375	.000	111.20683	-3.90683
108.00	303.00	4998.00	.75	1.375	.000	111.78919	-3.78919
112.30	398.00	5013.00	.75	1.375	.000	112.38955	-.08955
114.20	511.00	5037.00	.75	1.375	.000	113.11041	1.08959
116.20	606.00	5060.00	.75	1.375	.000	113.71955	2.48045
110.50	211.00	5617.00	.75	1.375	.000	111.90306	-1.40306
113.10	306.00	5632.00	.75	1.375	.000	112.50342	.59658
113.60	404.00	5646.00	.75	1.375	.000	113.12112	.47888
117.00	512.00	5671.00	.75	1.375	.000	113.81235	3.18765
116.10	595.00	5686.00	.75	1.375	.000	114.33896	1.76104
111.90	212.00	6260.00	.75	1.375	.000	112.61488	-.71488
113.60	312.00	6287.00	.75	1.375	.000	113.25914	.34086
114.90	404.00	6317.00	.75	1.375	.000	113.85752	1.04248
115.90	507.00	6347.00	.75	1.375	.000	114.52351	1.37649
116.90	598.00	6306.00	.75	1.375	.000	115.03782	1.86218

5.4.3 Development of An Equation for Determining a Sound Power Level

The dependent variable, sound power level was then modeled by the following equation using the regression coefficients determined from table 5.16:

Sound Power Level (dBA) = 101.708 – 1.766(water) + .001(thrust) (8)

+ .007(rotational speed) + 2.588(bit size) - .640(drill steel type)

Utilizing equation (8) above, the mining community can now determine a sound power level, during the drilling cycle in high compressive rock media (>20,000 psi) for a roof bolting machine using a simple equation developed from laboratory testing and statistical modeling.

Using equation (8) from above, an example is shown below illustrating the use of the equation and determining a sound power level given a specific drilling method (wet, mist or vacuum), thrust setting, rotational speed, bit size and type of drill steel. Assume a roof bolter operator is drilling into a high-compressive strength media (>20,000 psi), using the wet method of drilling, using a 1.375-inch bit with round drill steel, a rotational speed set at 600 rpm and a thrust setting at 4,000 lbs. Using equation (8) above and inputting the specific drilling parameters, the mining community could then determine a sound power level with significant confidence as shown below:

Sound Power Level (dBA) = 101.708 – 1.766(water) + .001(thrust)

+ .007(rotational speed) + 2.588(bit size) - .640(drill steel type)

Sound Power Level (dBA) = 101.708 – 1.766(3) + .001(4,000) + 0.007(600) + 2.588(1.375) - .640(1)

= 101.708 – 5.30 + 4 + 4.20 + 3.56 – 0.640 = 107.53 dBA

By comparing the predicted sound power level of 107.53 dBA above to the measured sound power level from the laboratory measurement shown below is:

Sound Power dBA Laboratory	**Speed rpm**	**Thrust lbs**	**Water gpm**	**Bit Size in.**	**Drill Steel (hex/round)**
107.70	572.00	3987.00	3.00	1.375	1.000

Sound Power Level (dBA) = 107.70 – 107.53 = 0.17 dBA, which,

demonstrates a significant correlation between the measured and predicted (determined) sound power level from the statistical model. The statistical model equation (equation 8), provides the mining community with a simple and reliable approach in determining a sound power level for a roof bolting machine during the drilling operation in high compressive strength rock media, given any type of drilling method (vacuum, wet or mist) and drilling parameter configuration (thrust, rotational speed, bit size and type of drill steel). Chapter 6 will then offer and provide the mining community with two different approaches in predicting sound pressure levels at the operator position of a roof bolting machine. One method of prediction, will utilize overall sound power levels either measured from laboratory tests or determined (predicted) from equation (8). The other approach, a more sophisticated and reliable approach, would predict sound pressure levels at the operator position of the roof bolting machine, using full-octave band frequency measurements obtained from laboratory testing for input into a computer model for simulating and predicting sound pressure levels from sound power level measurements.

Chapter 6

DEVELOPMENT AND UTILIZATION OF MODELS FOR PREDICTING SOUND PRESSURE LEVELS FROM LABORATORY TESTS

6.1 Introduction

Underground mining machines are subject to many variables that can affect the noise levels measured. Some of these variables cannot be controlled while others can be influenced or even controlled by the machine operator. The acoustic environment in which the mining machines operate is a critical factor affecting the sound pressure levels measured. Underground mines are enclosed areas, which usually represent diffused fields. A diffuse sound field is a sound field in which the time average of the mean-square sound pressure is everywhere the same and the flow of acoustic energy in all directions is equally probable. The geometry and the composition of the surfaces influence the overall sound level by the number of rays (sound waves) being reflected or absorbed. Mine entries also have various shapes, rectangular, square, or arched, and various dimensions as well. These variations in shape and size affect the overall sound energy that is reflected or absorbed. These are the variables that cannot be controlled in the acoustic environment, and include geometry and composition of the surfaces, shape of the mine opening, and the compressive strength of the affected medium. Two methods of predicting the acoustic environment properties associated with underground coal mining machines and the sound pressure level experienced at the operator utilizing laboratory results are provided in this chapter. One model, demonstrates the prediction of sound pressure levels, given overall sound power levels and the second model, a more sophisticated and reliable modeling approach, utilizes full-octave band frequency measurements obtained from laboratory and mine testing for input, thereby, used for predicting sound pressure levels at the operator position. The objective for the development of the respective models is to provide a methodology for determining a miners' effective noise dosage related to measured and determined engineering noise control tests determined from laboratory trials dependent upon overall and full-octave band sound power levels. Upon completion of the models, the measured sound power determined in the laboratory, with a calculated or predicted sound absorption coefficient, could then be entered into the model to determine an operator's noise dosage relative to the drilling cycle of the roof bolting machine. The first model discussed will provide the mining community with a method to determine sound pressure levels experienced by the roof bolting operator, through inputting an overall sound power level. The second model presented will provide a more reliable approach in determining sound pressure levels experienced by the roof bolting machine operator utilizing full-octave band frequency sound power levels. This will be achieved using a ray-tracing program to predict the steady-state sound pressure level and the associated sound decay in a mine environment. This information will provide a snapshot of the environment and calculate the noise levels throughout the environment, additionally, it will account for the positions of an operator with respect to a machine and ultimately, provide the mining industry with a method to model a simple event within a mine section and determine the noise dosage to the roof bolting machine operator.

6.2 Model for Predicting Sound Pressure Levels Using Overall Sound Power Levels

6.2.1 Introduction

It would be a time consuming and complex task to try to develop a model of all shapes and sizes of different mines. However, the acoustic differences are small and can be broken down into two shapes, a tunnel or a flat room. The acoustic properties of these two shapes are flexible enough to be applied to most other shapes. Underground noise travels both as a direct path and as multiple reflected paths. The number of reflections depends on the shape, dimensions, and the absorption property of the walls and roof. This absorption property is called the sabine absorption coefficient, α, and is used to describe the degree of reflectivity of the walls and roof. The sabine absorption coefficient ranges from zero to one, where zero is total reflection and one is total absorption. A low sabine absorption coefficient means the environment is highly reverberant and a sabine absorption coefficient that is near one such as 0.9 means that most of the sound is absorbed upon reflection. In the case of a high sabine absorption coefficient a lower level of sound occurs as compared to a lower sabine absorption coefficient for that particular environment.

6.2.2 Predicting Underground Sound Pressure Levels from Measurements Above Ground

To predict underground sound levels from above ground measurements there are two basic techniques used. One method is the room acoustics method and the other is the imaging method. The room acoustic method describes the sound level in a large room where the sound undergoes a large number of reflections from the room's walls, roof, and floor. The imaging method is used to describe the tunnel surfaces, where the sound rays are traced from the source to the receiver and the sound energy is summed. The imaging method is more complex then the room acoustic method. The imaging method models a tunnel which is "U" shaped rather than a square channel, however the modeling of the square channel is acoustically accurate. The reason being is that the individual sound rays differ only in a small and random manner.

6.2.2.1 Differences Between the Room Acoustic Method and Imaging Method

To illustrate the difference between the room acoustic method and the imaging method for predicting underground sound pressure levels, figure 6.1 provides an example for a tunnel 200 ft long with a 10 ft-square cross-section. A sabine absorption coefficient of 0.2 is used for the walls with a source having a sound power of 100 dBA.

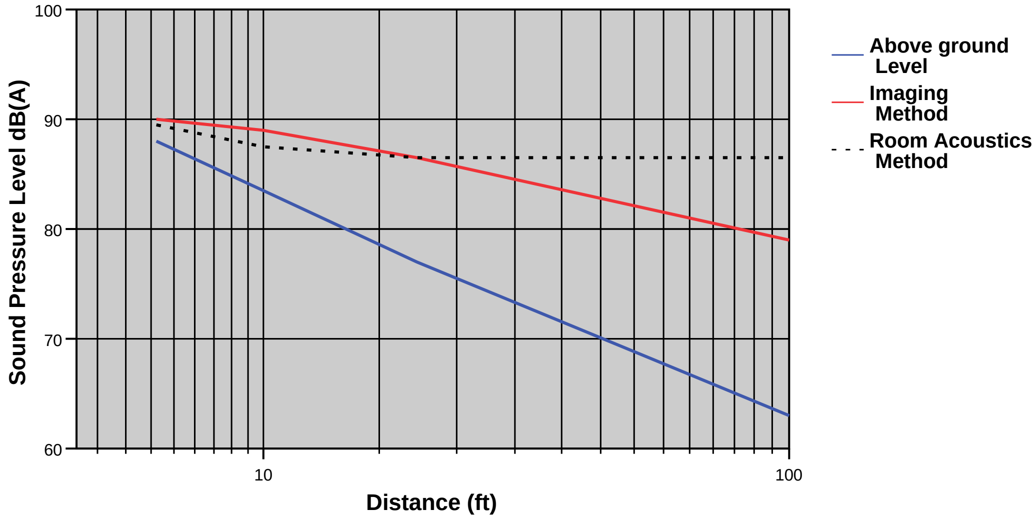


Figure 6.1 Comparison of Imaging and Room Acoustics Method of Predicting Sound Pressure Levels

The imaging and room acoustics predictive techniques are very close up to about 30 feet from the source of noise. Subsequent to 30 ft, the imaging method decreases at the same rate as the above ground sound level and the room acoustic method reaches some sound power value and does not decrease any further. The room acoustic method assumes a diffuse field throughout the tunnel where as the imaging method only assumes a diffuse field near the source, but not farther down the tunnel. The imaging method differs in sound levels as to where the location of the person is from the noise source. The room acoustics method differs in sound levels only until 30 ft. from the noise source and does not decrease after 30 ft. While observing machine operators they are located typically close to the noise source or in the near field. The near field is the sound field close to the sound source (between the source and the far field) where the instantaneous sound pressure and particle velocity are not in phase with each other. Conversely, the far field is a portion of a sound field of a sound source in which the sound pressure level decreases by 6 dB for each doubling of the distance from the source. In the case of operators located in the near field, both the room acoustics and imaging method would work for predicting sound pressure levels. However, when examining other mine personnel away from the noise source or within the far field, the sound pressure levels in the far field would have greater accuracy with the imaging method. The reason for this is the imaging method assumes a diffuse field only near the source, and not further down the tunnel thus giving a better representation of the sound in a tunnel.

6.2.2.2 Predicting Sound Levels at a Single Point

Patterson, et.al (23), developed curves, plotting the correction factors for using above ground measurements to predict underground sound pressure levels for tunnels (figure 6.2) and flat rooms (figure 6.3). The curves plotted represent different sabine absorption coefficients and are plotted as a function of normalized distance from the acoustic center of the noise source. The correction factor is larger for tunnels as compared to flat rooms; this is due to the tunnels being more confined than the rooms, therefore, creating more reflections of sound.

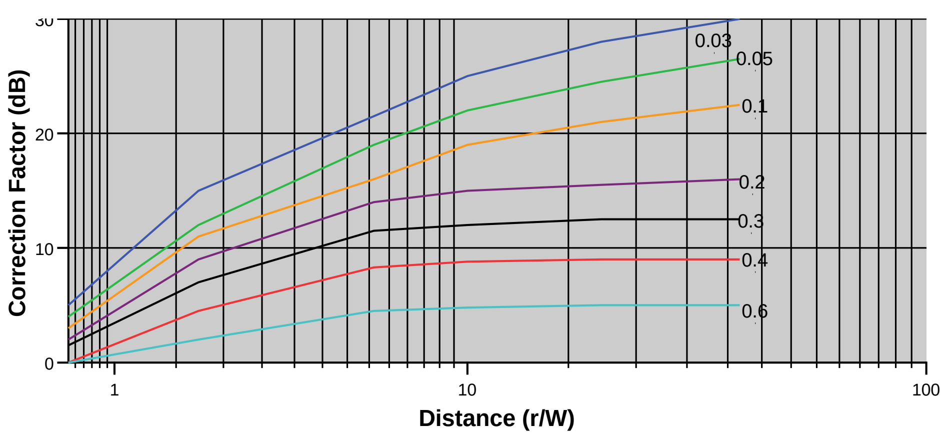


Figure 6.2 Correction Factors for Converting Above Ground Measurements to Underground Sound Pressure Levels (Tunnels)

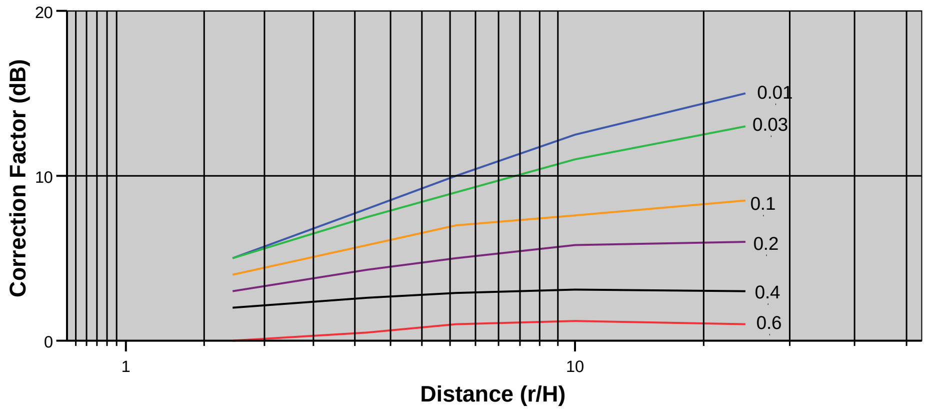


Figure 6.3 Correction Factors for Converting Above Ground Measurements to Underground Sound Pressure Levels (Flat Rooms)

The limitation of figures 6.2 and 6.3 is they only provide correction factors at a single point, relative to a measured distance from the source as measured above ground for determining sound pressure levels underground. To determine sound pressure levels below ground at any point, one would have to know the exact distances mine personnel are from the noise source and then measure sound pressure levels above ground from the specific distances to provide correction factors for determining sound pressure levels underground at the relative distances, a very cumbersome and unfriendly approach.

6.2.2.3 Predicting Sound Levels at Multiple Points

A more direct method in determining the underground sound pressure level at any point underground without having to conduct or measure all the above ground sound pressure level measurements would be to know or determine the sound power of the noise source above ground. Patterson, et.al (24), developed curves to determine the A-weighted sound pressure level at any point underground, using the measured or known sound power level of the machine. Figures 6.4 and 6.5 represent plots for determining two correction factors, namely G and F, for determining the underground A-weighted, sound pressure level at a specific location for tunnels and flat rooms, respectively if you can identify the sabine absorption coefficient and the sound power of the noise source.

The following equation is used to determine the underground A-weighted, sound pressure level.

$$L_p \text{ (underground)} = L_w \text{ (above ground)} - (G + F) \qquad (9)$$

where:

L_p (underground) = A-weighted sound pressure level, dBA – predicted underground

L_w (above ground) = A-weighted sound power level, dBA – measured above ground

G and F = Correction factors

Using the statistical model equation developed in the previous section, Development of An Equation for Determining a Sound Power Level, one could then predict the sound pressure level, experienced by a roof bolting machine operator utilizing this modeling approach. For example, assume a roof bolter operator is drilling into a high-compressive strength media (>20,000 psi), using the wet method of drilling, using a 1.375-inch bit with round drill steel, a rotational speed set at 600 rpm and a thrust setting at 4,000 lbs. Using the statistical model equation and inputting the specific drilling parameters, the sound power level is shown below:

Sound Power Level (dBA) = 101.708 – 1.766(water) + .001(thrust) + .007(rotational speed) + 2.588(bit size) - .640(drill steel type)

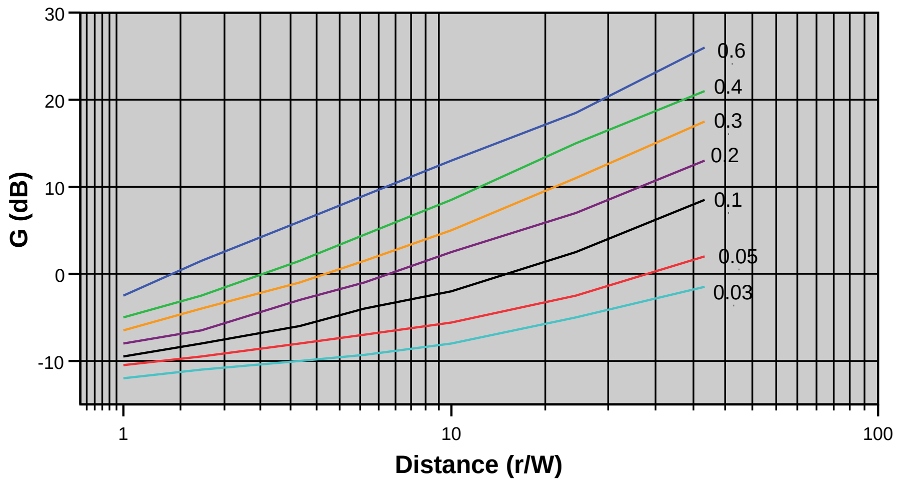
Sound Power Level (dBA) = 101.708 – 1.766(3) + .001(4,000) + 0.007(600) + 2.588(1.375) - .640(1)

= 101.708 – 5.30 + 4 + 4.20 + 3.56 – 0.640 = 107.5 dBA

Determining a sound power level of 107.5 dBA, one could then use figure 6.4 to determine the sound pressure level at a specific distance from the noise source, for example 30 ft. Assuming the tunnel width is 16 ft and the sabine absorption coefficient is 0.2, therefore, r would equal 30 ft and W would equal 16 ft and the normalized source-to-distance, r/W, would equal 30ft/16ft, or 1.9. Using figure 6.4, G would equal -2.5 dBA and F would equal 23 dBA and then using equation (9):

L_p (underground) = L_w (above ground) – (G + F)

L_p (underground) = 107.5 dBA – (-2.5 + 23) = 107.53 – (20.5) = 87.0 dBA, 30 ft from the noise source.



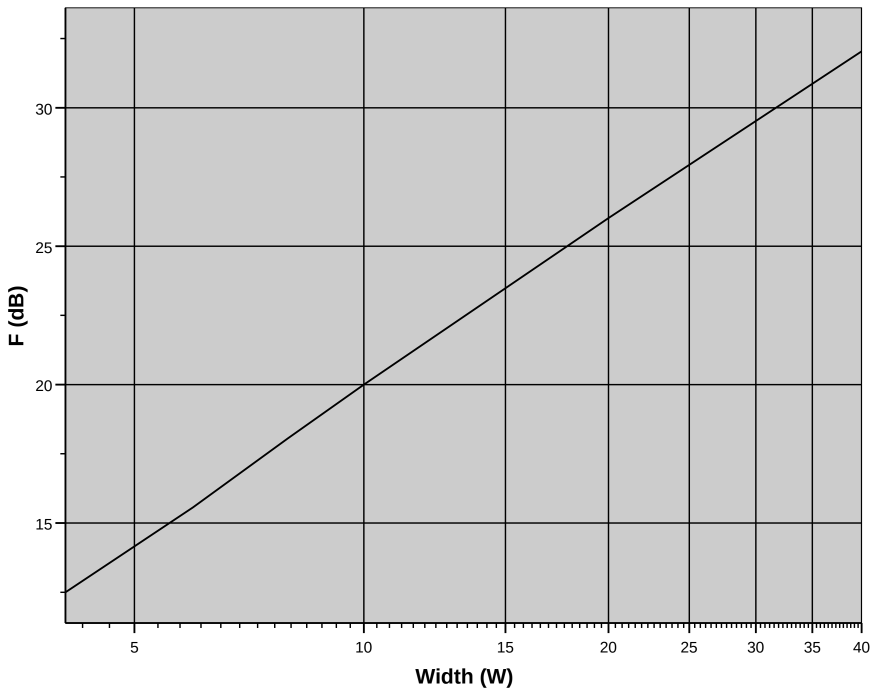
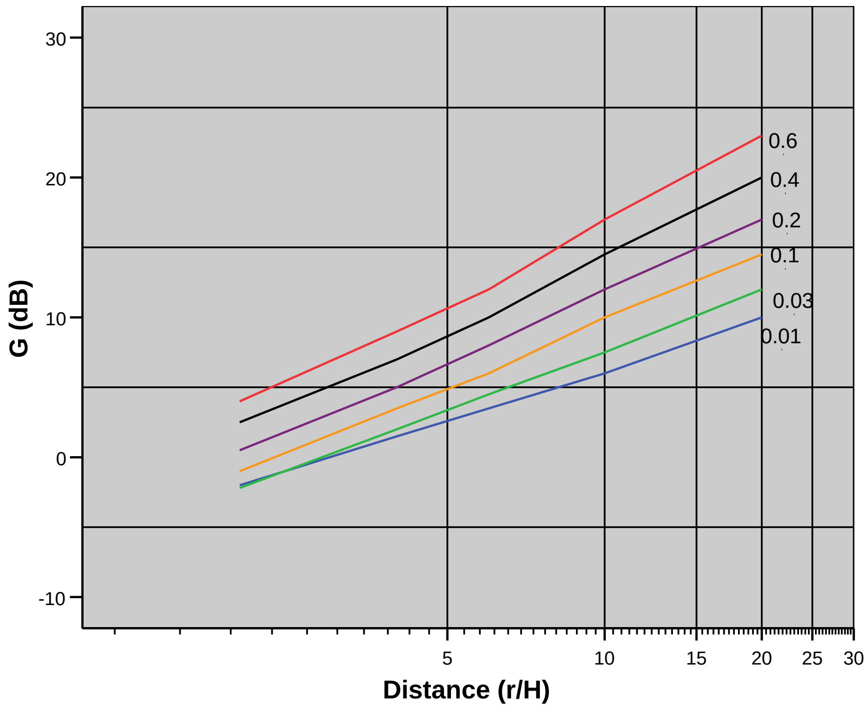


Figure 6.4 Correction Factors for Determining Underground Sound Pressure Levels from Sound Power Measurements Above Ground (Tunnels)



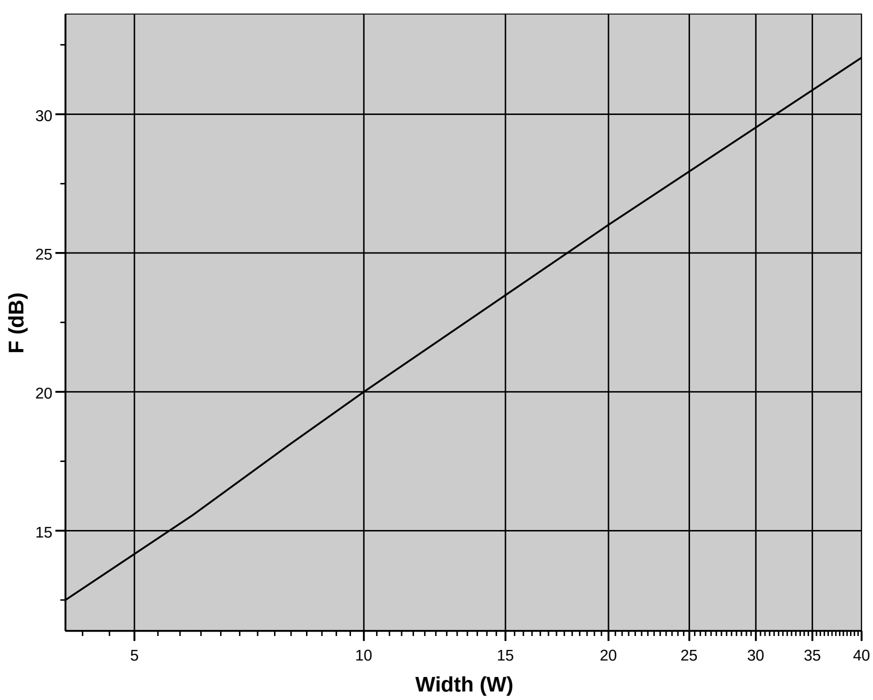


Figure 6.5 Correction Factors for Determining Underground Sound Pressure Levels from Sound Power Measurements Above Ground (Tunnels)

6.2.2.4 Predicting Sound Levels in the Near-Field

Determining an underground sound pressure level near the machine or the noise source is a more difficult task, due to encountering the geometric near field. The shape and size of the machine and the location of the noise source on the machine plays an important role in the behavior of sound pressure levels. For example, two machines may have far field sound pressure levels equal to each other, but could have very different sound pressure levels near the machine. For example, when measuring sound pressure levels close to the noise source, an error of one or two-feet can be much more significant than measuring a sound pressure level 40-50 ft away from the noise source.

To address the near field issue relative to sound pressure level measurements, Patterson (20), developed correction factor curves, which are used for calculating sound pressure levels close to the noise source for tunnels and flat rooms (figure 6.6). Several assumptions were determined when using the correction curves and consisted of: 1) the machine shape and size can influence the results and the curves are only approximations; 2) the location of the acoustic center of the noise source must be accurate and 3) the curves are on the conservative side and the predicted sound pressure levels may be 1-2 dBA greater than would be measured underground.

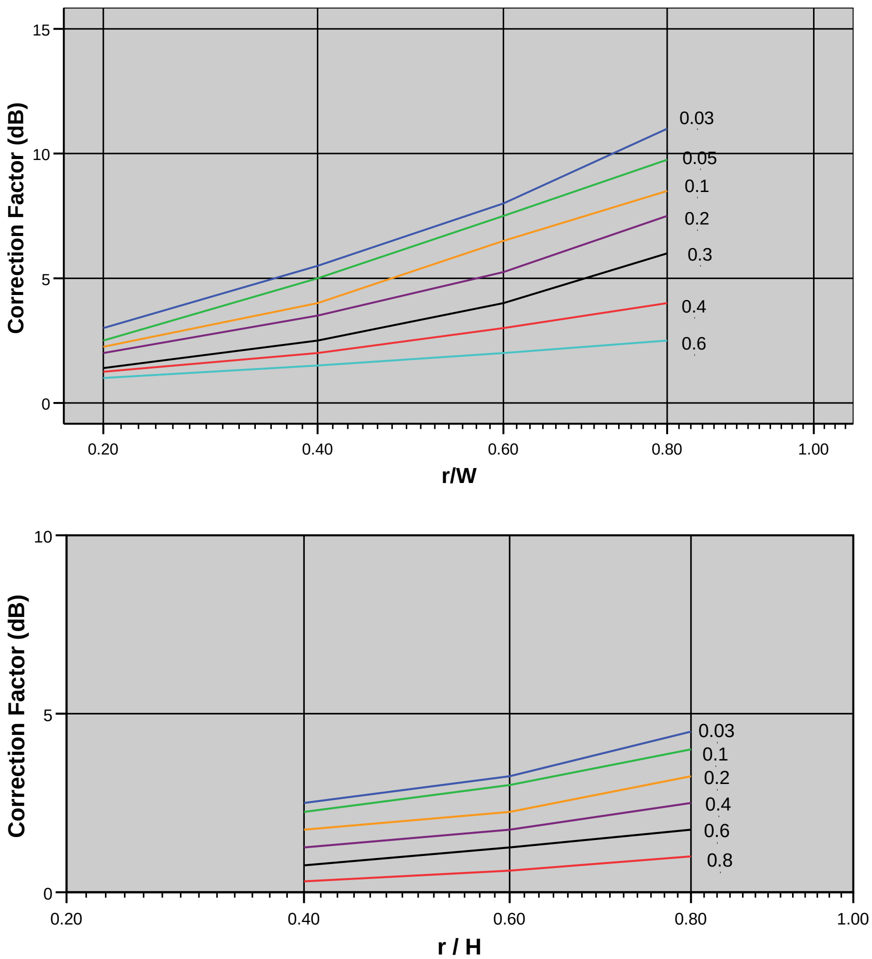


Figure 6.6 Correction Factors for Determining Sound Pressure Levels Underground in the Near Field (Top-Tunnel and Bottom-Flat Room)

As mentioned above, the acoustic center of a noise source has to be measured accurately. One can locate the acoustic center of a noise source by: 1) assuming all measurements for sound power are made at 25 ft from the geometric center of the machine; 2) record the sound pressure level 25 ft from the front of the machine; 3) move the microphone at the rear and move the microphone in and out until the same sound pressure level is experienced as in the front of the machine, the halfway distance between the two measurements is the acoustic center and 4) repeat the process on the left and right sides of the machine to find the acoustic center along that particular axis. For utilization of this model, knowledge of sound power level and the acoustic center are necessary information in predicting underground sound pressure levels.

Using figure 6.6 above, one could then determine or predict the underground sound pressure level at the operator position of a roof bolting machine taking into account the assumptions used for the development of the curves in figure 6.6 mentioned above. However, this type of approach for predicting sound pressure levels underground utilizes numerous assumptions and adopts a very conservative approach. Additionally, locating the acoustic center of the piece of equipment can also be very difficult, dependent upon the type, location and the number of noise sources associated with the particular machine. The location of the acoustic center depends upon numerous parameters and can be strongly influenced by minimal details of a machine, such as, the machine having a reflective surface behind a noise source, in which, would provide additional sound energy towards the operator, therefore the acoustic center would be closer than typically measured from the operator to the noise source. For the reasons mentioned above, this type of modeling approach, determining sound pressure levels in the near-field, is a very approximate approach. Section 6.3 provides a more reliable approach for determining sound pressure levels in the near-field.

<u>6.2.3 Limitations of Model Utilizing Overall Sound Power Levels</u>

Section 6.2 provided several methods for determining sound pressure levels underground using overall sound power levels measured. However, the approach contained several limitations. As mentioned in section 6.2.2.4, Predicting Sound Levels in the Near-Field, numerous assumptions were required and a conservative approach was used to predict sound pressure levels in the near-field. More importantly, the model predictions utilized absorption coefficients, which, were determined using the suitable methods available 30 years ago. The authors did mention that a more thorough investigation relative to the dependence of acoustic absorption on ore type and mine environment was needed to be conducted and many more measurements would be needed to obtain extreme confidence in the results of the model.

Section 6.3 provides a more reliable modeling approach, utilizing measured absorption coefficients, for predicting sound pressure levels underground using laboratory results. Additionally, the model developed in section 6.3, provides a more accurate description of the sound pressure levels experienced by operators of roof bolting machine equipment in the near-field.

6.3 Model for Predicting Sound Pressure Levels Using Full-Octave Band Frequency Sound Power Levels

6.3.1 Ray-tracing Technique

Ray-tracing is a technique that can be used to predict sound fields in mines of various shapes and sizes. A computer program will simulate rays that are emitted from each noise source in a random or deterministic fashion. Each ray in the program is then reflected and scattered by surfaces, barriers and objects until it reaches a receiver. The great potential of ray-tracing techniques is the ability to display contour maps of noise levels of various mining machines and then using the information to determine a noise dosage of operators in a particular mine environment.

6.3.2 Raynoise Computer Program

The Raynoise program was the noise modeling software utilized for displaying and predicting sound pressure levels experienced by roof bolter operators (figure 6.7).

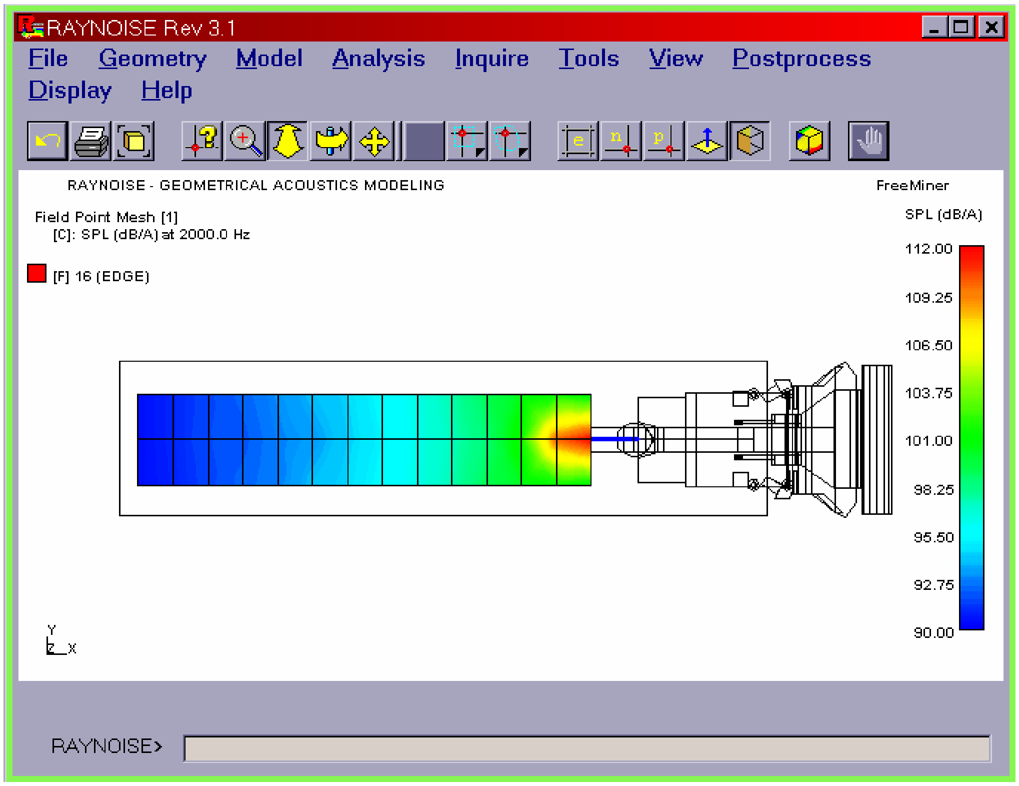


Figure 6.7 Sound Pressure Level Contour Plot Using the Raynoise Program

The Raynoise program uses a ray-tracing based technique to calculate the noise characteristics of a given source/room configuration. A key aspect of the package is that the noise sources and material properties are defined in terms of full octave-band, not one-third octave-band format. The program also has the capability of importing model information in AutoCAD DXF format. Additionally, the package has command file capabilities that allow complete model and test definitions to be written and processed. This capability is extremely helpful for processing a variety of tests in bulk and for varying parameters for a single test. The program also has command-line operation capabilities that allow it to be used as a 'black box' by other software. For example, "Rayserve" is an in-house package developed at the Pittsburgh Research Laboratory. Rayserve creates a shell around the Raynoise package that allows it to act as a noise profile engine, or "black box". The benefit is that many tests can be processed in bulk using the

Rayserve program (25). This is extremely beneficial because when Raynoise is running it takes a lot of processor time, making a computer unusable until model run completion. Rayserve also automatically calculates the overall sound pressure level results for a given test setup by running the test at each octave band frequency and combining the results. However, Raynoise does have some limitations. One limitation is the package can only make calculations for a specific frequency and to generate overall results, a model needs to be run at each octave band frequencies and the resultant sound pressure level for each frequency band is then combined interdependent of the Raynoise package.

6.3.3 Absorption Coefficients

Classic absorption/reverberation estimation using T60 measurements (measuring how sound decays over a period of time and distance) will not work well in the underground mining environment because the classic absorption theory assumes (1) a finite room, (2) a diffuse field and (3) relatively uniform absorption. None of these factors is true in an open ended mine entry. The assumption then is to treat the mine entry as an "infinite" duct, i.e. very little of the acoustic power traveling down the duct is ever reflected back into the source area. In order to determine the absorption coefficient, the measurements are matched to a ray model (or image source model) of the acoustic field radiated from the source in an "infinite" duct. The entry is modeled as a finite entry with an absorption coefficient of $\alpha = 1$ at both ends to make it appear infinite. The ray model (Figure 6.8) is used to calculate the sound pressure level at the measurement positions based on varying absorption coefficients relative to the acoustic environment.

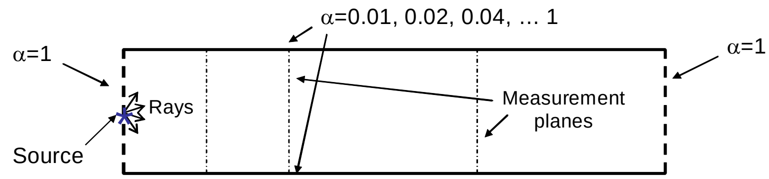


Figure 6.8 Illustration of Ray Tracing for Analyzing the Acoustic Environment

Since the entry, associated with underground coal mining, is fairly wide (>15ft across), this method will work well, even at low frequencies within the frequency spectrum. The procedure used for collecting acoustical data in the mine environment for estimating the absorption coefficients for utilization in the ray tracing model, is provided in section 6.3 below.

6.3.4 Method for Determining Absorption Coefficients in an Underground Coal Mine

The method utilized to determine the absorption coefficients in an underground coal mine is displayed below.

6.3.4.1 Underground Measurements and Testing Parameters

Figure 6.9 displays the measurement scheme used in determining the coefficients of absorption in an underground mine setting.

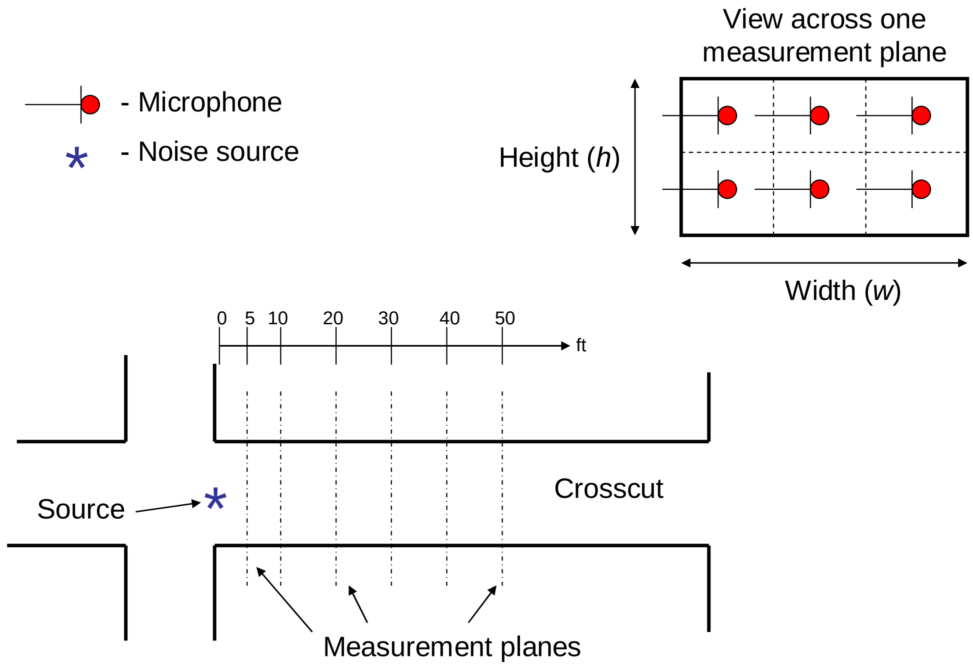


Figure 6.9 Measurement Layout Used for Determining Absorption Coefficients in an Underground Coal Mine

The calibrated noise source (fan) was positioned near the end of a crosscut, or the edge of the mine entry as shown in figure 6.9 above. Figure 6.10 shows a picture of the calibrated noise source to be utilized for conducting the underground mine tests.

Figure 6.10 Photograph of Calibrated Sound Source for Underground Testing

The noise source (fan) was placed at the midway point of the crosscut and at a position halfway between the floor and roof of the crosscut. The actual position of the noise source was recorded and documented for analysis procedures to be performed in determining the absorption coefficients of the mine environment. The octave-band sound power levels for the calibrated noise source are shown in table 6.1 below.

Table 6.1 One-Third Octave-Band Sound Power Levels for Calibrated Noise Source

Octave-band (Hz)	**Sound Power (dB)**
63	72.8
125	78.9
250	80.1
500	79.9
1000	83.6
2000	84.8
4000	83.0
8000	80.2

Additionally, the actual dimensions of the crosscut were measured and recorded. The crosscut was divided into equal areas or sub-sections and the center of each sub-section represented a measurement location as shown in figure 6.9 above. Several measurement planes were developed and measured to collect the acoustical data across the measured planes within each subsection previously established. At each measurement location, the one-third octave band sound pressure level was measured due to the calibrated noise source and recorded at the 63-hertz thru 8,000-hertz one-third octave bands. A Brüel and Kjaer 2260 Investigator was used to collect the one-third octave band data and shown in figure 6.11 below. The Brüel and Kjaer 2260 Investigator is a handheld real-time one-third octave band device with frequency analysis, statistics and logging capabilities.

Figure 6.11 Photograph of a Brüel and Kjaer 2260 Investigator

Utilizing the measurement scheme from figure 6.9 for underground testing, the calibrated noise source (fan) was placed inside the right open end of a crosscut. A total of forty-eight, one-third octave band measurements were performed using the Brüel and Kjaer 2260 Investigator for characterization of the acoustical mining environment. Two measurements were conducted at each of the twenty-four monitoring points within the crosscut, therefore, accounting for forty-eight measurements. At each monitoring point, a measurement (bottom point) was conducted 0.7 meters from the floor and the other measurement was performed at 1.4 meters (top point) from the floor. The length of the crosscut measured 22 meters. Figure 6.12 provides the location of the measuring points (twenty-four) and the position of the measurement planes with respect to the width and height of the crosscut, utilized for characterizing the acoustical properties of the mining environment.

	22m	**19m**	**16m**	**13m**	**10m**	**7m**	**4m**	**1m**	
	22	19	16	13	10	7	4	1	
	23	20	17	14	11	8	5	2	source
	24	21	18	15	12	9	6	3	
width	6.6m	6.0m	5.3m	5.6m	5.7m	5.6m	5.6m	5.1m	
height	2.3m	2.3m	2.2m	2.1m	2.3m	2.3m	2.2m	2.1m	

Figure 6.12 Measurement Locations for Determining Acoustical Properties Underground

An example of the one-third octave data collected for all forty-eight measuring points is shown in table 6.2.

Table 6.2 Example of the One-Third Octave Data Collected Underground

Instrument:	2260
Start Time:	08/06/2004 03:28:40 AM
End Time:	08/06/2004 03:28:55 AM
Elapsed Time:	0:00:15
Bandwidth:	1/3 Octave
Calibration Time:	11/04/2003 04:19:15 PM
Calibration Level:	93.9 dB

08/06/2004 03:28:40 AM - 03:28:55 AM

Hz	LLeq	LLSMax	LLSMin
63	65.54	66.76	63.02
80	64.3	65.54	62.53
100	67.56	68.79	65.12
125	74.08	74.55	72.75
160	66.04	67.56	64.64
200	62.93	63.53	62.25
250	64.64	65.79	60.93
315	66.06	66.88	63.42
400	69.09	70.01	67.7
500	68.58	70.31	67.53
630	67.25	68.15	66.38
800	69.44	70.33	68.2
1000	72.41	73.18	70.13
1250	73.39	73.95	70.66
1600	73.86	74.46	71.57
2000	72	72.48	70.25
2500	71.18	71.54	68.81
3150	69.72	70.19	67.8
4000	68.36	68.59	66.33
5000	67.96	68.16	65.92
6300	66.32	66.6	64.32
8000	64.58	64.78	62.72
A	82.19	82.49	80.13
L	83.43	83.68	81.45

It should be noted that Table 6.2 represents data collected for one measuring point, for this case it was measurement location number one, bottom measurement (see figure 6.12), therefore, forty-seven additional tests were conducted representing a similar format for obtaining the necessary data for characterization of the mining environment and for input into the Raynoise program.

6.3.4.2 Utilizing the Excelparse Program for Calculating Octave-Band Information

As mentioned in section 6.3.4.1, data from underground testing was collected in one-third octave bands. The program, Raynoise, used for displaying and predicting sound pressure levels experienced by roof bolter operators requires full-octave band data. Therefore, a program was developed, referred to as Excelparse, to convert the one-third octave band data collected from underground testing to full-octave band data for input into the Raynoise program.

Upon completion of the underground testing, the data was downloaded to a portable computer. The data is in an Excel format with a separate file for each point measured as shown in section 6.3.4.1 (table 6.2). The Excelparse program extracts the sound pressure level information from each individual file and combines the results for all points measured into one file. Figure 6.13 displays a screenshot of the data from the Excelparse program.

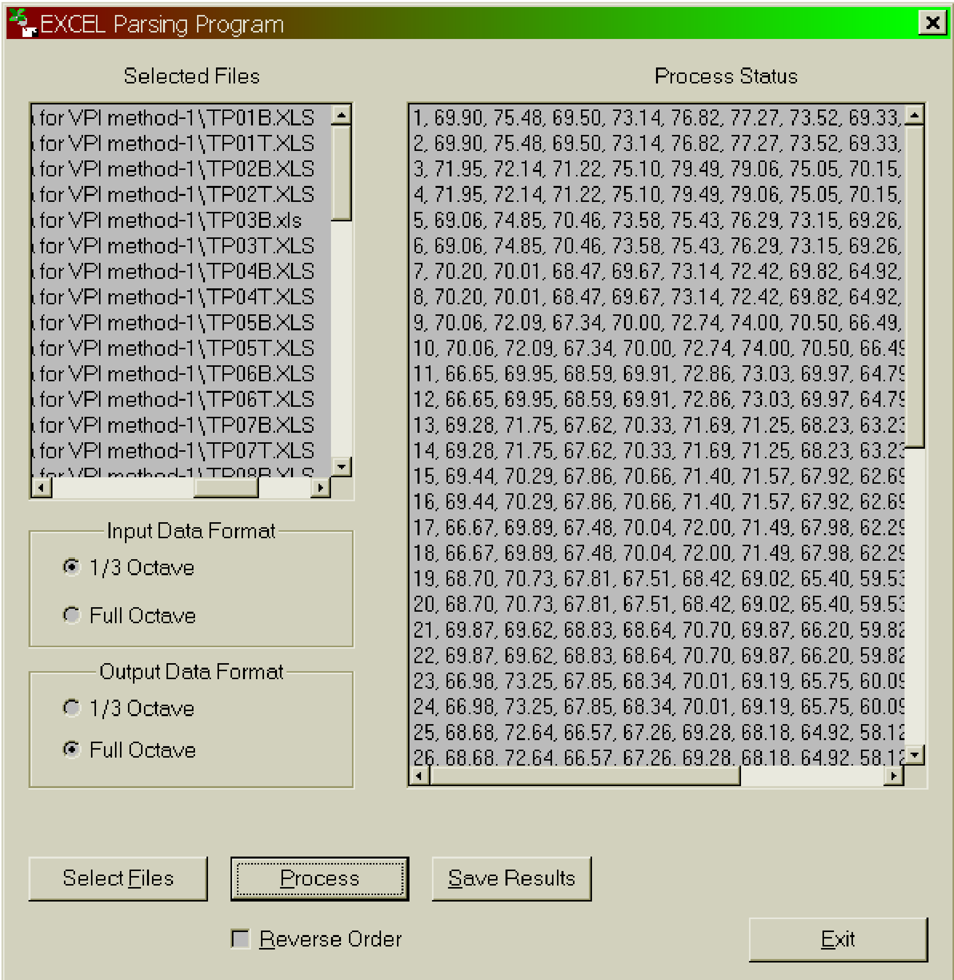


Figure 6.13 Screenshot of the Excelparse Program

The program determines full-octave band data from the one-third octave band data collected from the underground measurements. The equation used in the program which converts one-third to full-octave band sound pressure levels is shown below.

$$SPL = 10 * LOG10\ (temp) \qquad (9)$$

where

SPL = Sound Pressure Level (in respective full-octave band)

$(temp) = 10^{(\text{Previous one-third octave}/10)} + 10^{(\text{Actual one-third octave}/10)} + 10^{(\text{Next one-third octave}/10)}$

For example, by utilizing equation 8 and table 6.2 above, the full-octave band of 63 Hz could be obtained from one-third octave band data as shown below:

$$SPL\ (63\ Hz\text{-}Octave\ Band) = 10 * LOG10\ \{10^{(65.44/10)} + 10^{(65.54/10)} + 10^{(64.3/10)}\} \qquad (10)$$

yields the following:

$$SPL\ (63\ Hz\text{-}Octave\ Band) – 10 * LOG10\ \{10^{(6.54)} + 10^{(6.55)} + 10^{(6.43)}\}$$

$$SPL\ (63\ Hz\text{-}Octave\ Band) – 10 * LOG10\ \{3,467,368.50 + 3,548,133.89 + 2,691,534.80\}$$

$$SPL\ (63\ Hz\text{-}Octave\ Band) – 10 * LOG10\ \{9,707,037.19\}$$

$$SPL\ (63\ Hz\text{-}Octave\ Band) – 10 * 6.99$$

$$SPL\ (63\ Hz\text{-}Octave\ Band) – 69.9\ dB$$

Table 6.3, shown below, represents the full-octave band data (for 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2,000 Hz, 4,000 Hz and 8,000 Hz), generated from the Excelparse program for all forty-eight measuring points within the crosscut in the underground coal mine as shown in figure 6.12.

Table 6.3 Measured Full-Octave Band Sound Pressure Levels from Underground Testing

Point Number	Full-Octave Bands							
	63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
	dB	dB	dB	dB	dB	dB	dB	dB
1	69.9	75.48	69.5	73.14	76.82	77.27	73.52	69.33
2	69.9	75.48	69.5	73.14	76.82	77.27	73.52	69.33
3	71.95	72.14	71.22	75.1	79.49	79.06	75.05	70.15
4	71.95	72.14	71.22	75.1	79.49	79.06	75.05	70.15
5	69.06	74.85	70.46	73.58	75.43	76.29	73.15	69.26
6	69.06	74.85	70.46	73.58	75.43	76.29	73.15	69.26
7	70.2	70.01	68.47	69.67	73.14	72.42	69.82	64.92
8	70.2	70.01	68.47	69.67	73.14	72.42	69.82	64.92
9	70.06	72.09	67.34	70	72.74	74	70.5	66.49
10	70.06	72.09	67.34	70	72.74	74	70.5	66.49
11	66.65	69.95	68.59	69.91	72.86	73.03	69.97	64.79
12	66.65	69.95	68.59	69.91	72.86	73.03	69.97	64.79
13	69.28	71.75	67.62	70.33	71.69	71.25	68.23	63.23
14	69.28	71.75	67.62	70.33	71.69	71.25	68.23	63.23
15	69.44	70.29	67.86	70.66	71.4	71.57	67.92	62.69
16	69.44	70.29	67.86	70.66	71.4	71.57	67.92	62.69
17	66.67	69.89	67.48	70.04	72	71.49	67.98	62.29
18	66.67	69.89	67.48	70.04	72	71.49	67.98	62.29
19	68.7	70.73	67.81	67.51	68.42	69.02	65.4	59.53
20	68.7	70.73	67.81	67.51	68.42	69.02	65.4	59.53
21	69.87	69.62	68.83	68.64	70.7	69.87	66.2	59.82
22	69.87	69.62	68.83	68.64	70.7	69.87	66.2	59.82
23	66.98	73.25	67.85	68.34	70.01	69.19	65.75	60.09
24	66.98	73.25	67.85	68.34	70.01	69.19	65.75	60.09
25	68.68	72.64	66.57	67.26	69.28	68.18	64.92	58.12
26	68.68	72.64	66.57	67.26	69.28	68.18	64.92	58.12
27	70.27	74.89	67.77	68.55	69	68.38	64.35	58.33
28	70.27	74.89	67.77	68.55	69	68.38	64.35	58.33
29	67.68	70.5	68.16	67.9	69.37	68.71	64.47	58.29
30	67.68	70.5	68.16	67.9	69.37	68.71	64.47	58.29
31	67.63	68.81	65.75	67.2	67.02	66.64	62.24	56.68
32	67.63	68.81	65.75	67.2	67.02	66.64	62.24	56.68
33	68.92	71.99	66.8	67.43	67.99	66.82	63.08	56.85
34	68.92	71.99	66.8	67.43	67.99	66.82	63.08	56.85
35	67.89	69.57	68.24	66.78	68.06	66.64	62.53	56.69
36	67.89	69.57	68.24	66.78	68.06	66.64	62.53	56.69
37	67.24	70.63	65.12	66.65	66.32	64.99	60.93	55.36
38	67.24	70.63	65.12	66.65	66.32	64.99	60.93	55.36
39	67.59	70.58	65.24	66.98	65.87	65.17	60.36	55.49
40	67.59	70.58	65.24	66.98	65.87	65.17	60.36	55.49
41	67.63	68.89	67.42	65.77	66.1	64.52	60.41	55.19
42	67.63	68.89	67.42	65.77	66.1	64.52	60.41	55.19
43	64.84	69.52	64.85	64.69	63.02	62.58	58.19	54.77
44	64.84	69.52	64.85	64.69	63.02	62.58	58.19	54.77
45	66.79	72.14	63.97	63.53	64.85	63.72	58.62	54.77
46	66.79	72.14	63.97	63.53	64.85	63.72	58.62	54.77
47	69.33	72.9	65.59	64.33	64.86	63.65	59.51	54.88
48	69.33	72.9	65.59	64.33	64.86	63.65	59.51	54.88

6.3.4.3 Development of an Equivalent Model in Raynoise for Predicting Sound Pressure Levels

The test conditions documented from the underground testing in figure 6.6 where then used to create an equivalent underground model utilizing the Raynoise package. The specific information used for input into the Raynoise package consisted of: 1) the height above the floor of the noise source and the X and Y coordinates relative to the placement and location of the calibrated noise source; 2) the height above the floor relative to the bottom and top measurement points as shown in figure 6.12; 3) the total length of the crosscut being examined; 4) the crosscut height and width at each measurement plane location and 5) the sound power output of the calibrated noise source in full-octave band format as displayed in table 6.1. Inputting the test conditions mentioned above, an equivalent Raynoise model was constructed (25). The structural information for the equivalent model was determined thru the development of an AutoCAD drawing of the crosscut and then inputted into the Raynoise package. The measurement points within the model are then defined utilizing the underground measurements collected relative to the height above the floor in relation to the top and bottom point measurements for input into the Raynoise model. The calibrated noise source is then placed in the position as performed for the underground measurements and the sound power output is set for input into the Raynoise model as shown in Figure 6.14 below.

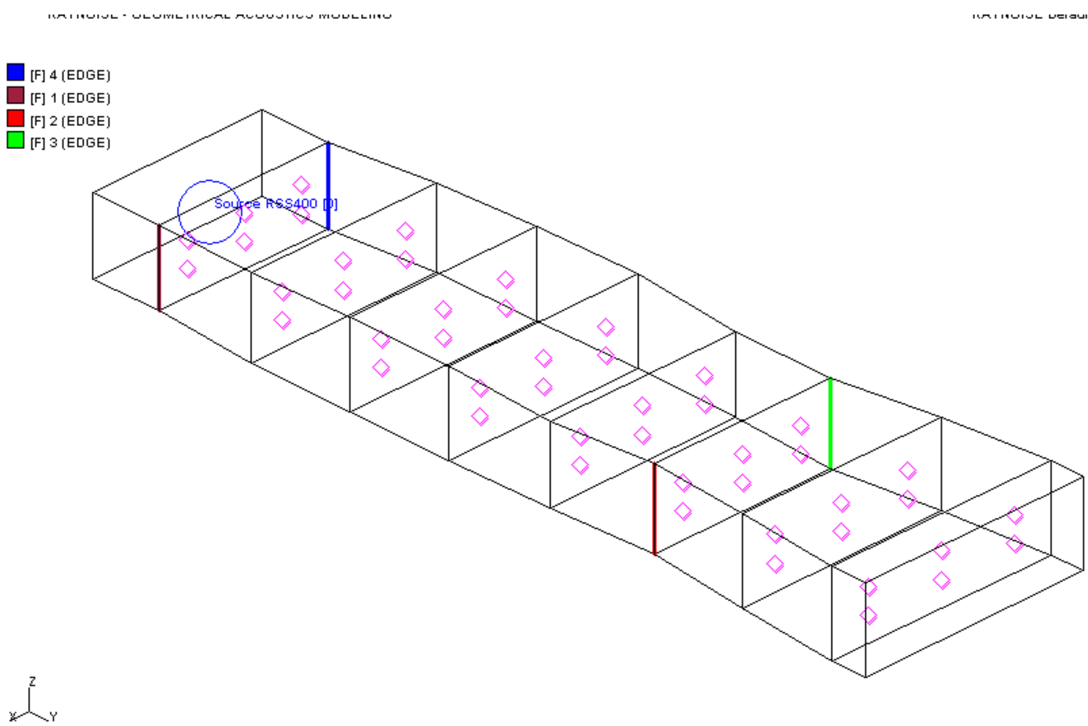


Figure 6.14 Test Layout for First Run in Raynoise Model

Due to the geometric underground measurements conducted in figure 6.12, a total of four diffraction edges were added to the model to account for the changing geometry of the crosscut measured underground. These edges are shown as (F)1 thru (F)4 shown in figure 6.14. An initial set of absorption coefficients, in which, are full-octave band based, were then inputted into the model relative to the underground mining environment. The first set of absorption coefficients inputted into the Raynoise model for the first run were selected from previous research conducted by Patterson, et.al (24) are shown in table 6.4 below.

Table 6.4 Absorption Coefficients Utilized for First Run of Raynoise Model

Octave-band (Hz)	**Absorption Coefficient**
63	.035
125	.04
250	.17
500	.14
1000	.21
2000	.24
4000	.33
8000	.45

The absorption coefficients were determined from a basic equation, where the volume, surface area and decay time are inputted as shown below:

$$\alpha = 0.05 * V/S * 1/T60 \quad (11)$$

where V represents the volume, S is the surface area and T60 represents the decay time. The decay time is determined by the amount of time it takes for sound to dissipate by 60 dB in each octave band for a given position.

A full-octave band test of the model, utilizing the absorption coefficients from table 6.4 was then processed utilizing the Raynoise program and Rayserve package, mentioned previously. For example, figure 6.15 displays graphically, the results for sound pressure levels experienced at the 1,000 Hz octave band relative to the absorption coefficients utilized in table 6.4. Seven additional plots for each of the other full-octave bands were processed and constructed, in which, were utilized for comparing the results from the actual underground testing displayed in table 6.3.

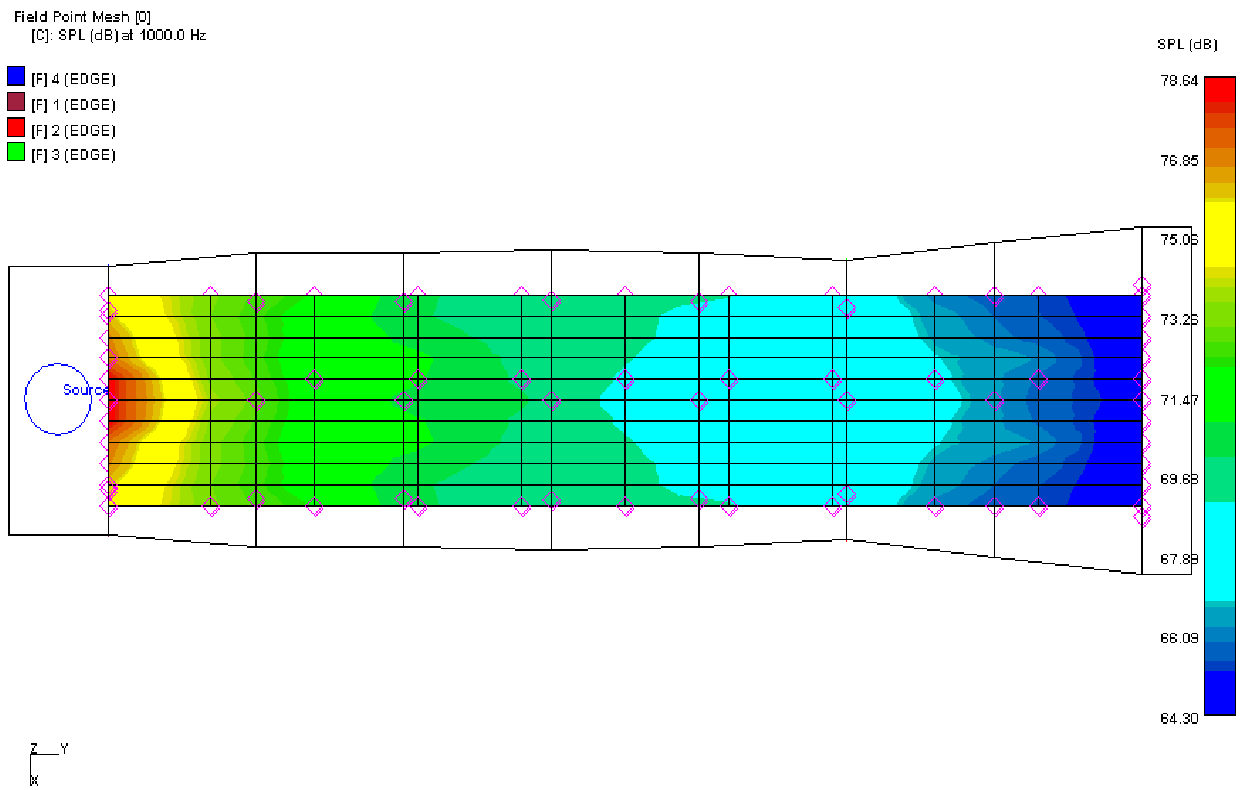


Figure 6.15 Sound Pressure Levels at 1,000 Hz Full-Octave Band

The linear sound pressure level information for each of the full-octave bands were also organized into a file and imported into Excel for comparing the calculated sound pressure level results to the measured sound pressure levels from table 6.3. The calculated sound pressure level results are shown in table 6.5 below.

Table 6.5 Calculated Full-Octave Band Sound Pressure Levels – First Run of Model

Point Number	Octave Band (Hz)								
	63	125	250	500	1000	2000	4000	8000	Sound Pressure Level dB
1	70	74.1	73.5	74.1	75.9	75.9	73.2	70.2	82.9
2	70.1	74.1	73.5	74.1	76	76	73.2	70.2	82.9
3	72	76	76	76.5	78.6	78.8	76.4	73.8	85.5
4	71.5	75.6	75.5	76	78.1	78.2	75.9	73.3	85.0
5	70	74.1	73.5	74.1	75.9	75.9	73.2	70.2	82.9
6	70.1	74.1	73.5	74.1	76	76	73.2	70.2	82.9
7	66.8	70.9	69.9	70.6	72.2	72.2	69.1	65.7	79.2
8	66.9	70.9	70	70.7	72.3	72.2	69.2	65.8	79.3
9	67.3	71.3	70.4	71.1	72.7	72.7	69.7	66.2	79.7
10	67.6	71.6	70.6	71.3	72.9	72.8	69.8	66.3	79.9
11	66.8	70.9	69.9	70.6	72.2	72.2	69.1	65.7	79.2
12	66.9	70.9	70	70.7	72.3	72.2	69.2	65.8	79.3
13	65.8	69.8	68.3	69.1	70.4	70.2	66.8	62.9	77.5
14	65.9	69.9	68.4	69.1	70.5	70.3	66.9	63	77.6
15	65.9	69.9	68.4	69.2	70.6	70.4	67	63.1	77.7
16	66.1	70.1	68.6	69.4	70.8	70.6	67.1	63.2	77.9
17	65.8	69.8	68.3	69.1	70.4	70.2	66.8	62.9	77.5
18	65.9	69.9	68.4	69.1	70.5	70.3	66.9	63	77.6
19	65.1	69.1	67.1	68	69.1	68.8	65.1	60.9	76.3
20	65.3	69.3	67.3	68.2	69.3	69	65.3	61	76.5
21	65.8	69.8	67.9	68.8	69.9	69.6	65.9	61.6	77.1
22	65.7	69.7	67.7	68.6	69.7	69.4	65.7	61.5	76.9
23	65.1	69.1	67.1	68	69.1	68.8	65.1	60.9	76.3
24	65.3	69.3	67.3	68.2	69.3	69	65.3	61	76.5
25	65.3	69.2	67.2	68.1	69.1	68.8	65	60.5	76.4
26	65.4	69.4	67.2	68.1	69.2	68.8	65	60.6	76.4
27	64.9	68.8	66.5	67.5	68.4	68	64.2	59.7	75.7
28	65	69	66.7	67.7	68.6	68.3	64.4	59.9	76.0
29	65.3	69.2	67.2	68.1	69.1	68.8	65	60.5	76.4
30	65.4	69.4	67.2	68.1	69.2	68.8	65	60.6	76.4
31	64.4	68.4	66	67	67.9	67.5	63.5	58.9	75.2
32	64.3	68.2	65.9	66.9	67.8	67.4	63.4	58.8	75.1
33	64.3	68.3	66	66.9	67.8	67.4	63.5	59	75.2
34	64.4	68.4	65.8	66.8	67.6	67.2	63.1	58.5	75.1
35	64.4	68.4	66	67	67.9	67.5	63.5	58.9	75.2
36	64.3	68.2	65.9	66.9	67.8	67.4	63.4	58.8	75.1
37	62.3	66.3	63.8	64.8	65.6	65.1	61.1	56.4	73.0
38	62.6	66.6	64.2	65.1	66	65.6	61.5	56.8	73.4
39	62.5	66.5	64.3	65.2	66.2	65.8	61.9	57.4	73.5
40	63.4	67.4	65.1	66	66.9	66.5	62.5	57.8	74.3
41	62.3	66.3	63.8	64.8	65.6	65.1	61.1	56.4	73.0
42	62.6	66.6	64.2	65.1	66	65.6	61.5	56.8	73.4
43	61.2	65.1	62.5	63.6	64.3	63.8	59.7	54.9	71.7
44	61	65	62.5	63.5	64.3	63.9	59.8	55	71.7
45	61.2	65.2	62.9	63.8	64.8	64.4	60.6	56.1	72.1
46	61.4	65.4	63.1	64	65	64.6	60.8	56.5	72.3
47	61.2	65.1	62.5	63.6	64.3	63.8	59.7	54.9	71.7
48	61	65	62.5	63.5	64.3	63.9	59.8	55	71.7

Both files (measured and calculated) were then utilized to compare differences in sound pressure levels. Charts were generated plotting measured vs. calculated sound pressure level at each measurement point for each octave band (63 Hz, 125 Hz, 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz, 4,000 Hz and 8,000 Hz) sound pressure level for comparison purposes as shown in figures 6.16 thru 6.23 below (25).

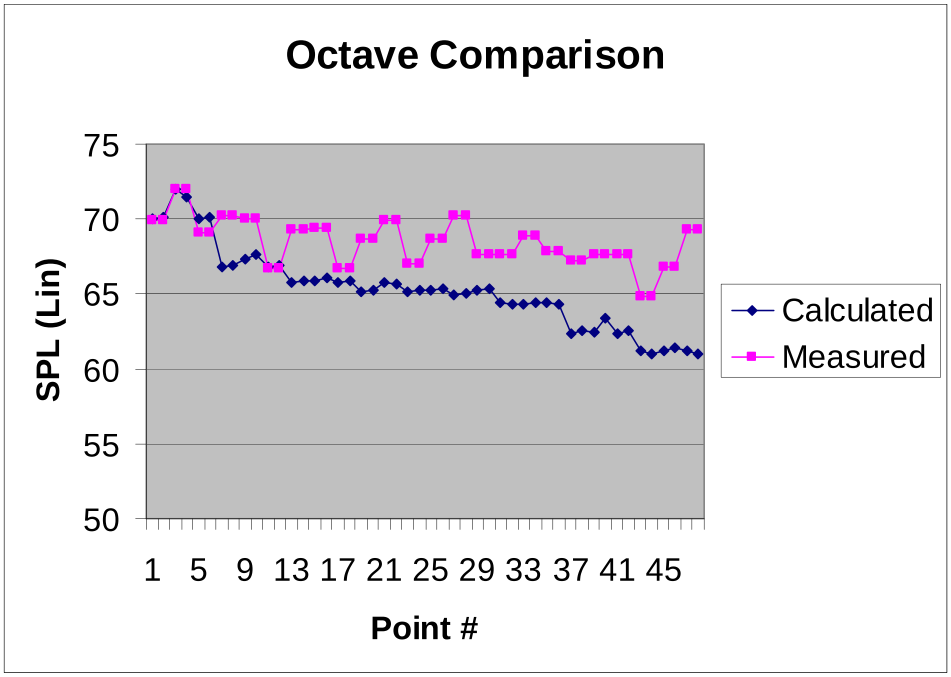


Figure 6.16 Comparing Calculated vs. Measured Sound Pressure Levels for 63-Hz Octave Band.

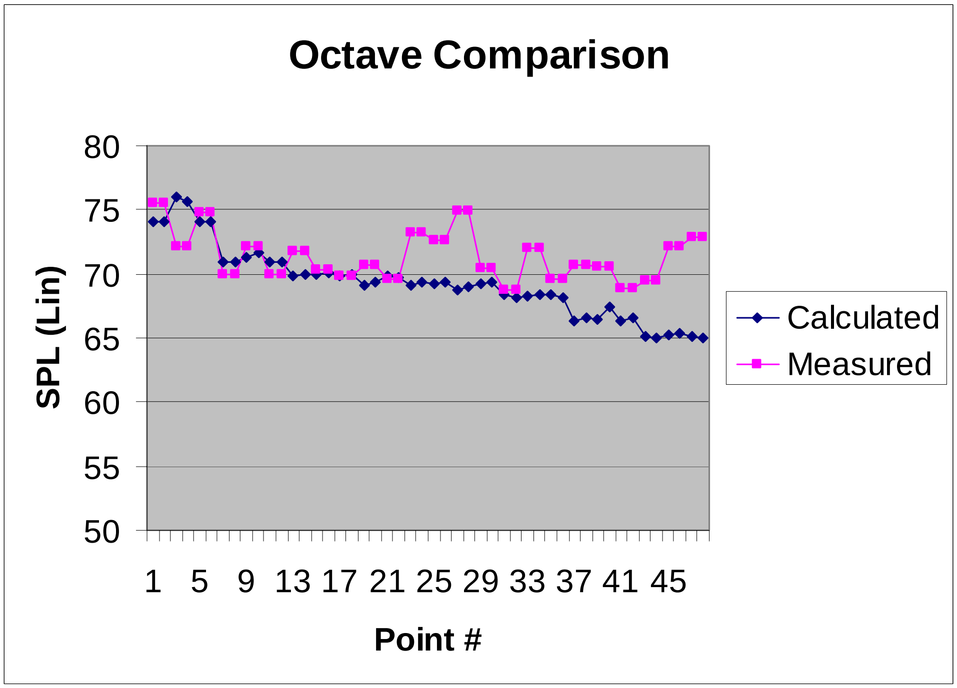


Figure 6.17 Comparing Calculated vs. Measured Sound Pressure Levels for 125-Hz Octave Band.

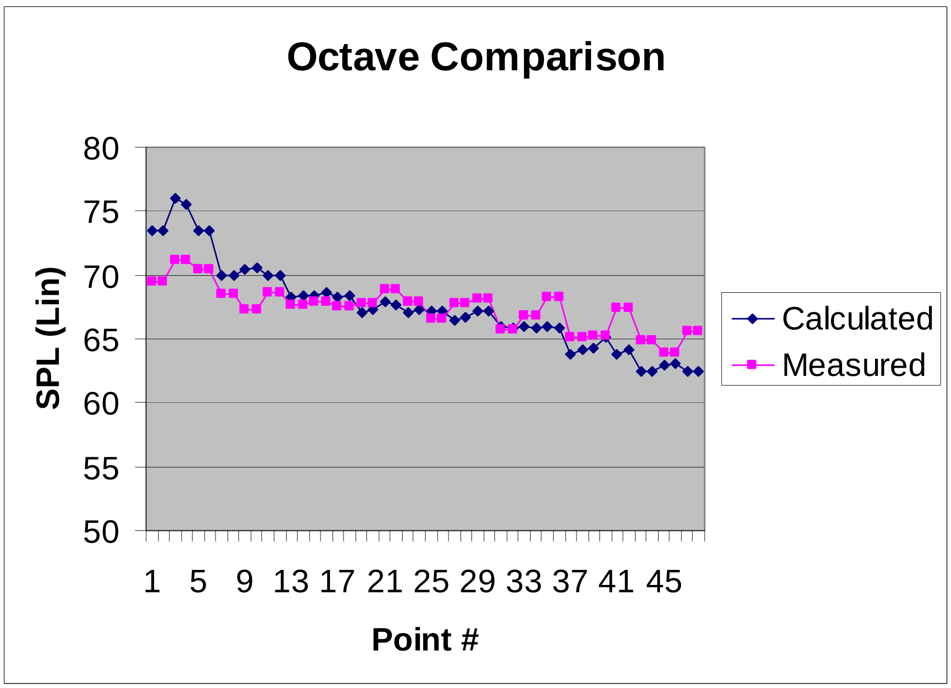


Figure 6.18 Comparing Calculated vs. Measured Sound Pressure Levels for 250-Hz Octave Band.

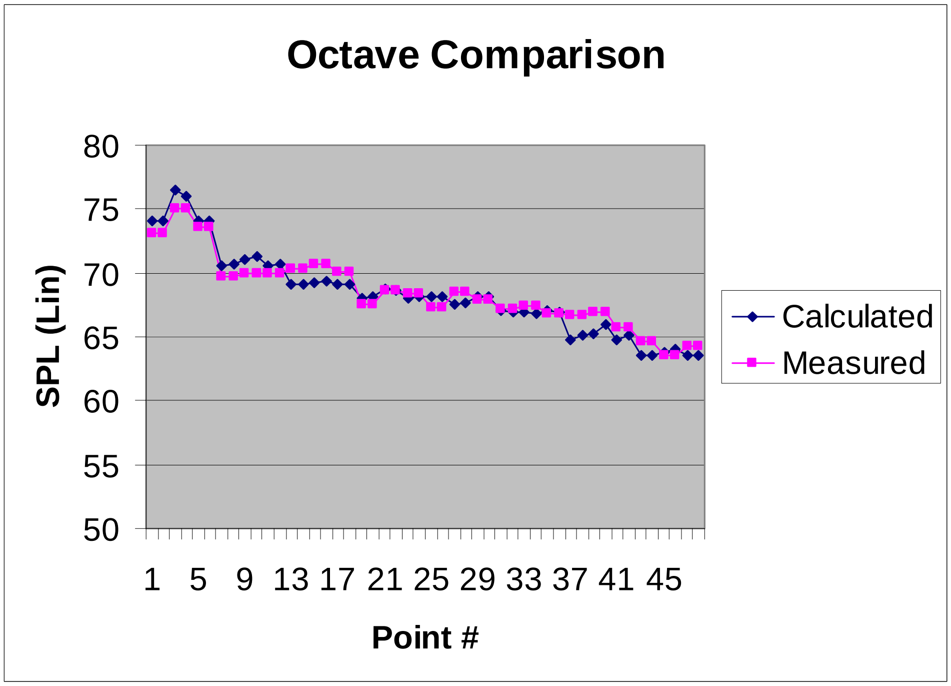


Figure 6.19 Comparing Calculated vs. Measured Sound Pressure Levels for 500-Hz Octave Band.

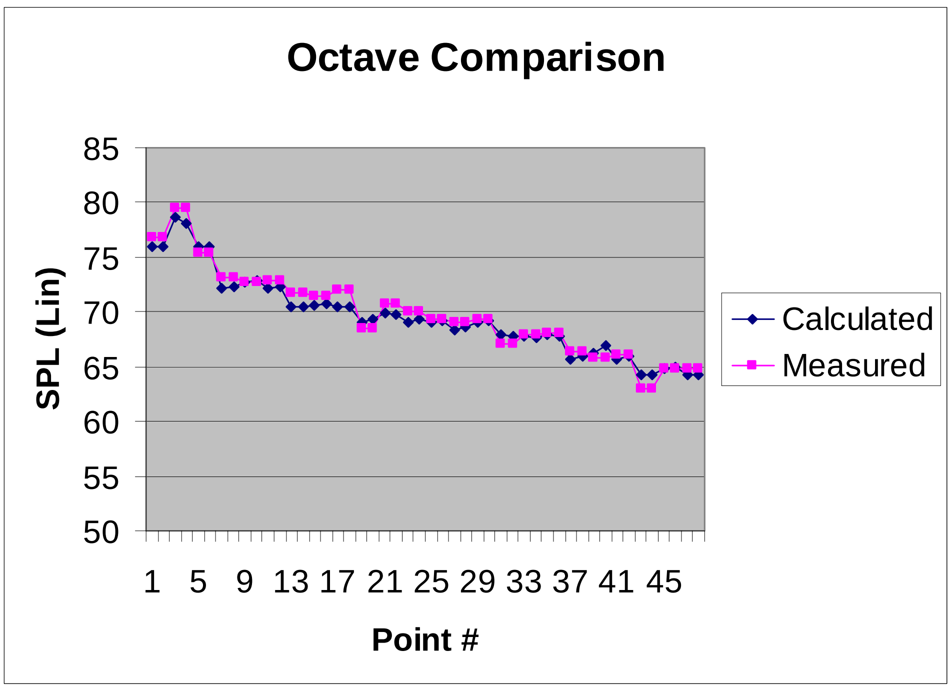


Figure 6.20 Comparing Calculated vs. Measured Sound Pressure Levels for 1,000-Hz Octave Band.

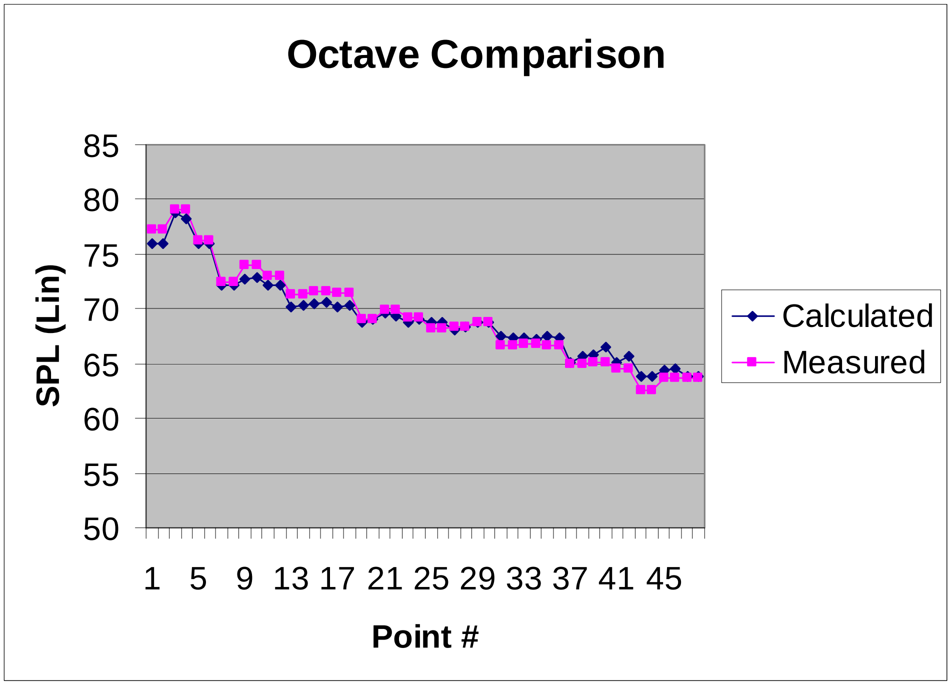


Figure 6.21 Comparing Calculated vs. Measured Sound Pressure Levels for 2,000-Hz Octave Band.

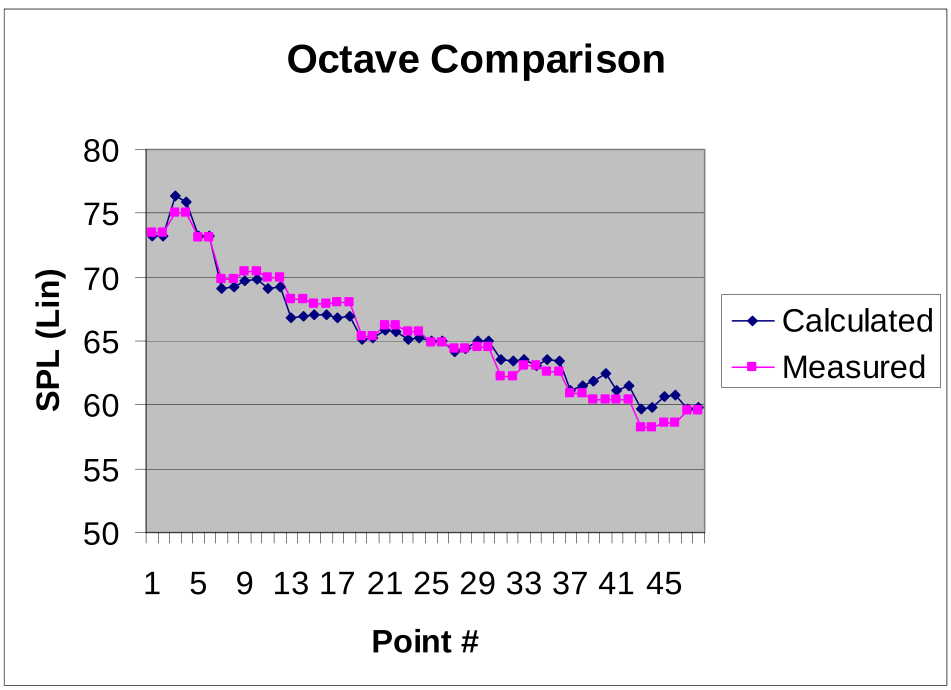


Figure 6.22 Comparing Calculated vs. Measured Sound Pressure Levels for 4,000-Hz Octave Band.

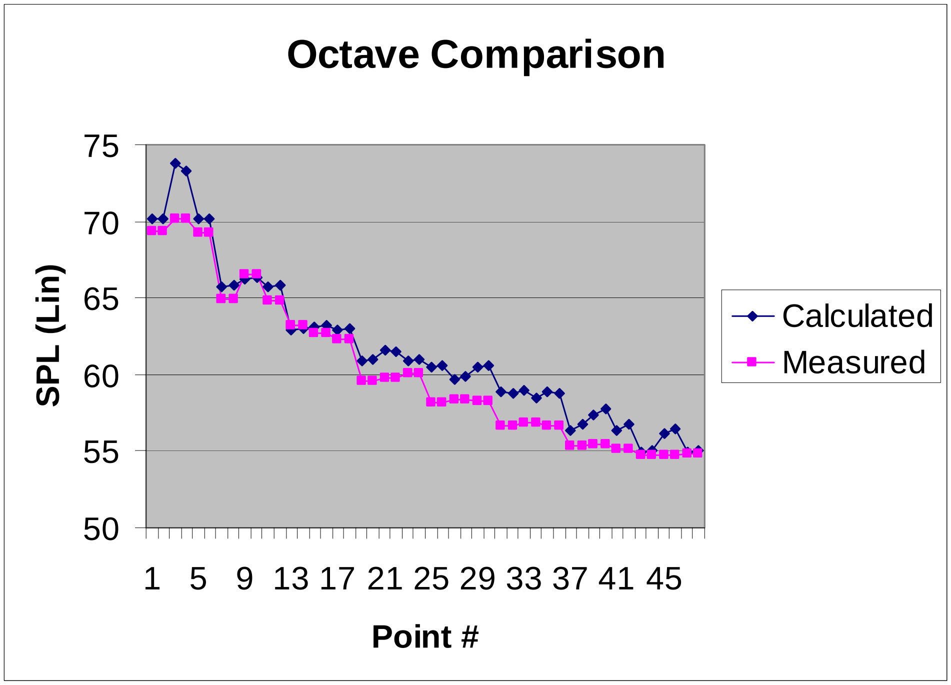


Figure 6.23 Comparing Calculated vs. Measured Sound Pressure Levels for 8,000-Hz Octave Band.

The calculated results at each of the eight full-octave bands were then compared to the measured results. The modeled absorption coefficients were then adjusted to bring the sound pressure level results closer to the measured sound pressure levels and the model was then processed again. Consequently, after five model runs, the error between the measured and calculated sound pressure levels were minimized and a set of full-octave band absorption coefficients for the mine cross-section were determined. Plots comparing the measured and calculated sound pressure levels for each of the eight full-octave bands are shown below in figures 6.24 thru 6.31. Additionally, table 6.6 displays the calculated sound pressure levels after the fifth model run in determining the absorption coefficients thru comparing sound pressure levels (measured and calculated). Table 6.7 provides the difference in dB, between the measured and calculated sound pressure levels for all forty-eight monitoring points and full-octave band frequencies.

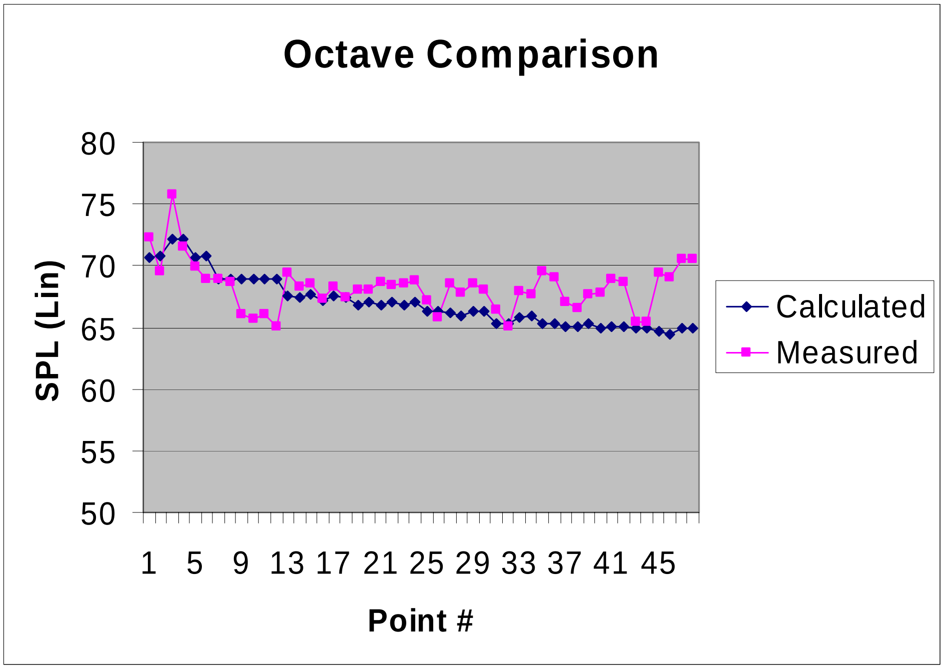


Figure 6.24 Comparing Calculated vs. Measured Sound Pressure Levels for 63-Hz Octave Band (Model Run 5)

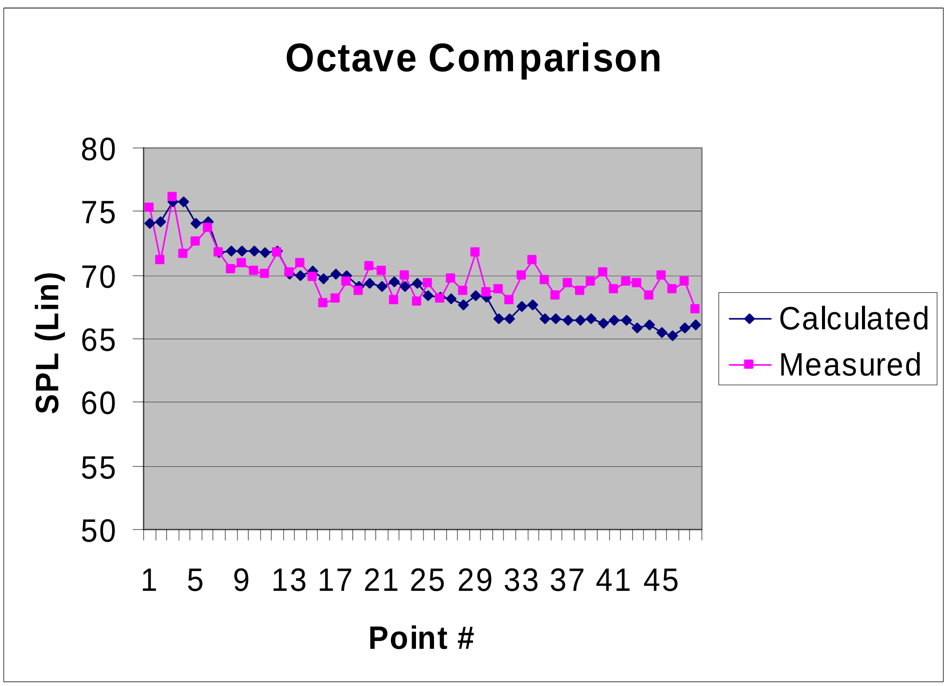


Figure 6.25 Comparing Calculated vs. Measured Sound Pressure Levels for 125-Hz Octave Band (Model Run 5)

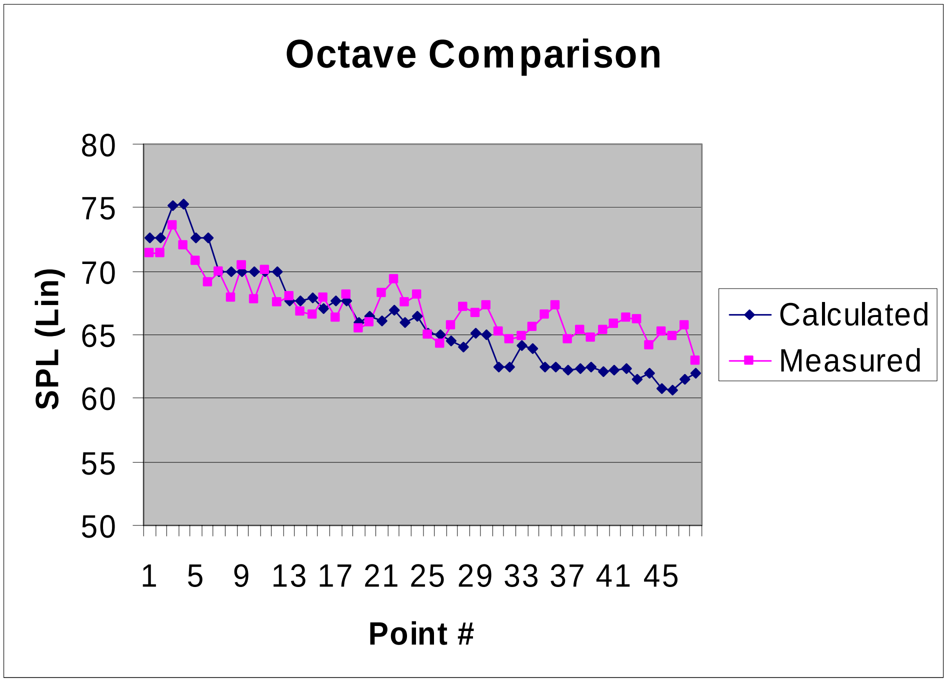


Figure 6.26 Comparing Calculated vs. Measured Sound Pressure Levels for 250-Hz Octave Band (Model Run 5)

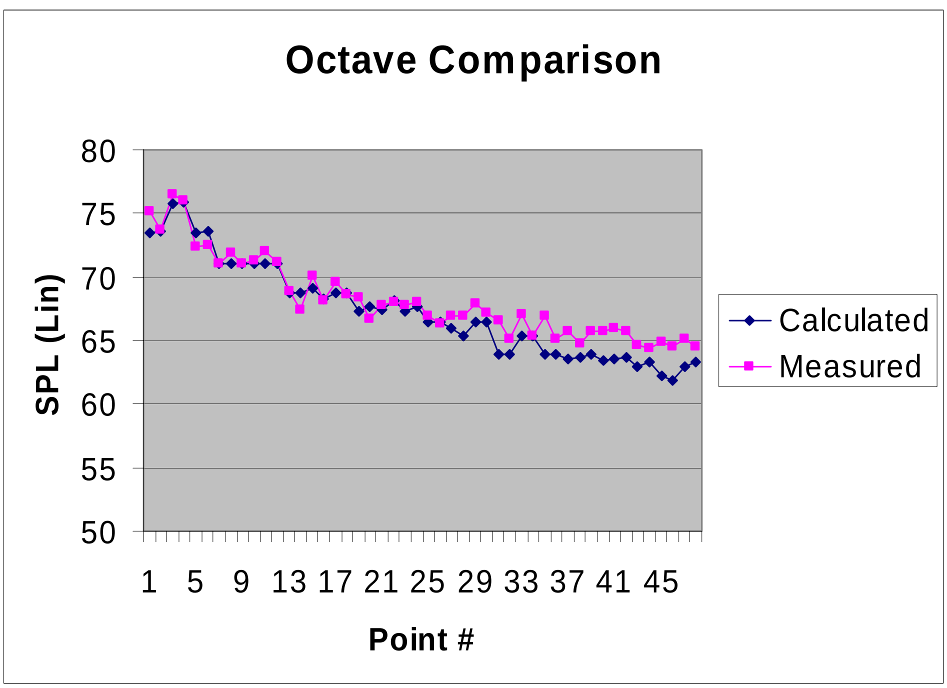


Figure 6.27 Comparing Calculated vs. Measured Sound Pressure Levels for 500-Hz Octave Band (Model Run 5)

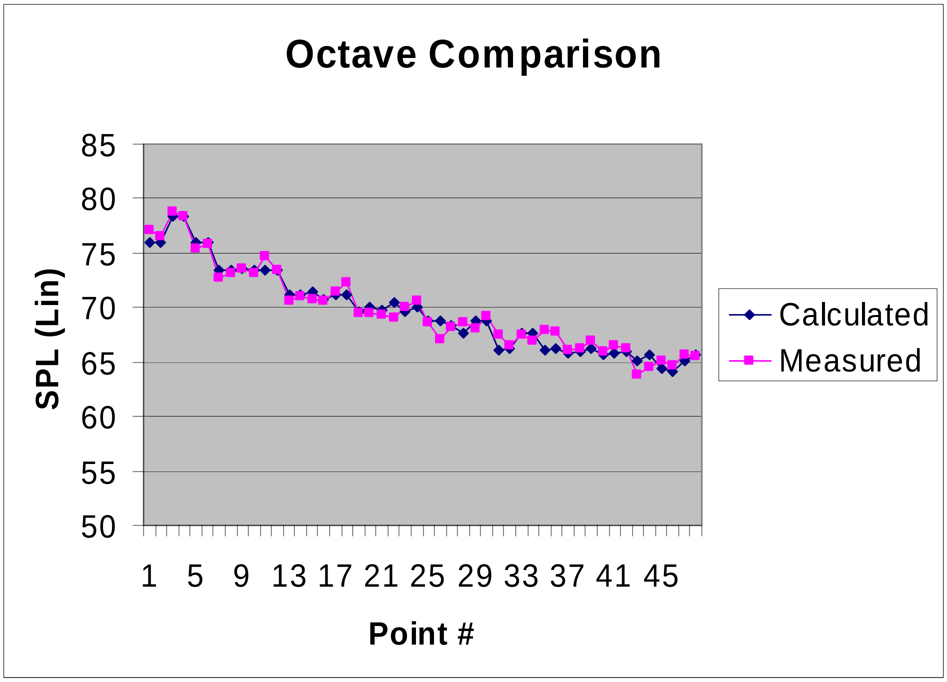


Figure 6.28 Comparing Calculated vs. Measured Sound Pressure Levels for 1,000-Hz Octave Band (Model Run 5)

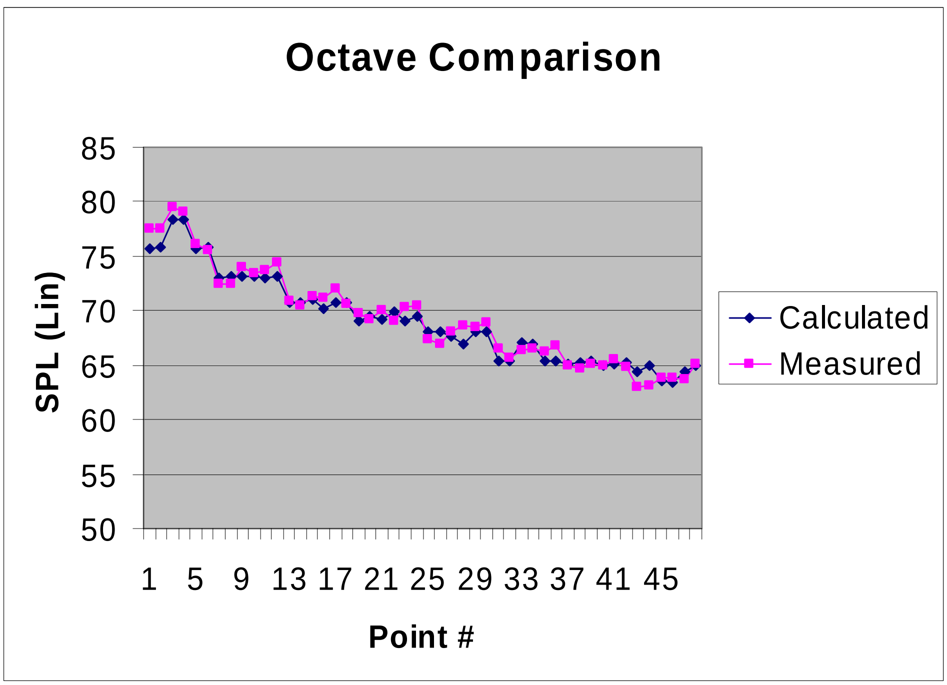


Figure 6.29 Comparing Calculated vs. Measured Sound Pressure Levels for 2,000-Hz Octave Band (Model Run 5)

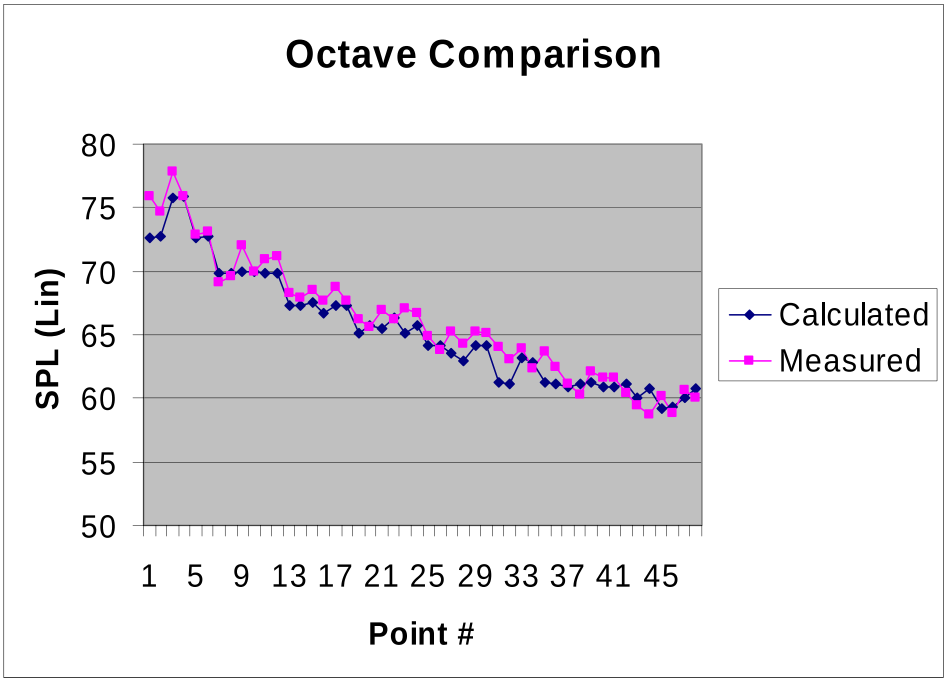


Figure 6.30 Comparing Calculated vs. Measured Sound Pressure Levels for 4,000-Hz Octave Band (Model Run 5)

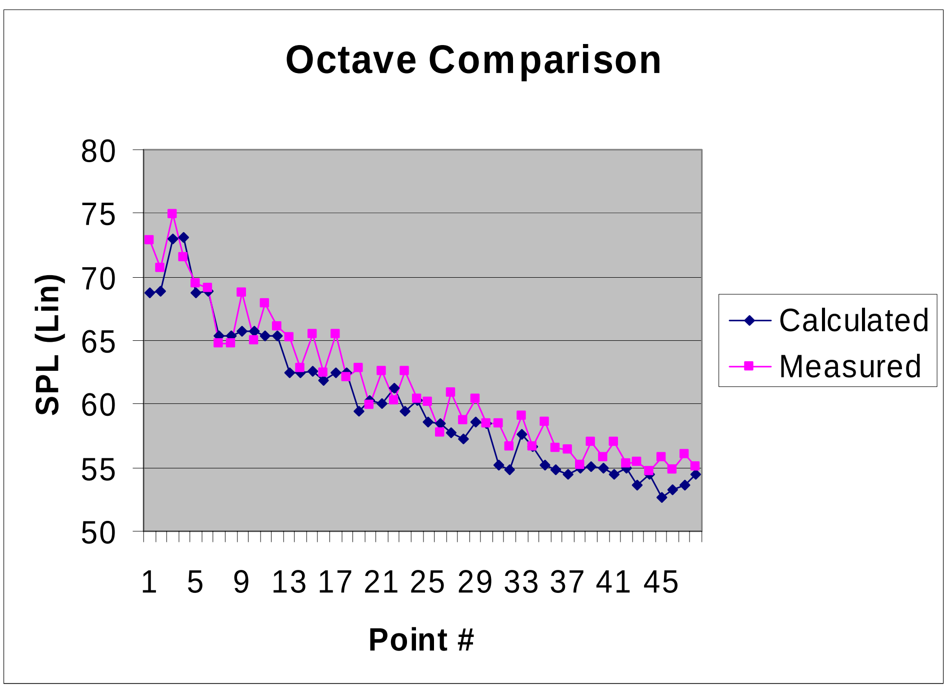


Figure 6.31 Comparing Calculated vs. Measured Sound Pressure Levels for 8,000-Hz Octave Band (Model Run 5)

Table 6.6 Calculated Full-Octave Band Sound Pressure Levels – Fifth Run of Model

	Full-Octave Band, Hz								
Point Number	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**Sound Pressure Level, dB**
1	70.7	74.1	72.6	73.5	75.9	75.7	72.6	68.8	82.5
2	70.8	74.2	72.6	73.6	76	75.8	72.7	68.9	82.6
3	72.2	75.8	75.2	75.8	78.3	78.3	75.8	73	85.0
4	72.2	75.8	75.3	75.9	78.4	78.4	75.9	73.1	85.1
5	70.7	74.1	72.6	73.5	75.9	75.7	72.6	68.8	82.5
6	70.8	74.2	72.6	73.6	76	75.8	72.7	68.9	82.6
7	68.9	71.8	69.9	71	73.4	73	69.8	65.4	80.0
8	68.9	71.9	69.9	71	73.4	73.1	69.8	65.4	80.0
9	68.9	71.9	70	71.1	73.5	73.2	70	65.7	80.1
10	68.9	71.9	70	71	73.4	73.1	69.9	65.7	80.1
11	68.9	71.8	69.9	71	73.4	73	69.8	65.4	80.0
12	68.9	71.9	69.9	71	73.4	73.1	69.8	65.4	80.0
13	67.5	70.1	67.7	68.8	71.2	70.8	67.3	62.5	77.9
14	67.4	70	67.7	68.8	71.2	70.8	67.3	62.5	77.9
15	67.7	70.3	67.9	69.1	71.4	71	67.5	62.6	78.1
16	67.2	69.7	67.1	68.3	70.7	70.2	66.7	61.8	77.4
17	67.5	70.1	67.7	68.8	71.2	70.8	67.3	62.5	77.9
18	67.4	70	67.7	68.8	71.2	70.8	67.3	62.5	77.9
19	66.8	69.1	66	67.3	69.6	69.1	65.1	59.4	76.4
20	67	69.3	66.4	67.7	70	69.5	65.7	60.3	76.8
21	66.8	69.1	66.1	67.4	69.7	69.2	65.5	60.1	76.5
22	67.1	69.5	66.9	68.1	70.4	69.9	66.3	61.2	77.1
23	66.8	69.1	66	67.3	69.6	69.1	65.1	59.4	76.4
24	67	69.3	66.4	67.7	70	69.5	65.7	60.3	76.8
25	66.3	68.4	65.1	66.4	68.7	68.1	64.2	58.6	75.6
26	66.3	68.3	65	66.4	68.7	68.1	64.2	58.5	75.5
27	66.2	68.2	64.5	66	68.3	67.6	63.5	57.7	75.2
28	65.9	67.7	64	65.4	67.6	67	63	57.3	74.6
29	66.3	68.4	65.1	66.4	68.7	68.1	64.2	58.6	75.6
30	66.3	68.3	65	66.4	68.7	68.1	64.2	58.5	75.5
31	65.3	66.6	62.5	63.9	66.1	65.4	61.3	55.2	73.3
32	65.3	66.6	62.5	63.9	66.2	65.4	61.1	54.8	73.3
33	65.8	67.6	64.1	65.4	67.7	67.1	63.2	57.6	74.7
34	65.9	67.7	63.9	65.4	67.6	66.9	62.8	56.6	74.6
35	65.3	66.6	62.5	63.9	66.1	65.4	61.3	55.2	73.3
36	65.3	66.6	62.5	63.9	66.2	65.4	61.1	54.8	73.3
37	65.1	66.4	62.2	63.6	65.8	65.1	60.9	54.5	73.0
38	65.1	66.4	62.3	63.7	65.9	65.2	61.1	54.9	73.1
39	65.3	66.6	62.5	63.9	66.2	65.4	61.2	55.1	73.3
40	65	66.2	62.1	63.4	65.6	65	60.9	55	72.9
41	65.1	66.4	62.2	63.6	65.8	65.1	60.9	54.5	73.0
42	65.1	66.4	62.3	63.7	65.9	65.2	61.1	54.9	73.1
43	64.9	65.9	61.5	62.9	65.1	64.4	60.1	53.6	72.5
44	65	66.1	62	63.3	65.6	64.9	60.8	54.5	72.8
45	64.7	65.5	60.8	62.2	64.4	63.6	59.2	52.7	71.9
46	64.5	65.2	60.6	61.9	64.1	63.4	59.3	53.3	71.7
47	64.9	65.9	61.5	62.9	65.1	64.4	60.1	53.6	72.5
48	65	66.1	62	63.3	65.6	64.9	60.8	54.5	72.8

Table 6.7 Differences Relative to the Measured and Calculated Sound Pressure Levels

	Full-Octave Band, Hz							
Point Number	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
1	1.6	1.13	-1.17	1.64	1.17	1.78	3.25	4.12
2	-1.3	-3.02	-1.13	0.07	0.58	1.79	1.99	1.81
3	3.62	0.36	-1.64	0.73	0.51	1.15	1.99	1.94
4	-0.61	-4.1	-3.27	0.14	-0.03	0.74	0.04	-1.57
5	-0.83	-1.44	-1.85	-1.17	-0.55	0.35	0.26	0.73
6	-1.91	-0.47	-3.53	-1.14	-0.22	-0.19	0.44	0.22
7	0	0	0	0	-0.7	-0.6	-0.7	-0.6
8	-0.28	-1.51	-2.05	0.94	-0.32	-0.65	-0.16	-0.7
9	-2.83	-0.98	0.48	-0.03	0.1	0.73	1.97	3.03
10	-3.25	-1.62	-2.24	0.35	-0.25	0.27	0.1	-0.7
11	-2.87	-1.77	0.2	0.97	1.26	0.73	1.12	2.46
12	-3.8	-0.15	-2.33	0.13	0.06	1.32	1.41	0.73
13	1.98	0.06	0.38	0.13	-0.61	0.06	0.96	2.78
14	0.92	0.89	-0.83	-1.35	-0.14	-0.29	0.56	0.37
15	0.84	-0.42	-1.33	1.04	-0.7	0.35	0.96	2.89
16	0.15	-1.89	0.79	-0.11	-0.07	1.01	1.02	0.67
17	0.84	-1.97	-1.39	0.84	0.32	1.16	1.48	2.98
18	-0.02	-0.55	0.43	-0.13	1.14	-0.22	0.31	-0.41
19	1.21	-0.38	-0.46	1.1	-0.1	0.72	1.11	3.48
20	1.01	1.39	-0.44	-0.97	-0.49	-0.31	-0.14	-0.43
21	1.82	1.17	2.18	0.39	-0.3	0.79	1.42	2.53
22	1.35	-1.49	2.49	-0.02	-1.36	-0.78	-0.06	-0.91
23	1.76	0.85	1.49	0.47	0.51	1.23	1.99	3.22
24	1.74	-1.34	1.7	0.35	0.59	0.91	1	0.14
25	0.84	0.97	-0.07	0.59	-0.03	-0.78	0.71	1.62
26	-0.48	-0.14	-0.75	-0.08	-1.59	-1.18	-0.45	-0.71
27	2.3	1.5	1.23	0.99	-0.07	0.5	1.76	3.19
28	1.94	1.02	3.18	1.53	1	1.62	1.31	1.4
29	2.2	3.36	1.65	1.48	-0.69	0.35	1.03	1.86
30	1.81	0.28	2.31	0.77	0.5	0.77	0.9	-0.02
31	1.08	2.29	2.71	2.72	1.44	1.12	2.73	3.28
32	-0.28	1.42	2.14	1.24	0.29	0.32	1.92	1.8
33	2.09	2.36	0.76	1.6	-0.18	-0.66	0.71	1.48
34	1.79	3.41	1.75	-0.05	-0.66	-0.38	-0.42	0.03
35	4.29	3.05	4.03	3.05	1.78	0.85	2.39	3.37
36	3.74	1.74	4.83	1.22	1.6	1.35	1.4	1.76
37	1.96	2.94	2.49	2.16	0.29	-0.18	0.27	1.87
38	1.44	2.32	3.09	1.04	0.29	-0.47	-0.82	0.31
39	2.39	2.87	2.23	1.85	0.7	-0.31	0.84	1.89
40	2.79	4.04	3.22	2.28	0.29	-0.11	0.72	0.78
41	3.8	2.47	3.61	2.39	0.77	0.36	0.7	2.46
42	3.58	3.06	4.04	2.07	0.31	-0.35	-0.65	0.45
43	0.48	3.5	4.72	1.75	-1.21	-1.36	-0.69	1.82
44	0.42	2.32	2.18	1.04	-1.07	-1.75	-2.12	0.27
45	4.76	4.43	4.43	2.67	0.66	0.22	0.92	3.13
46	4.54	3.7	4.29	2.64	0.55	0.48	-0.51	1.49
47	5.61	3.52	4.2	2.27	0.56	-0.66	0.58	2.44
48	5.49	1.24	0.94	1.26	-0.12	0.2	-0.75	0.58

As shown in table 6.7 and figures 6.24 thru 6.27, the differences between the measured and calculated sound pressure levels for the 63 Hz, 125 Hz, 250 Hz and 500 Hz full-octave bands are typically larger as compared to the other full-octave bands. It should be noted that the measured and calculated sound pressure levels are displayed as linear values in the tables and figures. Once the data was filtered, utilizing an A-weighting of the data, the differences in the lower frequency bands was negligible due to the type of filtering. Additionally, the frequency bands of major interest relative to the drilling portion of a roof bolting machine are the 1,000 Hz to 4,000 Hertz full-octave bands. Therefore, the differences in measured and calculated sound pressure levels after the fifth run of the model relative to the full-octave bands of interest, provided a good fit and the final absorption coefficients determined from the model are shown in table 6.8.

Table 6.8 Final Absorption Coefficients Determined from Model Runs

Octave-band (Hz)	**Absorption Coefficient**
63	.03
125	.04
250	.20
500	.14
1000	.15
2000	.19
4000	.28
8000	.45

The absorption coefficients determined, were then inputted into the Raynoise program to predict sound pressure levels at the operator position of the roof bolting machine as described in the next section.

6.3.5 Predicting Sound Pressure Levels Underground Due to Drilling Cycle of Roof Bolting Machine

Once the absorption coefficients were determined from section 6.3.4 and displayed in table 6.8, several other pieces of information were required for input into the model to determine or predict the sound pressure levels underground. Namely, the full-octave band sound power level information received from the laboratory testing for a specific test, the specific roof bolting machine characteristics designed from the drafting package, AutoCAD, the geometry of the section of the underground mine to be modeled and a measurement grid within the geometric section representing the point locations for determining the sound pressure levels.

6.3.5.1 Full-Octave Band Sound Power Levels from Laboratory Testing

Table 6.9, illustrated below, provides the one-third octave-band as well as full-octave band sound power levels as an example for input into the Raynoise modeling program for predicting sound pressure levels. This example illustrates the octave-band and one-third octave band information from one of the laboratory test conducted for high-compressive strength media (>20,000 psi), using a 1.375-inch drill bit, round drill steel, a rotational speed of 600 rpm and a thrust setting of 4,242 lbs.

Table 6.9 Full-Octave and One-Third Octave Band Sound Power Levels From Laboratory Test (1.375-inch drill bit, round drill steel, rotational speed of 600 rpm and thrust setting of 4,242 lbs.)

		dBA				dBA
One-Third Octave band Center Frequency (Hz)	**50**	78.4		Octave band Center Frequency (Hz)	**63**	81.6
	63	76.9			**125**	88.5
	80	74.0			**250**	96.5
	100	87.0			**500**	96.9
	125	78.8			**1,000**	96.1
	160	81.0			**2,000**	100.8
	200	93.1			**4,000**	105.9
	250	93.0			**8,000**	101.4
	315	85.9			**Overall**	109.0
	400	90.2				
	500	92.7				
	630	93.1				
	800	91.8				
	1,000	89.8				
	1,250	92.0				
	1,600	93.8				
	2,000	96.2				
	2,500	97.3				
	3,150	100.6				
	4,000	102.0				
	5,000	100.7				
	6,300	98.9				
	8,000	96.9				
	10,000	90.4				
	Overall	109.0				

Therefore, the octave-band sound power levels from any of the tests conducted in the laboratory can be used as input for determining sound pressure levels utilizing the Raynoise modeling program.

6.3.5.2 Specific Characteristics of the Roof Bolting Machine

AutoCAD is a standard drafting package that is used to create the structural and machine models used to create testing environments for the Raynoise program. Due to input constraints with the Raynoise program, the drawings were limited to using the 3DPolyline entities to create the models (25). Objects with different material properties in a given model or structure drawing can be placed on different layers within AutoCAD and this can be read in as SET information by the Raynoise package where specific absorption, diffusion, transmission coefficients for each set can be assigned. Figures 6.32 and 6.33 listed below are drawings developed from the AutoCAD drafting package for two types of roof bolting machines. Figure 6.32 represents a Fletcher Roof Ranger II roof bolting machine and figure 6.33 illustrates a Fletcher HDDR roof bolting machine. Figures 6.32 and 6.33 were used as input to the Raynoise program relative to machine characteristics of the roof bolting machine.

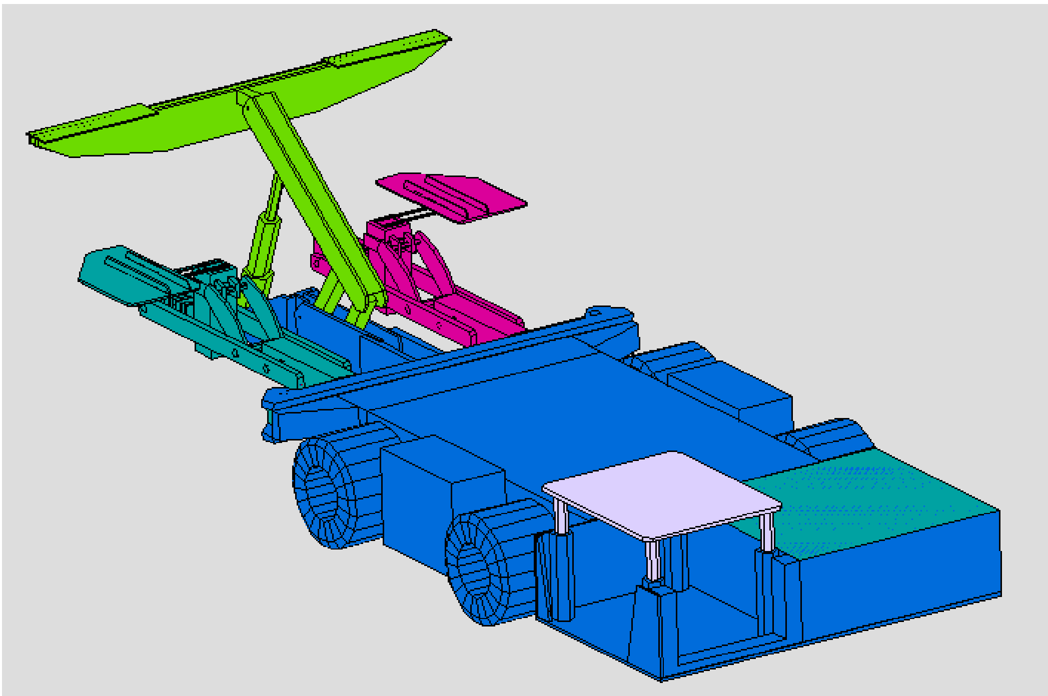


Figure 6.32 AutoCAD drawing of a Roof Ranger II Roof Bolting Machine

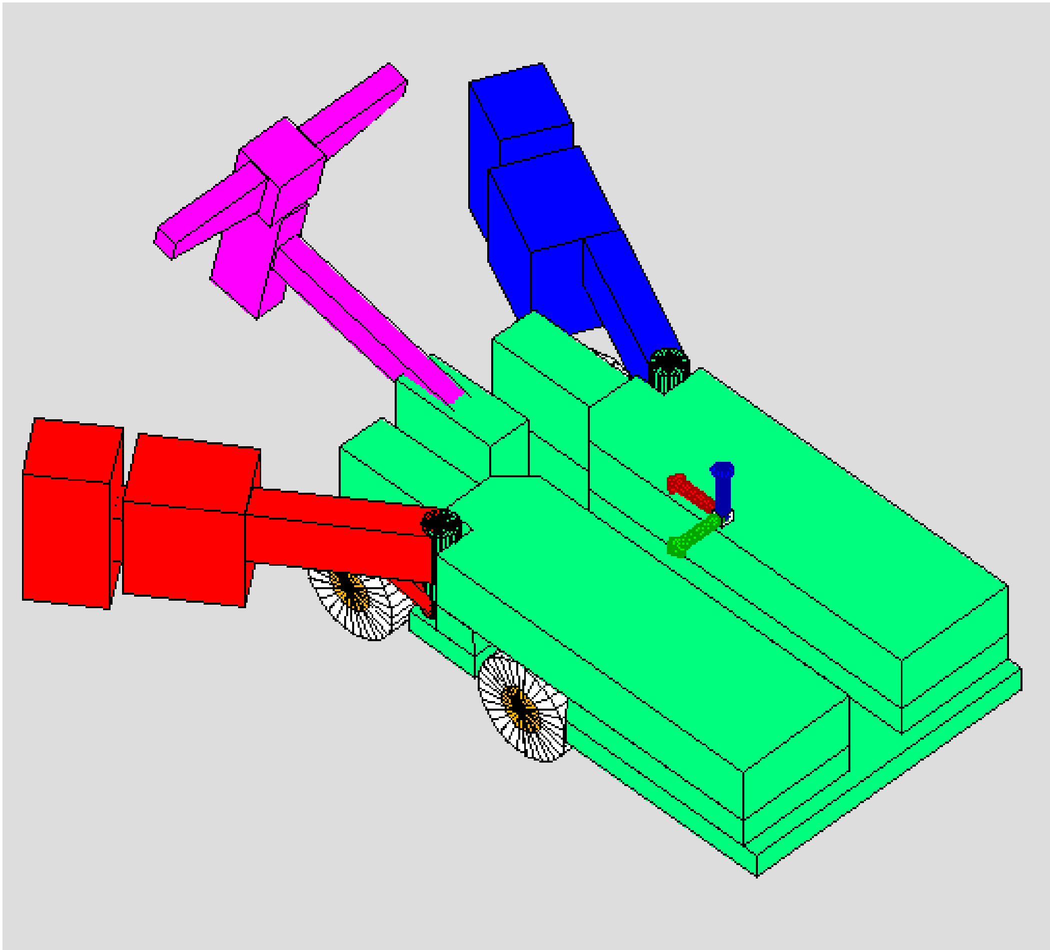


Figure 6.33 AutoCAD drawing of a HDDR Roof Bolting Machine

6.3.5.3 Establishment of a Measurement Grid for the Underground Mine Section

Section 6.3.4.3, discussed earlier, provided the geometric configuration of an underground mine section, which was developed from in-mine measurements. To determine or predict sound pressure levels at specific points within the underground mine section, a measurement grid or mesh was required to be constructed for input into the Raynoise program. The measurement grid was developed and the associated measuring points were determined. The grid was developed utilizing measuring points that were on one-meter centers relative to the width of the entry or crosscut and located five-feet above the floor surface. The height measurement of five-feet was selected because this distance, on average, represents the average ear-height of an individual. Figures 6.34 thru 6.36, shown below, illustrate the measurement grids developed for a roof bolting machine located at the working face, crosscut and intersection, respectively. Figures 6.34 thru 6.36 were generated and required for input into the Raynoise program.

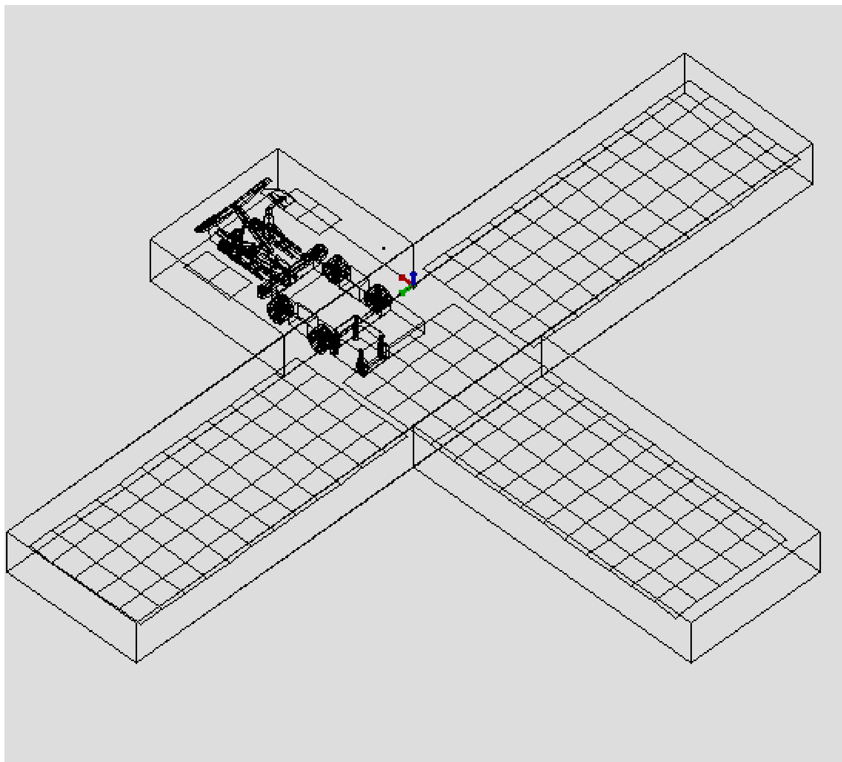


Figure 6.34 Measurement Grid Developed for a Roof Bolting at the Mine Face

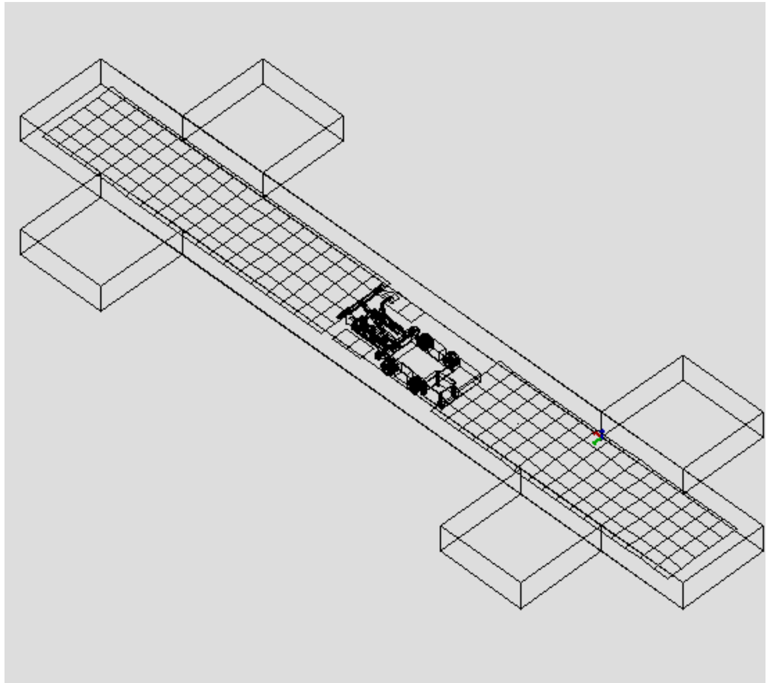


Figure 6.35 Measurement Grid Developed for a Roof Bolting Machine at a Crosscut

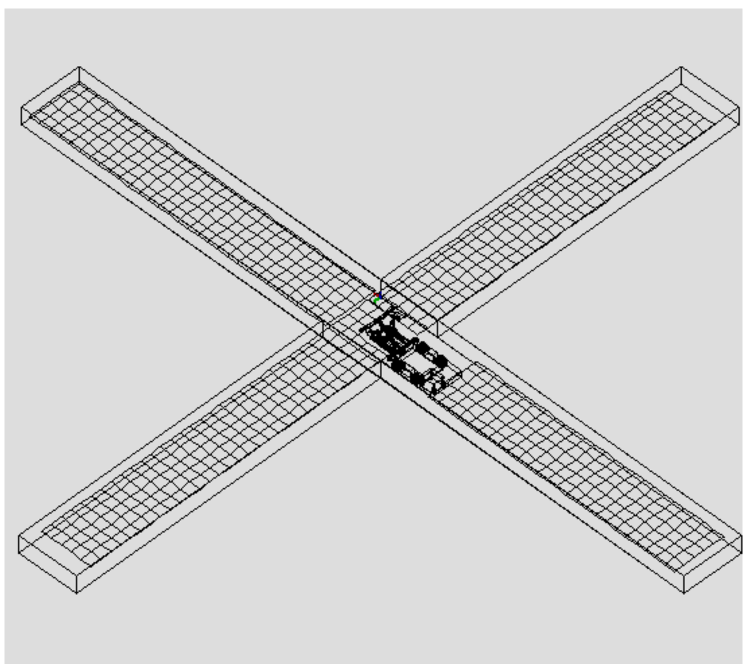


Figure 6.36 Measurement Grid Developed for a Roof Bolting Machine at an Intersection

6.3.5.4 Development of a Command File for Input into Raynoise Program

The construction of a command file (CMD) is necessary for using the Raynoise program (25). The command file provided properties related to the sound power of the noise source or sources, the type of noise source, e.g. line source or point source and the absorption or sabine coefficients relative to the acoustic properties associated with the underground mine section, equipment, etc. A point source is defined as a single noise source at a given location and a line source is a group of point sources along a straight line with the same acoustical characteristics. Research results have shown the dominant noise sources of a roof bolting machine are the drill bit, the drill steel, and the drill chuck. These noise sources would correspond to three point sources on a line source extending from the bit to the chuck, with the drill bit/contact surface as one source, the drill steel another and the third source being the drill chuck. A line source was chosen from the drill chuck to the drill bit/contact surface for the model run. Figure 6.37, shown below, provides a screenshot of a typical command file for input into the Raynoise program.

```
Source 1
    Name 'RSource'
    Power 85.6009 89.3762 101.134 96.5119 97.3544 103.333 103.685 97.1487
    Position Line 5.05 2.1 1.8 5.05 2.1 .84 Divide 3
    Return
Source 2
    Name 'LSource'
    Power 85.6009 89.3762 101.134 96.5119 97.3544 103.333 103.685 97.1487
    Position Line 5.05 3.44 1.8 5.05 3.44 .84 Divide 3
    Return
Material 1
    Name 'Default'
    Sabine 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
    Return
Material 2
    Name 'Anechoic'
    Sabine 1 1 1 1 1 1 1 1
    Return
Material 3
    Name 'Coal'
    Sabine .03 .04 .2 .14 .15 .19 .28 .45
    Return
Assign
    Material 2
    Elements Set 5
    Return
Assign
    Material 3
    Elements Set 1
    Elements Set 2
    Elements Set 3
    Elements Set 4
    Return
Assign
    Material 1
    Elements Set 6
    Elements Set 7
    Elements Set 8
    Elements Set 9
    Elements Set 10
    Return
Mapping Source All Frequency 63 Return
```

Figure 6.37 Screenshot of a Command File for Input into Raynoise Program

6.3.5.5 <u>Sound Pressure Levels Determined from Raynoise Program</u>

Once all of the required input parameters for the Raynoise program are constructed, determined and entered as discussed in sections 6.3.5.1 thru 6.3.5.4, the predicted or determined underground sound pressure levels can then be determined and viewed using the Raynoise program. An example of this view is shown in Figure 6.38, displaying the sound pressure levels attributed to a Roof Ranger II roof bolting machine drilling a bolt hole at the face of 6-foot-high underground coal mine.

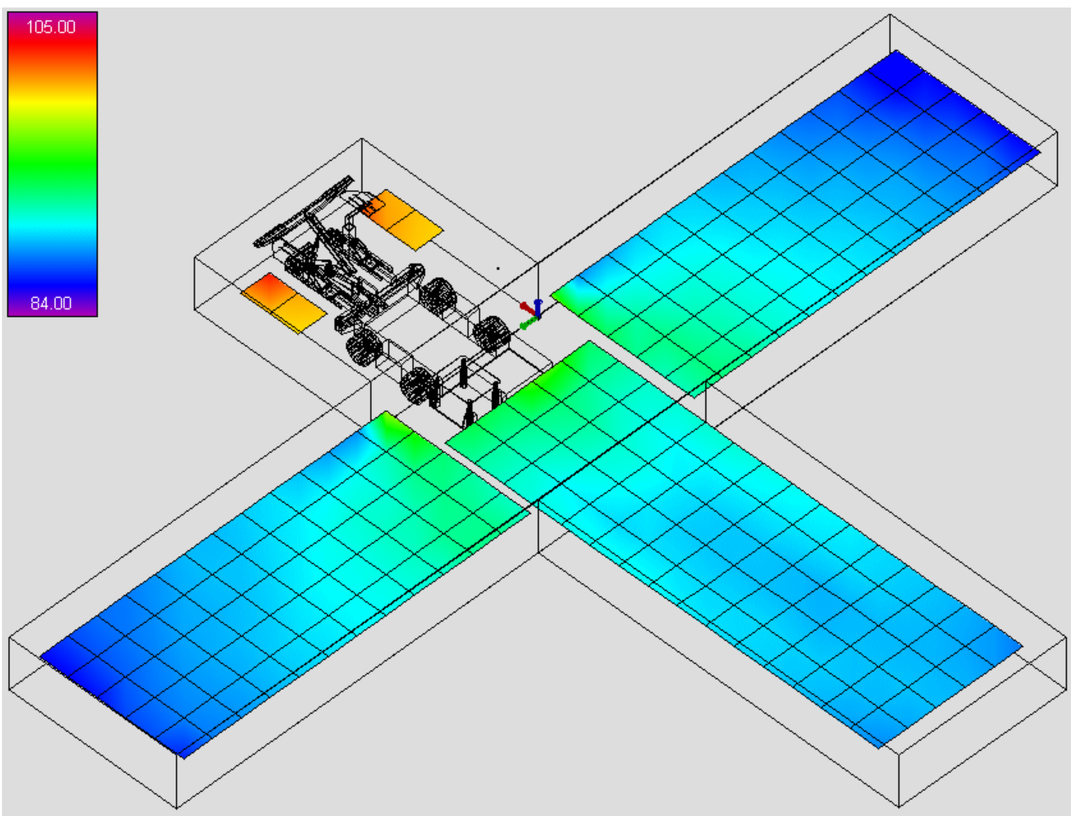


Figure 6.38 Determined Sound Pressure Level Contours in an Underground Coal Mine

The sound pressure levels can be viewed or displayed as contour plots, as shown in figure 6.38, or interpreted numerically as shown in figure 6.39.

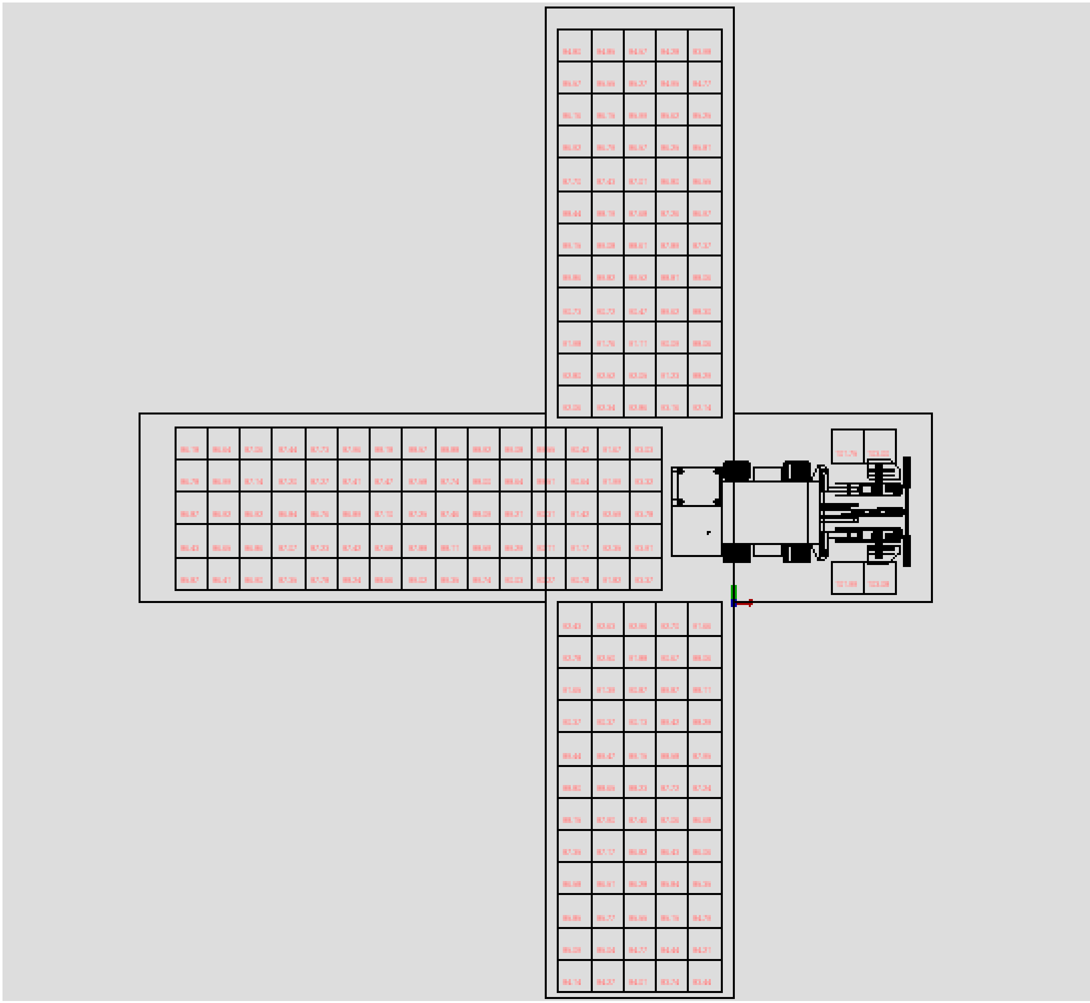


Figure 6.39 Determined Sound Pressure Levels (Numerical) in an Underground Coal Mine

Additionally, the program can provide a “zoom” view, relative to the determined sound pressure levels. Figure 6.40 shows a closer, or “zoom” view of the numerical sound pressure levels near and around a roof bolting machine.

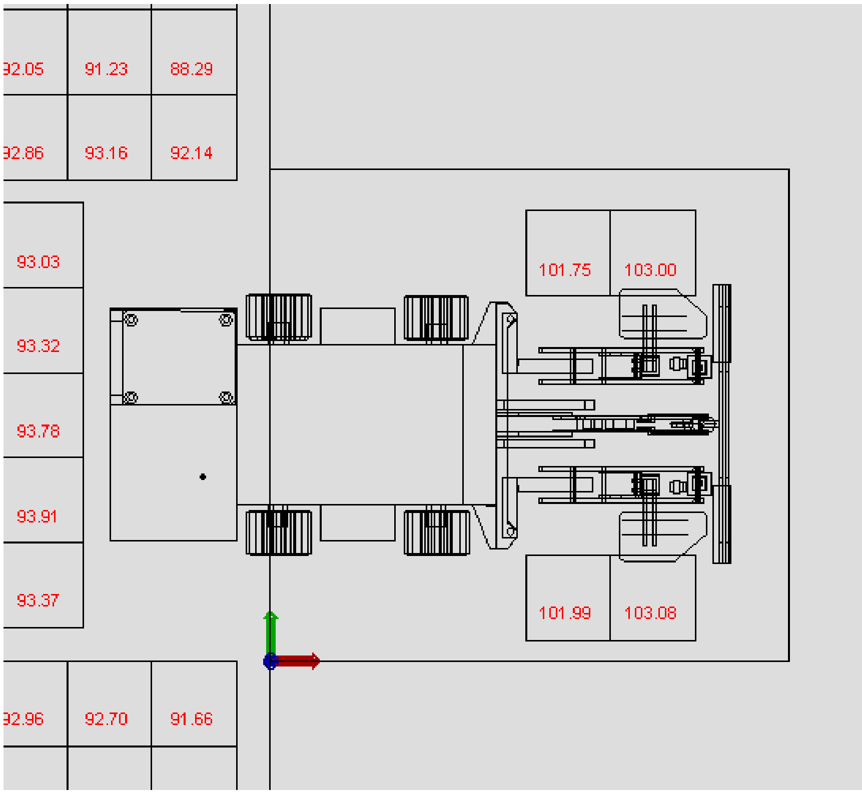


Figure 6.40 Zoom-view of Determined Sound Pressure Levels Near a Roof Bolting Machine

6.3.5.6 Comparing Sound Pressure Levels - Model Prediction vs. Underground Measurements

Sound pressure level measurements were conducted at the operator position of a Roof Ranger II roof bolting machine in an underground coal mine. The underground mine height varied from approximately 4 to 5 feet and the thickness of the coal seam varied from 32-40 inches. The mine operator provided the opportunity to measure sound pressure levels relative to two bolting machines utilizing a vacuum system and mist system drilling method respectively. The roof bolting plan for the section is illustrated in figure 6.41 below.

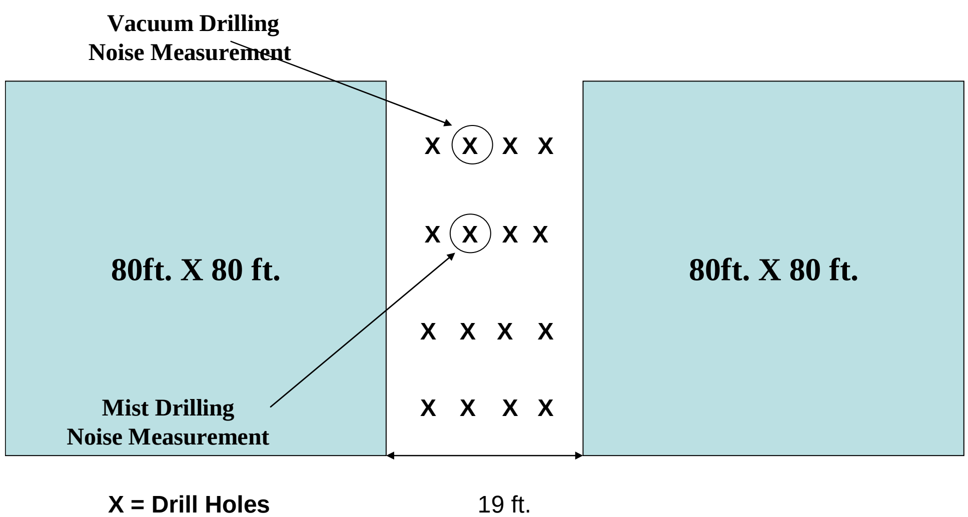


Figure 6.41 Roof Bolting Plan at the Underground Coal Mine

Each roof bolting machine utilized a 1-inch drill bit, hex drill steel and drilled to a depth of 5 feet into the immediate roof. The roof consisted of a highly fractured shale rock consistent of a rock type with a low compressive strength (approximately 6,000 psi). The drilling configurations for both machines were set at a rotational speed of 500 rpm and a thrust of approximately 6,500 lbs.

Sound pressure level measurements were conducted at the operator position of each machine. Table 6.10, illustrated below provides the results of the sound pressure level testing.

Table 6.10 Sound Pressure Level Measurements at Operator Position of Roof Bolting Machine

Operation of Roof Bolting Machine	**Roof Ranger II (Vacuum) dBA**	**Roof Ranger II (Mist System) dBA**
Idling	82	82
Mist System On No drilling	NA	88
Drilling	101	96

The sound pressure levels experienced at the operator position during drilling utilizing the vacuum system of drilling was 101 dBA. Utilizing a mist system type of drilling, the operator was exposed to a sound pressure level of 96 dBA, resulting in a 5 dBA difference in sound pressure level.

The next step was to utilize the Raynoise program to compare the measured underground sound pressure level experienced at the operator position to the predicted sound pressure level determined thru the modeling approach. The first step was to characterize the geometric configuration of the mine layout in AutoCAD as shown in figure 6.41, secondly the specific characteristics of the roof bolting machine were then processed in AutoCAD and placed within the mine layout. A measurement mesh or grid was then developed to characterize sound pressure levels at specific locations within the mine section. Figure 6.42 displays the geometric configuration of the mine section, the location of the roof bolting machine and the measurement mesh used for predicting sound pressure levels. A total of 246 measurement locations within the mine section were selected and shown below.

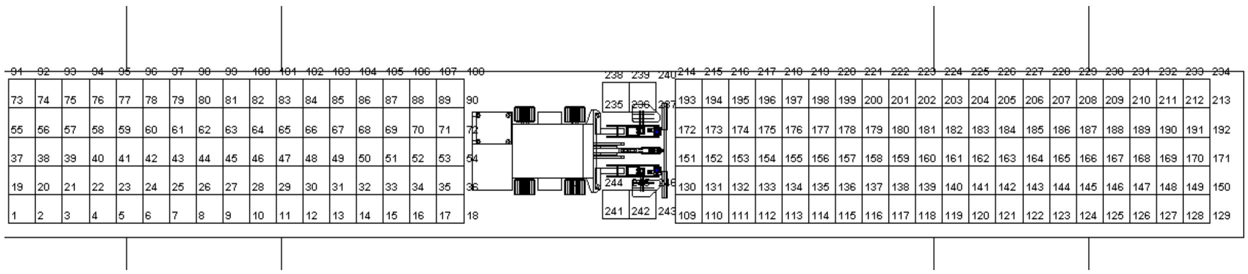


Figure 6.42 Model Simulation for Predicting Sound Pressure Levels

Additionally, full-octave band sound power levels, obtained from the reverberation room testing, were then utilized for input into the program. Table 6.11 below provides the full-octave band sound power levels based on a test in the reverberation room relative to a rock media with a compressive strength equal to 6,000 psi, a 1-inch drill bit, hex drill steel, a rotational speed of 500 rpm and a thrust setting of 6,363 lbs.

Table 6.11 Full-Octave Band Sound Power Levels - Compressive strength-6,000 psi, hex drill steel, 1-inch bit, rotational speed-500 rpm, and Thrust setting-6,363 lbs

Octave-band (Hz)	**Sound Power Level dBA**
63	85.6
125	89.4
250	101.1
500	96.5
1000	97.4
2000	103.3
4000	103.7
8000	97.1

Therefore, the mine configuration or layout, the roof bolting machine characteristics, a measurement grid or mesh, the full-octave band sound power levels and the sabine or absorption coefficients determined from section 6.3.4 were then inputted into the Raynoise program for predicting or determining sound pressure levels within the mine section and at the operator position of the roof bolting machine. The results of the model run are displayed graphically, as sound pressure level contours, shown in figure 6.43 below.

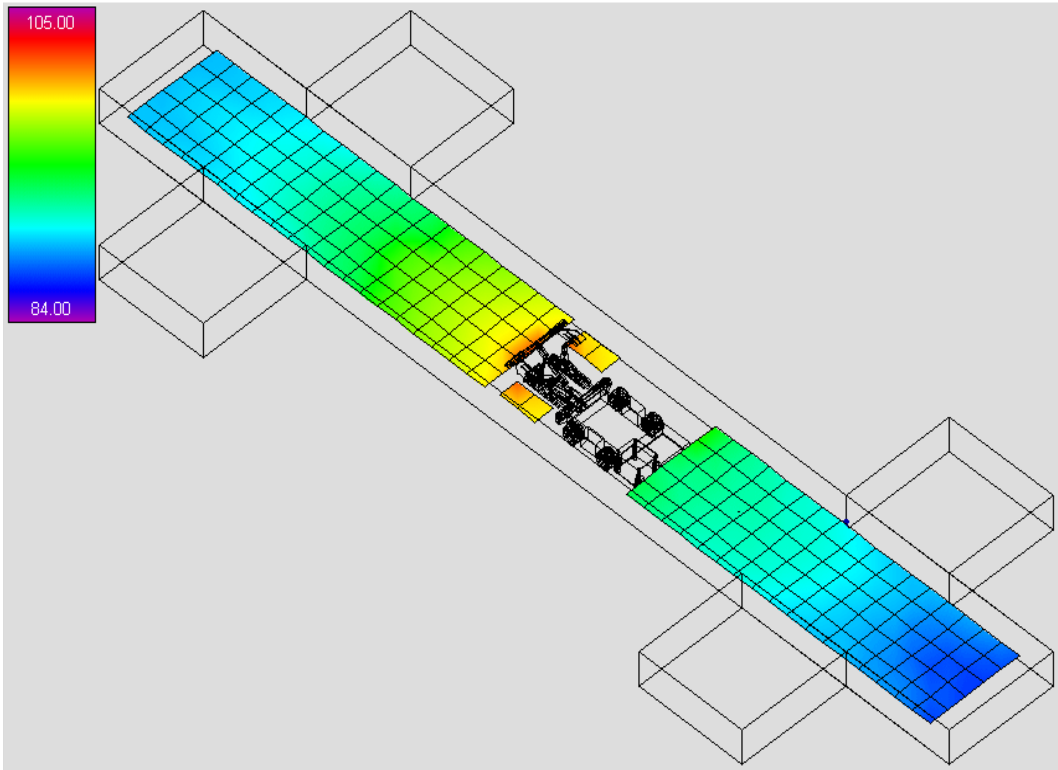


Figure 6.43 Sound Pressure Level Contours for Model Run

Furthermore, table 6.12 provides the results of the model run in numerical form for each of the 246 measurement positions as displayed in figure 6.42. The table provides the predicted or determined sound pressure levels for each full-octave band (63 Hz, 125 Hz, 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz, 4,000 Hz and 8,000 Hz) relative to each of the 246 measurement positions. The table also provides the overall linear and a-weighted sound pressure level at each measurement position.

Table 6.12 Sound Pressure Level Results (Numerically) of the Model Run

Location	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	dBA	dB
1	65.3	68.8	77.4	74.0	74.6	79.8	78.5	69.0	84.1	84.7
2	66.1	69.6	78.2	74.7	75.4	80.5	79.2	69.6	84.8	85.4
3	66.6	70.2	78.7	75.3	75.9	81.1	79.8	70.2	85.4	86.0
4	66.8	70.3	79.0	75.5	76.2	81.4	80.1	70.5	85.6	86.3
5	67.1	70.7	79.3	75.8	76.5	81.7	80.4	70.8	85.9	86.6
6	67.6	71.2	79.8	76.3	77.0	82.2	80.8	71.2	86.4	87.0
7	67.6	71.2	79.9	76.4	77.0	82.3	80.9	71.4	86.5	87.1
8	68.2	71.7	80.3	76.9	77.5	82.7	81.4	71.8	86.9	87.6
9	68.8	72.4	81.1	77.6	78.2	83.4	82.1	72.7	87.7	88.3
10	69.5	73.1	81.7	78.2	78.9	84.1	82.8	73.2	88.3	89.0
11	70.4	73.9	82.5	79.1	79.7	84.9	83.6	74.1	89.1	89.8
12	71.0	74.5	83.1	79.7	80.3	85.5	84.2	74.6	89.7	90.4
13	71.4	74.9	83.7	80.2	80.8	86.1	84.8	75.3	90.3	91.0
14	71.8	75.3	84.1	80.6	81.3	86.5	85.3	75.9	90.8	91.4
15	72.2	75.7	84.7	81.1	81.8	87.0	85.9	76.6	91.3	91.9
16	72.9	76.4	85.4	81.8	82.5	87.8	86.6	77.3	92.1	92.7
17	73.6	77.2	86.3	82.7	83.4	88.7	87.6	78.4	93.0	93.6
18	74.5	78.1	87.3	83.6	84.3	89.7	88.6	79.5	94.0	94.6
19	65.0	68.6	77.2	73.7	74.4	79.6	78.2	68.7	83.8	84.4
20	65.2	68.8	77.4	74.0	74.6	79.8	78.5	69.0	84.0	84.7
21	65.5	69.1	77.8	74.3	75.0	80.2	78.9	69.5	84.4	85.1
22	65.7	69.2	78.0	74.5	75.2	80.4	79.2	69.8	84.7	85.3
23	66.1	69.7	78.6	75.0	75.7	80.9	79.7	70.4	85.2	85.8
24	67.0	70.6	79.4	75.9	76.5	81.8	80.5	71.1	86.1	86.7
25	67.9	71.5	80.3	76.7	77.4	82.6	81.4	72.0	86.9	87.5
26	68.8	72.3	81.0	77.5	78.2	83.4	82.1	72.6	87.6	88.3
27	69.7	73.3	81.9	78.4	79.1	84.3	83.0	73.3	88.5	89.2
28	70.5	74.1	82.6	79.2	79.8	85.0	83.6	73.9	89.3	89.9
29	71.2	74.7	83.3	79.8	80.5	85.7	84.3	74.6	89.9	90.5
30	71.5	75.0	83.6	80.1	80.8	86.0	84.6	74.8	90.2	90.8
31	71.7	75.3	83.8	80.4	81.0	86.2	84.8	75.1	90.4	91.1
32	72.4	76.0	84.7	81.2	81.9	87.1	85.7	76.1	91.3	91.9
33	72.6	76.1	84.9	81.4	82.0	87.3	86.0	76.5	91.5	92.2
34	72.8	76.4	85.3	81.7	82.4	87.7	86.5	77.2	92.0	92.6
35	73.5	77.0	86.2	82.5	83.2	88.6	87.5	78.5	92.9	93.5
36	74.5	78.1	87.3	83.6	84.3	89.7	88.7	79.7	94.0	94.6
37	64.7	68.3	77.0	73.5	74.2	79.4	78.1	68.5	83.6	84.3
38	64.6	68.2	77.1	73.5	74.2	79.5	78.3	68.8	83.8	84.4
39	64.6	68.2	77.3	73.7	74.3	79.6	78.5	69.2	84.0	84.5
40	65.0	68.6	77.7	74.1	74.7	80.1	78.9	69.6	84.4	85.0
41	65.6	69.1	78.2	74.6	75.2	80.5	79.4	70.0	84.8	85.4
42	67.0	70.5	79.4	75.8	76.5	81.8	80.5	71.0	86.1	86.6
43	67.8	71.4	80.1	76.6	77.3	82.5	81.2	71.5	86.7	87.4
44	69.1	72.7	81.2	77.8	78.4	83.6	82.2	72.4	87.8	88.5
45	70.1	73.6	82.0	78.6	79.3	84.4	82.9	73.0	88.6	89.2
46	70.9	74.4	82.9	79.5	80.1	85.3	83.8	73.9	89.5	90.1
47	71.5	75.0	83.6	80.1	80.8	85.9	84.5	74.8	90.2	90.8

Location	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	dBA	dB
48	71.8	75.4	83.8	80.4	81.1	86.2	84.8	74.9	90.4	91.1
49	72.3	75.9	84.4	81.0	81.6	86.8	85.4	75.7	91.1	91.7
50	72.5	76.1	84.8	81.3	81.9	87.2	85.8	76.2	91.4	92.0
51	72.5	76.0	84.9	81.4	82.0	87.3	86.2	77.0	91.6	92.2
52	73.0	76.6	85.6	82.0	82.7	88.0	86.9	77.7	92.3	92.9
53	73.1	76.6	85.8	82.1	82.8	88.1	87.1	78.0	92.4	93.1
54	73.8	77.4	86.7	83.0	83.7	89.1	88.1	79.2	93.4	94.0
55	64.7	68.3	77.0	73.5	74.2	79.4	78.1	68.4	83.6	84.3
56	64.9	68.5	77.3	73.8	74.4	79.7	78.4	68.9	83.9	84.6
57	64.7	68.3	77.2	73.6	74.3	79.6	78.3	68.9	83.9	84.4
58	65.2	68.8	77.7	74.1	74.8	80.0	78.8	69.4	84.4	84.9
59	66.0	69.6	78.5	74.9	75.6	80.9	79.7	70.3	85.2	85.8
60	66.7	70.2	79.1	75.5	76.2	81.5	80.2	70.8	85.8	86.4
61	67.6	71.2	79.9	76.4	77.1	82.3	81.0	71.4	86.5	87.2
62	68.5	72.1	80.7	77.3	77.9	83.1	81.8	72.2	87.3	88.0
63	69.9	73.5	82.0	78.6	79.2	84.4	83.0	73.2	88.6	89.3
64	70.9	74.4	82.8	79.5	80.1	85.2	83.8	73.8	89.5	90.1
65	71.4	74.9	83.4	80.0	80.6	85.8	84.3	74.3	90.0	90.6
66	71.8	75.3	83.8	80.4	81.0	86.2	84.7	74.8	90.4	91.0
67	72.3	75.8	84.4	80.9	81.6	86.8	85.3	75.6	91.0	91.6
68	72.3	75.9	84.5	81.0	81.7	86.9	85.5	75.9	91.1	91.7
69	72.6	76.2	84.9	81.4	82.1	87.3	86.0	76.5	91.6	92.2
70	72.9	76.5	85.4	81.8	82.5	87.8	86.6	77.3	92.1	92.7
71	72.9	76.5	85.5	81.9	82.6	87.9	86.7	77.4	92.2	92.8
72	73.5	77.1	86.1	82.5	83.2	88.5	87.3	77.8	92.8	93.4
73	65.4	68.9	77.3	73.9	74.6	79.7	78.3	68.5	84.0	84.6
74	65.4	69.0	77.4	74.0	74.6	79.8	78.4	68.7	84.0	84.7
75	65.7	69.2	77.9	74.4	75.1	80.3	79.0	69.4	84.5	85.2
76	65.8	69.3	78.2	74.6	75.3	80.5	79.3	69.9	84.8	85.4
77	66.1	69.7	78.6	75.0	75.7	81.0	79.8	70.5	85.3	85.9
78	66.8	70.4	79.3	75.8	76.4	81.7	80.5	71.2	86.0	86.6
79	67.4	71.0	79.8	76.3	77.0	82.2	81.0	71.6	86.5	87.1
80	68.3	71.9	80.6	77.1	77.7	83.0	81.7	72.2	87.2	87.9
81	69.3	72.8	81.4	77.9	78.6	83.8	82.4	72.8	88.0	88.6
82	70.3	73.8	82.4	79.0	79.6	84.8	83.5	73.8	89.0	89.7
83	71.2	74.7	83.3	79.9	80.5	85.7	84.3	74.6	89.9	90.6
84	71.7	75.3	83.9	80.4	81.0	86.2	84.9	75.2	90.5	91.1
85	71.9	75.5	84.1	80.6	81.3	86.5	85.1	75.4	90.7	91.3
86	72.1	75.6	84.4	80.9	81.5	86.7	85.4	75.9	91.0	91.6
87	72.4	75.9	84.7	81.2	81.9	87.1	85.8	76.2	91.3	92.0
88	72.8	76.4	85.3	81.7	82.4	87.7	86.5	77.2	92.0	92.6
89	73.4	77.0	86.2	82.5	83.2	88.5	87.4	78.3	92.8	93.4
90	74.0	77.6	86.8	83.1	83.8	89.1	88.0	78.8	93.4	94.0
91	65.0	68.5	77.1	73.6	74.3	79.5	78.1	68.5	83.7	84.3
92	65.8	69.3	77.9	74.4	75.1	80.3	78.9	69.3	84.5	85.1
93	66.3	69.9	78.5	75.0	75.7	80.9	79.6	70.0	85.1	85.8
94	66.5	70.1	78.8	75.3	76.0	81.2	79.9	70.4	85.5	86.1
95	66.7	70.3	79.0	75.5	76.1	81.4	80.1	70.5	85.6	86.3
96	67.7	71.2	79.8	76.3	77.0	82.2	80.8	71.1	86.4	87.0

Location	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	dBA	dB
97	67.5	71.1	79.7	76.2	76.9	82.1	80.8	71.3	86.3	87.0
98	67.8	71.4	80.1	76.6	77.3	82.5	81.2	71.8	86.7	87.4
99	68.5	72.1	80.8	77.3	78.0	83.2	82.0	72.6	87.5	88.1
100	69.4	73.0	81.7	78.2	78.9	84.1	82.8	73.3	88.3	89.0
101	70.5	74.1	82.7	79.3	79.9	85.1	83.8	74.2	89.3	90.0
102	71.0	74.5	83.2	79.7	80.4	85.6	84.3	74.7	89.8	90.5
103	71.4	75.0	83.7	80.2	80.8	86.1	84.7	75.1	90.3	90.9
104	71.6	75.2	83.9	80.4	81.1	86.3	85.0	75.6	90.6	91.2
105	72.1	75.7	84.6	81.0	81.7	87.0	85.8	76.6	91.3	91.9
106	72.6	76.1	85.2	81.6	82.3	87.6	86.5	77.3	91.9	92.5
107	73.1	76.7	85.9	82.3	82.9	88.3	87.3	78.2	92.6	93.2
108	73.9	77.5	86.7	83.0	83.7	89.1	88.1	79.1	93.4	94.0
109	79.2	82.8	92.6	88.7	89.4	94.9	94.2	86.0	99.4	99.9
110	78.3	81.9	91.3	87.5	88.2	93.7	92.8	84.3	98.1	98.6
111	77.6	81.1	90.4	86.7	87.4	92.7	91.8	83.2	97.1	97.7
112	76.8	80.4	89.5	85.8	86.5	91.8	90.8	81.9	96.1	96.8
113	76.3	79.8	88.7	85.1	85.8	91.1	90.0	80.9	95.4	96.0
114	75.8	79.4	88.1	84.6	85.2	90.5	89.3	80.1	94.8	95.4
115	75.4	78.9	87.6	84.1	84.7	89.9	88.7	79.4	94.2	94.8
116	75.0	78.5	87.2	83.7	84.3	89.5	88.3	79.1	93.8	94.4
117	74.4	78.0	86.4	83.0	83.6	88.8	87.5	78.1	93.1	93.7
118	73.9	77.4	85.9	82.5	83.1	88.3	86.9	77.5	92.5	93.2
119	73.0	76.5	85.0	81.6	82.2	87.4	86.1	76.8	91.7	92.3
120	71.9	75.5	84.1	80.6	81.2	86.4	85.2	75.9	90.7	91.3
121	71.0	74.5	83.1	79.6	80.2	85.5	84.2	74.9	89.7	90.4
122	70.1	73.6	82.1	78.7	79.3	84.5	83.2	73.8	88.8	89.4
123	69.6	73.1	81.7	78.2	78.9	84.1	82.8	73.6	88.3	89.0
124	69.3	72.9	81.6	78.0	78.7	83.9	82.7	73.6	88.2	88.8
125	68.6	72.1	80.9	77.4	78.0	83.3	82.0	72.8	87.6	88.2
126	68.3	71.8	80.6	77.0	77.7	82.9	81.7	72.4	87.2	87.8
127	68.1	71.6	80.3	76.8	77.4	82.7	81.4	72.0	86.9	87.6
128	67.7	71.2	79.9	76.4	77.0	82.2	81.0	71.6	86.5	87.1
129	67.5	71.0	79.6	76.2	76.8	82.0	80.8	71.5	86.3	86.9
130	80.0	83.6	93.9	89.8	90.5	96.1	95.8	88.2	100.7	101.3
131	78.7	82.3	92.1	88.1	88.9	94.4	93.8	85.7	98.9	99.5
132	77.9	81.5	91.0	87.2	87.9	93.3	92.5	84.1	97.7	98.3
133	77.1	80.7	89.9	86.2	86.9	92.3	91.4	82.7	96.7	97.3
134	76.8	80.3	89.5	85.8	86.5	91.8	90.8	82.1	96.2	96.8
135	76.1	79.7	88.6	85.0	85.6	90.9	89.8	80.8	95.2	95.8
136	75.4	79.0	87.7	84.1	84.8	90.1	88.9	79.8	94.4	95.0
137	75.0	78.6	87.1	83.7	84.3	89.5	88.3	79.0	93.8	94.4
138	74.6	78.1	86.6	83.2	83.8	89.0	87.7	78.3	93.2	93.9
139	74.3	77.8	86.3	82.8	83.5	88.7	87.3	78.0	92.9	93.6
140	73.8	77.3	85.7	82.3	83.0	88.1	86.8	77.3	92.4	93.0
141	73.0	76.5	85.1	81.6	82.2	87.4	86.1	76.7	91.7	92.3
142	72.1	75.7	84.3	80.8	81.5	86.7	85.4	76.1	91.0	91.6
143	71.2	74.8	83.5	80.0	80.6	85.9	84.7	75.4	90.2	90.8
144	70.3	73.9	82.7	79.1	79.8	85.0	83.8	74.7	89.3	89.9
145	69.5	73.0	81.9	78.3	79.0	84.3	83.1	74.0	88.6	89.2

Location	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	dBA	dB
146	68.7	72.3	81.1	77.6	78.2	83.5	82.4	73.3	87.8	88.4
147	68.2	71.8	80.5	77.0	77.6	82.9	81.7	72.6	87.2	87.8
148	68.0	71.5	80.1	76.7	77.3	82.5	81.2	72.0	86.8	87.4
149	67.8	71.4	79.9	76.5	77.1	82.3	81.0	71.6	86.5	87.2
150	67.7	71.3	79.7	76.3	76.9	82.1	80.7	71.3	86.3	87.0
151	82.5	86.2	97.1	92.8	93.6	99.4	99.4	92.4	104.1	104.6
152	79.4	83.0	93.1	89.1	89.8	95.4	94.9	87.1	99.9	100.5
153	78.4	82.0	91.6	87.7	88.5	93.9	93.3	85.1	98.4	99.0
154	77.5	81.1	90.5	86.7	87.4	92.8	92.0	83.5	97.2	97.8
155	77.0	80.5	89.7	86.0	86.7	92.0	91.1	82.4	96.4	97.0
156	76.3	79.9	88.9	85.2	85.9	91.2	90.2	81.3	95.5	96.2
157	75.9	79.5	88.3	84.7	85.4	90.6	89.5	80.5	95.0	95.6
158	75.4	78.9	87.6	84.1	84.8	90.0	88.8	79.7	94.3	94.9
159	75.0	78.5	87.1	83.6	84.3	89.5	88.3	79.0	93.8	94.4
160	74.4	77.9	86.4	83.0	83.6	88.8	87.5	78.2	93.1	93.7
161	74.0	77.5	86.0	82.5	83.2	88.4	87.0	77.6	92.6	93.3
162	73.3	76.9	85.4	81.9	82.6	87.8	86.4	77.0	92.0	92.7
163	72.4	76.0	84.6	81.1	81.8	87.0	85.7	76.4	91.3	91.9
164	71.2	74.8	83.5	80.0	80.7	85.9	84.7	75.5	90.2	90.8
165	70.5	74.0	82.9	79.3	80.0	85.2	84.1	75.0	89.6	90.2
166	70.0	73.5	82.4	78.8	79.5	84.8	83.6	74.5	89.1	89.7
167	69.4	73.0	81.8	78.3	78.9	84.2	83.0	73.9	88.5	89.1
168	68.8	72.4	81.2	77.7	78.3	83.6	82.5	73.4	87.9	88.5
169	68.5	72.0	80.8	77.3	77.9	83.2	82.0	72.8	87.5	88.1
170	68.0	71.6	80.3	76.8	77.4	82.7	81.5	72.2	87.0	87.6
171	67.7	71.3	79.9	76.4	77.1	82.3	81.0	71.7	86.5	87.2
172	82.5	86.2	97.1	92.8	93.5	99.3	99.3	92.3	104.0	104.6
173	79.4	83.1	93.1	89.1	89.8	95.4	94.9	87.1	99.9	100.5
174	78.4	82.0	91.7	87.8	88.5	94.0	93.3	85.2	98.5	99.0
175	77.5	81.1	90.5	86.7	87.4	92.8	92.0	83.5	97.2	97.8
176	76.9	80.4	89.6	85.9	86.6	91.9	91.0	82.2	96.3	96.9
177	76.3	79.9	88.8	85.2	85.9	91.2	90.1	81.3	95.5	96.1
178	75.9	79.4	88.2	84.7	85.3	90.6	89.4	80.4	94.9	95.5
179	75.4	78.9	87.6	84.1	84.7	90.0	88.8	79.6	94.3	94.9
180	74.9	78.5	87.1	83.6	84.2	89.5	88.2	79.0	93.7	94.4
181	74.5	78.0	86.5	83.1	83.7	88.9	87.6	78.3	93.2	93.8
182	74.0	77.5	86.0	82.5	83.2	88.3	87.0	77.5	92.6	93.2
183	73.3	76.8	85.3	81.9	82.5	87.7	86.4	76.9	92.0	92.6
184	72.4	75.9	84.6	81.1	81.7	87.0	85.7	76.4	91.2	91.9
185	71.3	74.9	83.6	80.1	80.7	86.0	84.8	75.5	90.3	90.9
186	70.5	74.1	82.9	79.3	80.0	85.2	84.1	74.9	89.6	90.2
187	69.8	73.4	82.2	78.6	79.3	84.5	83.3	74.2	88.8	89.4
188	69.3	72.8	81.6	78.1	78.7	84.0	82.8	73.6	88.3	88.9
189	68.7	72.2	81.0	77.5	78.2	83.4	82.3	73.2	87.7	88.3
190	68.3	71.8	80.6	77.0	77.7	83.0	81.8	72.6	87.3	87.9
191	68.0	71.5	80.2	76.7	77.4	82.6	81.4	72.2	86.9	87.5
192	67.5	71.1	79.7	76.2	76.8	82.0	80.8	71.5	86.3	86.9
193	80.0	83.6	93.9	89.8	90.5	96.2	95.9	88.3	100.8	101.3
194	78.7	82.3	92.0	88.1	88.8	94.3	93.7	85.5	98.8	99.4

Location	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	dBA	dB
195	77.9	81.5	90.9	87.1	87.8	93.2	92.4	83.9	97.6	98.2
196	77.2	80.7	89.9	86.2	86.9	92.3	91.3	82.7	96.7	97.2
197	76.7	80.3	89.3	85.7	86.4	91.7	90.7	81.8	96.0	96.6
198	76.1	79.6	88.5	84.9	85.6	90.8	89.7	80.7	95.1	95.8
199	75.5	79.1	87.8	84.2	84.9	90.1	88.9	79.8	94.4	95.0
200	75.1	78.6	87.2	83.7	84.4	89.6	88.3	79.1	93.8	94.5
201	74.7	78.2	86.7	83.3	83.9	89.1	87.8	78.4	93.3	94.0
202	74.3	77.8	86.3	82.8	83.5	88.7	87.3	78.0	92.9	93.6
203	73.7	77.3	85.7	82.3	82.9	88.1	86.7	77.3	92.4	93.0
204	72.8	76.4	84.9	81.4	82.1	87.3	86.0	76.6	91.5	92.2
205	71.9	75.5	84.1	80.6	81.3	86.5	85.2	75.9	90.7	91.4
206	71.0	74.5	83.2	79.7	80.3	85.6	84.4	75.1	89.9	90.5
207	70.0	73.6	82.3	78.8	79.4	84.6	83.4	74.2	88.9	89.5
208	69.2	72.8	81.5	78.0	78.6	83.8	82.6	73.5	88.2	88.7
209	68.5	72.0	80.7	77.2	77.8	83.1	81.9	72.7	87.4	88.0
210	68.1	71.7	80.3	76.8	77.4	82.7	81.4	72.2	86.9	87.6
211	68.0	71.5	80.0	76.6	77.2	82.4	81.1	71.9	86.7	87.3
212	67.9	71.4	79.9	76.5	77.1	82.3	81.0	71.6	86.5	87.2
213	68.0	71.5	80.0	76.5	77.2	82.4	81.0	71.6	86.6	87.3
214	79.4	83.0	92.8	88.9	89.6	95.1	94.5	86.3	99.6	100.2
215	78.4	82.0	91.5	87.7	88.4	93.8	93.0	84.5	98.2	98.8
216	77.6	81.2	90.5	86.7	87.4	92.8	91.9	83.2	97.2	97.8
217	76.9	80.5	89.5	85.9	86.6	91.9	90.9	82.0	96.2	96.8
218	76.3	79.9	88.8	85.2	85.9	91.2	90.1	81.0	95.5	96.1
219	75.7	79.3	88.0	84.5	85.2	90.4	89.2	80.0	94.7	95.3
220	75.3	78.8	87.5	84.0	84.6	89.9	88.6	79.3	94.1	94.8
221	74.9	78.4	87.0	83.5	84.2	89.4	88.1	78.8	93.6	94.3
222	74.3	77.9	86.4	82.9	83.6	88.8	87.4	78.0	93.0	93.7
223	73.8	77.3	85.7	82.3	83.0	88.1	86.8	77.3	92.4	93.0
224	72.6	76.1	84.6	81.1	81.8	87.0	85.7	76.3	91.2	91.9
225	71.2	74.7	83.2	79.8	80.4	85.6	84.2	74.9	89.8	90.5
226	70.5	74.1	82.5	79.1	79.7	84.9	83.6	74.2	89.1	89.8
227	69.8	73.4	81.9	78.4	79.1	84.3	83.0	73.7	88.5	89.2
228	69.4	72.9	81.5	78.0	78.7	83.9	82.6	73.4	88.2	88.8
229	69.4	73.0	81.6	78.1	78.8	84.0	82.8	73.6	88.3	88.9
230	68.4	72.0	80.8	77.2	77.9	83.2	82.0	72.8	87.5	88.1
231	68.3	71.9	80.7	77.1	77.8	83.1	81.9	72.7	87.4	88.0
232	68.1	71.7	80.4	76.9	77.5	82.8	81.5	72.3	87.1	87.7
233	67.7	71.2	80.0	76.5	77.1	82.4	81.2	71.9	86.7	87.3
234	67.3	70.9	79.6	76.1	76.7	82.0	80.8	71.6	86.3	86.9
235	79.5	83.1	93.1	89.1	89.9	95.4	94.9	86.8	99.9	100.5
236	80.3	83.9	94.2	90.1	90.9	96.5	96.1	88.3	101.0	101.6
237	82.3	86.0	96.8	92.5	93.3	99.1	99.0	91.7	103.7	104.3
238	78.9	82.5	92.4	88.5	89.2	94.8	94.1	85.9	99.2	99.8
239	79.6	83.3	93.4	89.4	90.1	95.7	95.3	87.3	100.3	100.8
240	79.8	83.4	93.7	89.6	90.3	95.9	95.5	87.6	100.5	101.0
241	78.8	82.4	92.3	88.4	89.1	94.6	94.1	85.9	99.1	99.7
242	79.3	82.9	93.1	89.0	89.8	95.3	94.9	86.9	99.9	100.4
243	79.6	83.2	93.4	89.3	90.1	95.7	95.3	87.5	100.2	100.8

Location	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	dBA	dB
244	79.6	83.2	93.3	89.3	90.0	95.6	95.1	87.0	100.1	100.7
245	80.3	83.9	94.3	90.2	91.0	96.6	96.3	88.6	101.2	101.7
246	82.5	86.1	97.1	92.7	93.5	99.3	99.3	92.2	104.0	104.5

In determining the validity of the model approach relative to comparing the actual underground measurements to the predicted or determined sound pressure levels when utilizing the model approach, measurement positions 235 thru 237, shown in figure 6.42, were examined to provide the predicted or determined sound pressure levels at the operator position of the roof bolting machine. Figure 6.44 displays a “snapshot” of the sound pressure level contours, along with the A-weighted sound pressure levels at measuring points 235 thru 237 of the model.

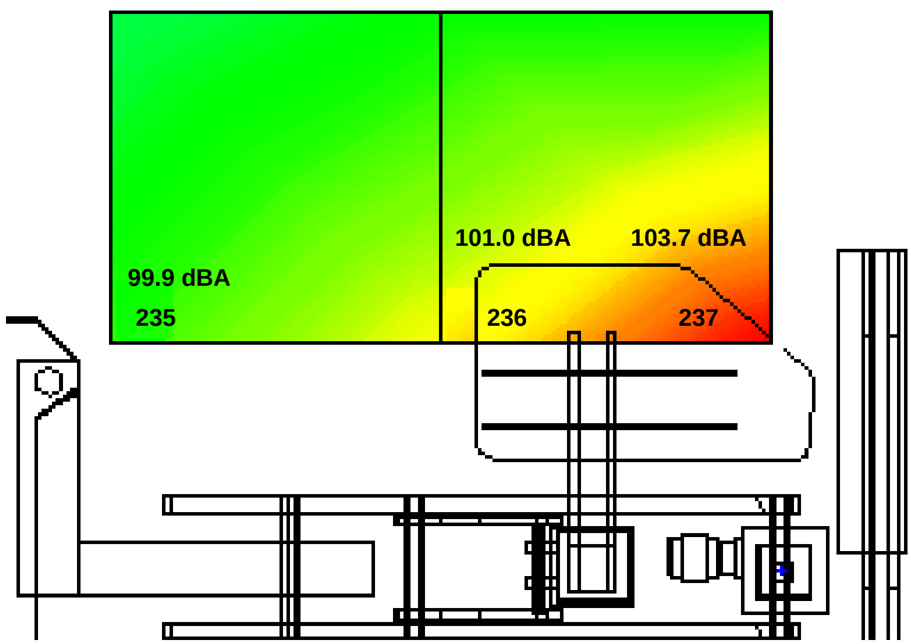


Figure 6.44 A-Weighted Sound Pressure Levels Near Operator Position of Roof Bolting Machine

Table 6.10 provided a sound pressure level of 101 dBA at the operator position of the roof bolting machine from underground measurements. The location of the measurement underground was the same location as measuring point number 236 utilized for the model approach. The determined or predicted sound pressure level using the modeling approach was 101 dBA, the same sound pressure level as measured underground. It should be noted, in order for model validation, data was collected in an actual underground mine environment. Due to mine accessibility, characterization of the acoustic environment, along with measuring sound pressure levels associated operators of roof bolting machines occurred in a mine with low compressive strength rock media during drilling operations. However, the research effort has proven that measuring laboratory sound power level results of the roof bolting machine given any compressive strength rock media, along with proper characterization of the acoustic and geological environment underground, one could predict the sound pressure level experienced by a roof bolting machine operator with confidence.

Therefore, this section provided the mining community with an approach, which utilizes sound power levels acquired from laboratory tests and measured absorption coefficients from underground testing to accurately predict or determine sound pressure levels, at any location in a mine section. The approach as compared to the modeling approach in section 6.2, provides a more reliable and accurate determination of sound pressure level at any position or location within a mine section without the limitations relative to absorption coefficients and near-field limitations as discussed in section 6.2. Section 6.3.6 below will demonstrate and provide an approach for determining the noise dosage of a roof bolting machine operator utilizing the predicted or determined sound pressure levels obtained from the modeling approach addressed from this section.

6.3.6 Determining Noise Dosage of a Roof Bolter Operator from Predicted Sound Pressure Levels

The noise dosage a worker receives can be expressed by the following equation:

$$Dose\% = (100/TC)[\int_0^{RTime} 2^{(LS-CL)/ER} dt] \qquad (12)$$

and $$Dose\% = (100/TC)(2^{(LS-CL)/ER})[\int_0^{RTime} dt]$$

therefore $$Dose\% = (100/TC)(2^{(LS-CL)/ER})(RTime)$$

where

Dose% = workers' noise dosage, percent

TC = criterion time, 8 hours or 28,800 seconds

LS = Sound pressure level, dBA

CL = Criterion level, dBA

ER = Exchange rate, dBA

RTime = Run time, seconds

Using equation (12) above, with a predicted or determined sound pressure level at the operator position of a roof bolting machine, the machine operators' noise dosage could then be determined. For instance, if we use the example illustrated above in section 6.3.5.6, where the compressive strength of the rock media was 6,000 psi and the roof bolting machine operator utilized the vacuum drilling method, with a 1-inch bit, hex drill steel, a rotational speed of 500 rpm and a thrust setting of 6,363 lbs, the measured and validated predicted sound pressure level was determined to be 101 dBA at the operator position of the machine. Using equation (12), the mining community can then determine the operators' noise dosage, relative to the MSHA-Permissible Exposure Limit (MSHA-PEL) (90 decibels, A-weighted, as an 8-hour time-weighted average [90 dBA as an 8-hr TWA]), with a 5 dBA exchange rate) or the NIOSH-Recommended Exposure Limit (NIOSH-REL) (85 decibels, A-weighted, as an 8-hour time-weighted average [85 dBA as an 8-hr TWA]), with a 3 dBA exchange rate (26) received per drilling an individual hole during the drilling cycle of the roof bolting machine as shown below.

$$Dose\% = (100/TC)(2^{(LS-CL)/ER})(RTime)$$

where

TC = 28,800 seconds

LS = 101 dBA

CL = 90 dBA

ER – 5 dBA

RTime = 50 seconds (based on a penetration rate of 1.2 inches/second and a hole depth of 5 ft)

therefore, the dose percentage of the roof bolter operator for this particular example would be:

$$Dose\% = (100/28{,}800)(2^{(101-90)/5})(50) = (.00347)(4.59)(50) = 0.80\%$$

Additionally, assuming similar rock media (compressive strength of 6,000 psi) and the operator of the roof bolting machine drilling 78 drill holes per shift for installation of roof bolts, the operator's noise dosage relative to only utilizing the roof bolting machine for drilling would be:

0.8% x (78 drill holes) = 62.4 % of the MSHA-PEL of 100%

In comparison, the NIOSH-REL noise dosage for the same situation mentioned above would be 546%, based on a criterion level of 85 dBA and an exchange rate of 3 dBA. Table 6.13 below, provides the noise dosage of a roof bolter operator (per hole and per shift), relative to a respective sound pressure level and based on a run time of each hole consisting of 50 seconds and assuming the operator will drill 78 holes per his working shift.

Table 6.13 Noise Dosage (MSHA and NIOSH) of Roof Bolting Machine Operator

Sound Pressure Level dBA	Run Time (per hole) (sec)	MSHA-Dose (per hole) (%)	NIOSH-Dose (per hole) (%)	Drill Holes (per shift)	MSHA-Dose (per shift) (%)	NIOSH-Dose (per shift) (%)
80	50	0.0	0.1	78	3.4	4.3
82	50	0.1	0.1	78	4.5	6.8
85	50	0.1	0.2	78	6.8	13.5
86	50	0.1	0.2	78	7.8	17.1
87	50	0.1	0.3	78	8.9	21.5
88	50	0.1	0.3	78	10.3	27.1
89	50	0.2	0.4	78	11.8	34.1
90	50	0.2	0.6	78	13.5	43.0
91	50	0.2	0.7	78	15.6	54.2
92	50	0.2	0.9	78	17.9	68.2
93	50	0.3	1.1	78	20.5	86.0
94	50	0.3	1.4	78	23.6	108.3
95	50	0.3	1.7	78	27.1	136.5
96	50	0.4	2.2	78	31.1	172.0
97	50	0.5	2.8	78	35.7	216.7
98	50	0.5	3.5	78	41.1	273.0
99	50	0.6	4.4	78	47.2	343.9
100	50	0.7	5.6	78	54.2	433.3
101	50	0.8	7.0	78	62.2	546.0
102	50	0.9	8.8	78	71.5	687.9
103	50	1.1	11.1	78	82.1	866.7
104	50	1.2	14.0	78	94.3	1091.9
105	50	1.4	17.6	78	108.3	1375.7
106	50	1.6	22.2	78	124.4	1733.3

Chapter 6 has provided the mining community with proven approaches to predict sound pressure levels, with relative certainty, at the operator position of a roof bolting machine and at differing locations within a mine section, utilizing laboratory testing results relative to the roof bolting machine. Additionally, the mining community was presented with an approach to characterize the noise dosage a roof bolting machine operator will receive, based on laboratory results. These approaches provide the mining industry with the opportunity to predict sound pressure levels and noise dosage to machine operators without the laborious effort of conducting numerous underground measurements.

CHAPTER 7

CONCLUSIONS

The evaluation of differing noise control technologies relative to a roof bolting machine was possible utilizing the acoustically controlled reverberation room at the Pittsburgh Research Laboratory, along with installing thrust, rotational speed and penetration sensors on the machine as discussed in Chapter 4. Chapter 5 of the research effort provided testing results related to using differing drilling configurations (thrust, rotational speed, penetration rate, bit size, type of drill steel) and drilling methods (vacuum or dry, wet, mist) in high compressive strength rock media (>20,000 psi) relative to sound power levels measured from the roof bolting machine. When comparing round and hex drill steel, round drill steel should be used when utilizing the vacuum type of drilling method and hex drill steel should be utilized when performing the wet or mist type of drilling method. While increasing the thrust does yield an increased sound power level for both of the round and hex drill steel, the differences are negligible. When comparing rotational speed affect relative to round or hex drill steel, the round drill steel, during vacuum type drilling, provides a lower sound power level than similar hex drill steel tests. For the wet or mist system type of drilling, there appears to be no difference between the one-inch and 1.375-inch round and hex drill steel. Upon comparing penetration rates relative to round or hex drill steel in relation to thrust or rotational speed, their appears to be minimal affect attributed to thrust or rotational speeds.

When comparing the one-inch diameter bits to the 1.375-inch diameter bits, the one-inch diameter drill bits are slightly quieter than the 1.375-inch diameter drill bits. The penetration rates relative to the one-inch drill bits are noticeably higher than the 1.375-inch bits, on an order of two to three times higher. When comparing the 1-inch bit to the 1.375-inch bit relative to rotational speed, the one-inch bit performed significantly better than the 1.375-inch bit. For optimal performance and lower sound power levels, rotational speeds in the range of 200-400 rpm performed better and were quieter.

When comparing the different types of drilling methods, specifically vacuum, wet and mist drilling, penetration rates utilizing a wet or mist system drilling technique were much higher than using a dry or vacuum type drilling method. Additionally, utilizing a wet or mist system proved to emit less noise than similar tests conducted under vacuum or dry conditions. Much of the difference is attributable to the lubricating affect of the water or mist, which attenuates the higher frequency noise during the drilling process.

The individual test data collected (approximately 500 tests) from the research effort was then compiled, summarized and statistically correlated for drilling into a high-compressive strength media (>20,000 psi) by developing one equation, in which, could be used to determine or predict overall sound power levels given any type of drilling method (vacuum, wet or mist) and using varying types of drilling parameters or configurations related to thrust, rotational speed, bit size and type of drill steel. The statistical model equation, provided the mining community with a simple and reliable approach to predict a sound power level for a roof bolting machine during the drilling operation in high compressive strength rock media, given any type of drilling method (vacuum, wet or mist) and drilling parameter configuration (thrust, rotational speed, bit size and type of drill steel). The coefficient of determination for the test data, R^2, or the measure of the goodness of fit of a linear model, was equal to .849, indicating the statistical model to be a good fit or a representation of the data set. Furthermore, the residuals of the data set (laboratory minus model values of sound power) provided an excellent correlation with each other. Five residuals out of 486, were determined to be plus or minus 3.5 to 4.0 dBA and nine residuals at plus or minus 3.0 to 3.5 dBA. The remaining 472 residuals all fell within plus or minus 0 to 3.0 dBA. Therefore, 97% of the data fell within a residual of 0 to 3.0 dBA and would be well received within the acoustical community, particularly during prediction exercises.

Chapter 6 then offered the mining community with two different approaches in predicting sound pressure levels at the operator position of a roof bolting machine. One method of prediction, utilized overall sound power levels either measured from laboratory tests or determined (predicted) from the statistical model equation. The other approach, a more sophisticated and reliable approach, predicted sound pressure levels at the operator position of the roof bolting machine as well as other locations within the underground mining section, using full-octave band frequency measurements obtained from laboratory testing for input into a computer model for simulating and predicting sound pressure levels from sound power level measurements. This approach, predicted the same sound pressure level at the operator position of a roof bolting machine, when compared to the actual sound pressure level from underground measurements. The approach, proved especially reliable, utilizing: 1) underground measurements to characterize the acoustic properties of an underground coal mine section in determining the correct sabine or absorption coefficients; 2) laboratory testing in the reverberation room to determine full-octave band sound power levels of the roof bolting machine and 3) the use of an acoustical ray-tracing computer model program for predicting sound pressure levels from the required input data as mentioned above.

The research effort has provided the mining community with: 1) an understanding on how differing drilling configurations and drilling methods attribute to the sound power levels generated from a roof bolting machine while drilling into a high compressive rock media; 2) optimal drilling configurations and drilling methods in reducing sound power levels of the roof bolting machine; 3) a statistically valid equation for determining sound power levels of a roof bolting machine given differing drilling configurations and drilling methods; 4) a method for predicting sound pressure levels at the operator position and multiple locations in an underground mine related to the drilling cycle of a roof bolting machine and 5) a method for determining an operators' noise dosage relative to a roof bolting machine given any type of drilling configuration or drilling method utilized.

CHAPTER 8

RECOMMENDATIONS FOR FUTURE RESEARCH

This research effort has provided the mining industry with: 1) a complete understanding on how differing drilling configurations and drilling methods attribute to the sound power levels generated from a roof bolting machine while drilling into a high compressive rock media; 2) optimal drilling configurations and drilling methods in reducing sound power levels of the roof bolting machine; 3) a statistically valid equation for determining sound power levels of a roof bolting machine given differing drilling configurations and drilling methods; 4) a method for predicting sound pressure levels at the operator position and multiple locations in an underground mine related to the drilling cycle of a roof bolting machine and 5) a method for determining an operators' noise dosage relative to a roof bolting machine given any type of drilling configuration or drilling method utilized.

Initially, this research program focused on the related sound power and sound pressure levels attributed to roof bolting machines when drilling into high compressive strength rock media (>20,000 psi). Additional research efforts should be performed to characterize sound power and sound pressure level emissions of roof bolting machines when drilling into either low or medium compressive strength rock media. A similar testing plan should be developed and performed comparable to the plan conducted for determining sound power levels while drilling into high compressive strength rock media (>20,000 psi). Sound power levels should be determined in the laboratory relative to utilizing differing drilling parameters (thrust, rotational speed, drill bit size and type of drill steel) and drilling methods (vacuum, wet or mist) while drilling into low or medium compressive strength rock media. Additionally, the data collected from each individual test in the laboratory should then be compiled and analyzed for comparing sound power levels relative to the differing drilling parameters and drilling methods. Furthermore, a statistical analysis should be conducted on the collected data to determine if a statistically valid equation could then be developed, in which, will provide the mining community with a reliable and valid equation for predicting overall sound power levels relative to differing drilling parameters and methods used in low or medium compressive strength rock media.

Secondly, further research should be conducted to continue to characterize and define the acoustical properties related to differing geometrical configurations in underground coal mines. The research program presented, only characterized underground coal mines with roof to floor heights of five and six feet, mine heights lower than five feet and greater than six feet should be investigated to verify if differing mine heights have an affect on the acoustical properties in underground coal mines, as well as examining the affect shotcrete or rock dust usage might have relative to the acoustical properties in underground coal mines.

Additionally, research efforts relative to absorption coefficient determination should span outside the underground coal industry into underground metal and non-metal operations. Eventually, the results of the research effort could possibly be a handbook, in which, would provide the mining industry with the appropriate absorption coefficients relative to the mine type, geometry and geological characteristics for predicting and determining sound power and sound pressure levels underground.

Finally, the research presented here only focused on the drilling cycle of the roof bolting machine, additional research should be conducted to characterize and monitor the sound power and sound pressure levels attributed to the bolting cycle of the machine and the corresponding noise dosage to the operator. Obtaining this information, would provide the mining industry with a complete understanding relative to the overall noise dosage presented to the operator of the roof bolting machine relative to both, the drilling and bolting cycle of the machine. Acquiring this additional information, would provide extremely useful in the development of engineering noise controls during the bolting cycle of the machine, thereby, reducing the noise exposure to the operator.

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