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A STUDY OF THE EFFECT OF UNDERGROUND DRILLING ENVIRONMENTS ON THE NOISE PRODUCED BY PERCUSSIVE ROCK DRILLS

by

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ABSTRACT

The aim of the investigation is to identify and interrelate particular parameters that influence the magnitude of noise levels to which rock drillers are subjected. The percussive rock drill is known to be an excessively noisy machine. Currently, exhaust mufflers and other silencing devices are being developed but as yet acceptable noise levels have not been established. The definition of acceptable sound power levels for drills must recognize that the sound levels to which the drill operator is exposed are modified by the acoustic properties of the working environment.

For the initial phase of the investigation a representative rock drill was selected as a noise source. Comparative sound levels generated by this machine were measured in a free field environment and in typical underground working places. Increases in the sound pressure levels in each octave band from 63 to 16,000 hertz were observed when the drill was operated in both stopes and drifts.

For the subsequent phase of the investigation, studies were conducted on an assortment of commercially available rock drills. The changes in measured sound levels have been related to:

the acoustic properties of the working place,
the drill position relative to the walls,
the length of drill steel exposed from the hole, and
the drill air supply pressure.

Based on the measurements taken throughout the investigation, sound pressure level correction factors are proposed. By applying these factors to sound levels generated under free field conditions, predictions of rock drill sound pressure levels present in underground working places can be made. In addition, when studies of rock drill noise levels in various operating configurations are being conducted, use of the factors permits reduction of observed sound level measurements to a common datum.

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INTRODUCTION

One of the more difficult problems in noise control in the mining industry is the abatement of percussive rock drill noise. Legislation in the 1960's resulted in the development of efficient exhaust mufflers (1,2,3,4) and compulsory hearing conservation programs (5). Further legislation is contemplated but at this stage more detailed knowledge regarding the characteristics of the drill as a noise source and the effect of the drilling environment on sound fields is required before meaningful limits can be specified.

Reduction in the noise levels by use of exhaust mufflers has increased the relative importance of other noise sources in the rock drill. The major noise sources have been identified by Holdo (6) as the exhaust and mechanical noises, comprising 87.5 and 12.5 percent respectively. Beiers (7) extended the identification to eleven separate sources and showed the effectiveness of some muffling devices. This paper will present ratings for the sound levels of various drills and an indication of the relative importance of the sound sources in each.

Rock drills are most commonly operated in relatively confined spaces in underground mines. Fischer (8) and Botsford (9) have both drawn attention to the increase in sound pressure levels (SPL's) that have been encountered underground and present a general indication of the increases to be expected. In order to formulate regulations governing the use of rock drills in underground mines it is necessary to have a quantitative description of these sound pressure level increases. Such a description must be related to identifiable acoustic characteristics of the environment.

This paper develops a procedure to interpret the sound pressure levels measured underground. The object is to reduce these working environment levels to their equivalent in a standard test environment. This information can then be applied to an in-situ determination of the effectiveness of silencing devices and the prediction of average exposure levels for the drill operators. It is hoped that this investigation will aid in the establishment of target sound pressure levels for percussive rock drills and the identification of guidelines within which silencing of these machines can be accomplished.

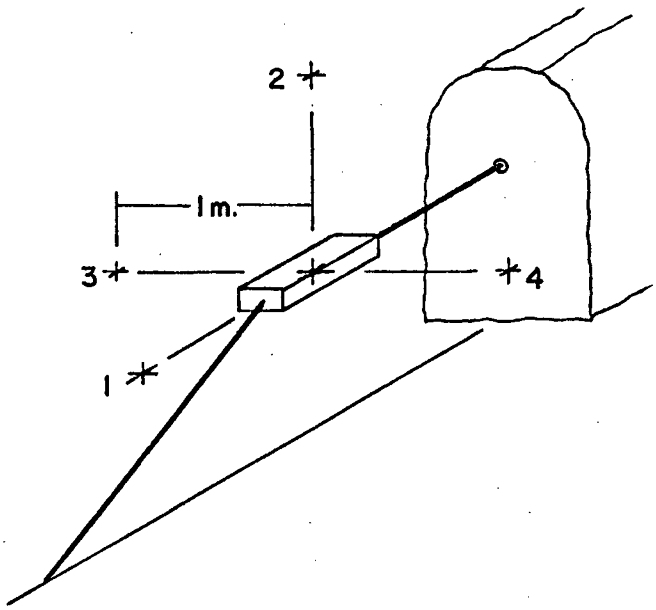

Fig. 1 Standard measurement positions for airleg drills as specified by the CAGI-PNEUROP Test Code.

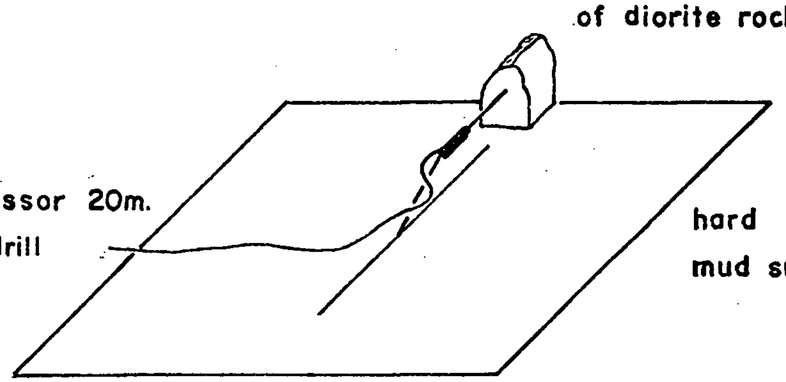

Fig. 2 The measurement of sound power levels was carried out in a quarry to obtain free field conditions.

MEASUREMENT OF SOUND PRESSURE LEVELS

The drills employed in all tests were the commercially available models of three manufacturers, in this paper designated as manufacturer A, B, and C. Four airleg drills and two stoper drills were tested utilizing 6 foot long, 7/8 inch diameter hexagonal steels and four winged tungsten carbide bits as standard ancillary equipment.

Noise levels were measured using Bruel & Kjaer instruments; a sound level meter, type 2209, an octave band filter, type 1613, and a one inch condenser microphone, type 4145. The microphone, covered with a foam wind-shield protector and mounted on a tripod, was connected to the sound level meter by a ten meter long extension cable. Output from the sound level meter was recorded at 7.5 ips speed setting on Ampex low noise tapes by a Uher 4200 Report tape recorder. Calibration levels were obtained from a Bruel & Kjaer pistonphone, type 4220. The tapes were analyzed in the laboratory by replay through the sound level meter and its associated octave band filter set.

As the percussive rock drill is a variable and directive noise source, the measurement positions and techniques must be standardized to obtain reproducible results. The Compressed Air and Gas Institute (CAGI) and the European Committee of Manufacturers of Compressed Air Equipment (PNEUROP) have prepared a test code (10) for the free field measurement of sound from pneumatic machinery including airleg and stoper rock drills. The CAGI-PNEUROP Test Code has been adopted as a standard procedure for this work.

The standard measurement positions for airleg drills as shown in Figure 1 are referenced by position number in the remainder of this paper. An idealized sketch of the free field test environment, as described in Section 7.2 of the CAGI-PNEUROP code, appears in Figure 2.

SOUND RADIATION PATTERNS

The sound fields around a type B airleg drill have been mapped in the free field test environment and in an underground drift. Figure 4 is a plan view of the so-called free field sound pattern, contoured at one decibel intervals on two horizontal planes. These contours illustrate the directivity of the drill noise and indicate that the major noise sources are the exhaust air and the drill steel. The relationship between the SPL's measured at the standard measuring points 1 through 4 and the overall sound field, indicates that these

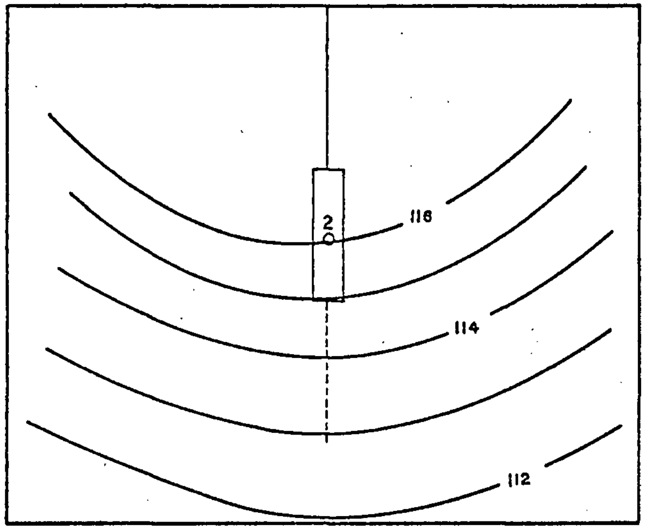

Fig. 3(a) SPL contours one meter above the drill

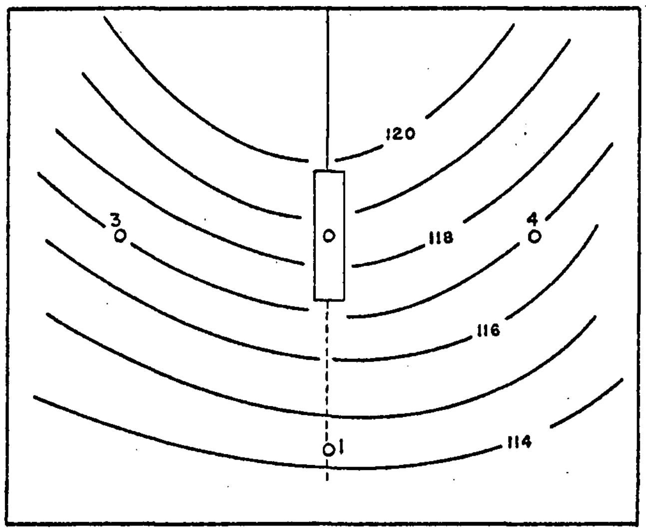

Fig. 3(b) SPL contours through the plane of the drill

Fig. 3 The plan views of the sound radiation patterns around the drill in a 10' x 10' drift illustrate how the sound levels are increased by reflections from the drilling face.

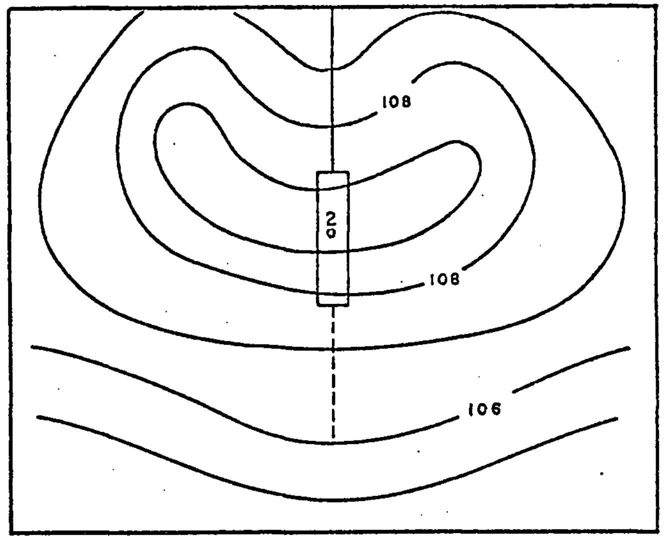

Fig. 4(a) SPL contours one meter above the drill

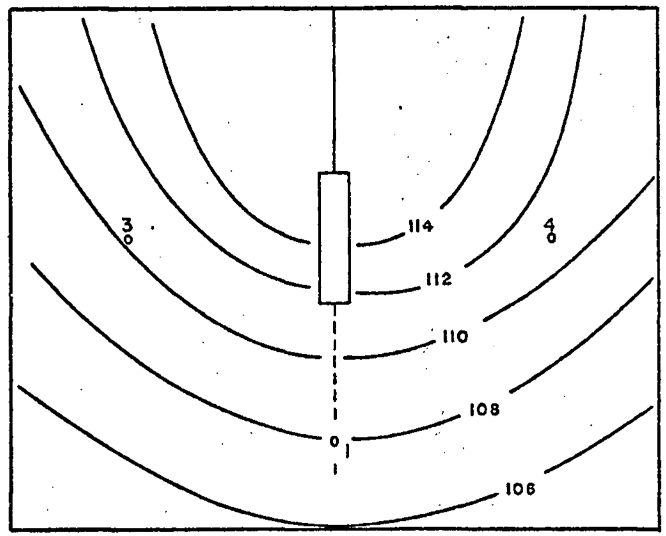

Fig. 4(b) SPL contours through the plane of the drill

Fig. 4 The plan views of the sound radiation patterns around the drill in a free field indicate the directivity of this noise source.

points can be used to obtain representative measurements of the noise produced by the drill.

The SPL's measured at the positions recommended by the CAGI-PNEUROP Test Code represent "near-field" levels. These measurements are not indicative of the noise levels that will be produced elsewhere in the working place but only of the levels in the immediate vicinity of the drill. If further information on the sound radiation pattern is desired, readings should be taken at points seven meters from the drill, well into the "far-field".

The sound field mapped in a 10' x 10' underground drift is contoured in Figure 3. The levels measured vary from six to eight decibels higher than at the corresponding points in Figure 4, the equivalent free field condition, and illustrate what is known as "reverberancy". The measured SPL is composed of the direct sound from the drill plus sound reflected from the floor and the walls of the drift. Beranek (11) calls fields like those of Figure 3 semi-reverberant fields and proposes that the SPL in such a field can be computed from the sound power level of the noise source and the acoustic properties of the enclosure.

SOUND POWER LEVEL

The sound power level of the test drill was determined by measuring the SPL's at eight points on the surface of a hemisphere 40 feet in diameter. The technique used was described by Zaveri (12) and gives the sound power level via equations 1, 2, and 3.

$$PWL = \overline{SPL} + 20 \log_{10}(2\pi r) \qquad 1.$$

$$\overline{SPL} = 10 \log_{10}\left(\frac{1}{8} \sum_{i=1}^{8} \left(\frac{P_i}{P_o}\right)^2 \right) \qquad 2.$$

$$\sum_{i=1}^{8} \left(\frac{P_i}{P_o}\right)^2 = \left(\frac{P_1}{P_o}\right)^2 + \left(\frac{P_2}{P_o}\right)^2 + \dots\dots\dots + \left(\frac{P_8}{P_o}\right)^2 \qquad 3.$$

where r = radius of the hemisphere = 20'

P_o = reference SPL = .0002 μbars

SPL = averaged sound pressure level in decibels

PWL = sound power level in decibels

Octave Band Mid-Frequency	Measured Sound Pressure Levels (dB) Microphone Positions 1	2	3	4	5	6	7	8	Sound Power Level (dB)
63	88	84	87	87	87	83	84	84	120
125	85	83	82	84	86	86	83	84	118.5
250	84	84	86	81	81	87	88	85	119
500	85	85	86	84	82	90	86	86	120
1,000	83	84	84	82	78	87	83	86	118
2,000	83	86	86	85	75	82	85	87	118.5
4,000	82	86	87	86	74	83	87	87	119.5
8,000	78	82	84	82	70	83	82	83	116
Linear	93	94	94	93	91	96	94	93	128
A-scale	90	92	92	91	83	90	92	92	125.5

Fig. 5 The Sound Power Level of the test drill was found to be 128 decibels overall.

The PWL for the test drill was measured in each of eight octave bands and the results so obtained are shown in Figure 5.

SEMI-REVERBERANT FIELDS

The sound pressure level in semi-reverberant fields can be computed by equation 4.

$$SPL = PWL - 10 \log_{10} \left(\frac{Q}{4\pi r^2} + \frac{4}{f(a)} \right) \qquad 4.$$

where Q = directivity factor with values 1,2,4, and 8, when the source is in mid air, on a hard floor, at an edge between walls, or at a corner of three hard walls, respectively.

r = radius of test sphere in feet (3.28 feet for CAGI positions)

a = sound absorption in sabines

Beranek (11) calls f(a) a room constant R which he defines by equation 5.

$$R = \frac{A\,\bar{a}}{1-\bar{a}} \qquad 5.$$

where $\bar{a}$ = average sound absorption coefficient of the room

A = area of the bounding surfaces

Young (13) lets f(a) = a and notes that "a" can be derived from measurements of the reverberation time of the room.

$$a = \frac{.05V}{T} \qquad 6.$$

where V = room volume in ft^3

T = reverberation time in seconds

The above considerations mean that before the SPL's can be computed in accord with equation 4, the acoustic characteristics of the environment must be identified.

UNDERGROUND DRILLING CONDITIONS

In this investigation the standards for all drills are defined in terms of free field ratings. As shown by Figure 2, these ratings were obtained with the drill located over a hard surface floor, drilling into a boulder the nominal surface area of which was less than 0.5 square meters.

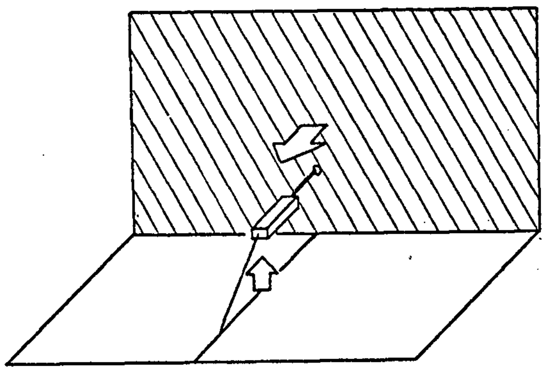

Fig. 6 - In stopes with a height of more than 3 meters the back is not an important reflecting surface.

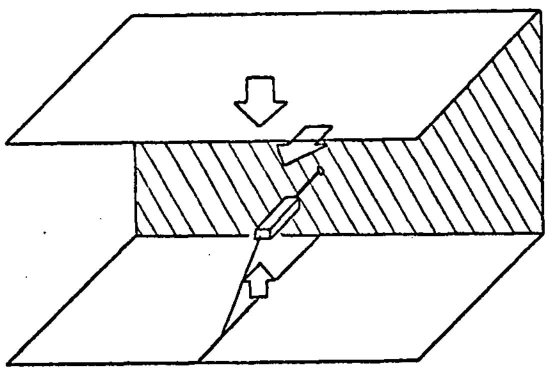

Fig. 7 - In stopes with a height of less than 3 meters the floor, the back, and the face being drilled reflect the sound at the drill operator.

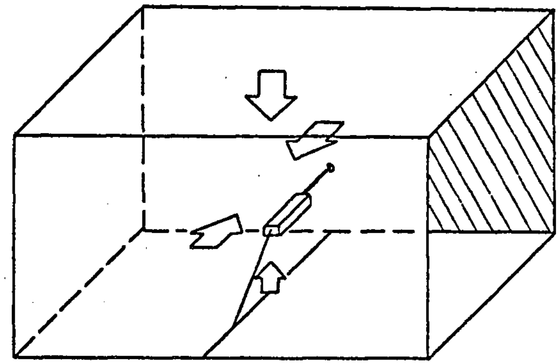

Fig. 8 - When sidewall cut is initiated at a point more than 3 meters from the drift face the sound levels are increased by reflections from four surfaces.

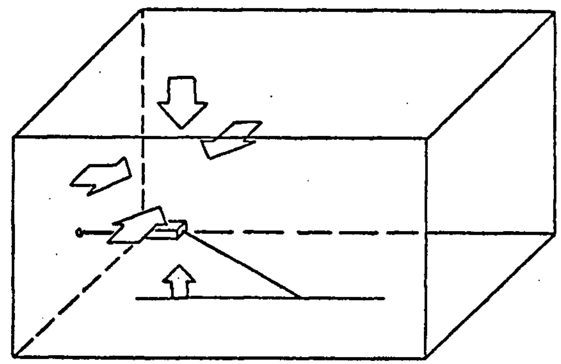

Fig. 9 - Drilling into the face of a drift places the drill and its operator into the most reverberant situation underground with three walls, the floor, and the back reflecting the sound waves.

In normal underground application the drilled medium is a solid rock wall, the surface layer of which is composed of interlocked rock fragments, and wherein the depth and extent of rock fragmentation are variable quantities. In addition, in such situations the drill is often located within a few meters of additional enclosing walls. Thus, in the free field condition only one significant sound reflecting surface, the floor, exists; whereas in actual underground situations additional reflecting surfaces of variable reflectivity occur. Figure 6, representing a high backed stope situation, shows the presence of one more reflecting surface additional to the floor surface. Figure 7, representing a low backed stope situation, shows the presence of two more reflecting surfaces additional to the floor surface.

One of two situations usually applies when a rock drill is operated in a drift. When a drift side slash is being drilled, as shown in Figure 8, the acoustic environment consists of four reflecting surfaces, whereas the drilling of a drift face, as shown in Figure 9, yields a total of five surfaces capable of reflecting sound back to the drill operator.

The rock walls encountered underground are not perfectly reflective but are typically very rough with relief that can be measured in feet. The absorption coefficients of these walls vary with rock type and with the sound frequency. Values of "a", the absorption coefficient, range from less than 0.05 for a smoothly blasted quartz wall to more than 0.3 for a wall treated with shotcrete. Diehl (14) quoted some values of absorption coefficients that can be applied to the drilling environment.

With respect to floor conditions in underground working places, since this reflecting surface is rarely hard and smooth its influence on working place acoustic properties is important. Normally the floor will be a flattened broken rock pile composed of rock fragments ranging from two feet in diameter down to slime size, and often the floor is partially covered by water. The range of conditions is sufficiently wide that a careful correlation was not attempted in this investigation but the influences are considered in the statement of correction factor tolerance limits. The correction for an area with an abnormally absorptive floor will fall near the low end of the range of a particular factor, whereas the correction for an area displaying a relatively hard floor surface will be near the high end of the range. The correlations presented in this paper are for average floor conditions such as those found in drifts where the broken rock is reasonably coarse (like gravel), packed by moderate traffic loads, and wet, but with less than 10% of the area covered with standing water.

When a rock drill is operated as shown in Figure 6, the geometric centre of the drill must be kept at least 1.0 meter from the wall to satisfy the CAGI requirements. In addition to this restriction, it must be recognized that the drill is a complex noise generator with sources of various sound power levels distributed over a length of from one to three meters in normal operation. These considerations mean that the directivity "Q" as employed in equation 4 is not well defined but has a value somewhere between 1 and 2.

Under the simplifying assumptions that the drill is a point source located at a distance "d" from a perfectly reflecting wall, the levels at the points 3 and 4 of Figure 1 can be computed from geometric considerations. The effect of wall distance shown in Figure 6 is to increase the SPL by one decibel when "d" equals one meter, and increasing to three decibels as "d" approaches zero.

SOUND LEVELS IN STOPES

Stopes are dynamic production areas displaying continuously changing geometric configurations. From an acoustic point of view stopes are reasonably large chambers with low absorption coefficients except over broken rock covered areas. These rock piles can be substantial in both volume and surface area. Usually, when rock drills are operated in stopes they are located against one wall distant from the other walls. The roof (or back) of the stope is from two to ten meters above the floor so that often it may be considered to be far from the drill and have no effect on the sound levels. Figures 6 and 7 conveniently idealize the typical stoping situations.

The SPL's at points 3 and 4 may be expected to increase by about four decibels for a drill operating under a very low back. These increases should fall to less than one decibel when the back is more than two meters above the

SOUND PRESSURE LEVEL CORRECTION FACTORS FOR STOPES FOR AIRLEG DRILLS OF TYPE B

Octave Band Mid-frequency	Correction Factors in dB re .0002 μbars			
	Back ≥ 3 meters high		Back ≤ 3 meters high	
	Mean (C)	Deviation	Mean (C)	Deviation
63	4	2	6	3
125	3	2	5	2
250	3	2	5	2
500	2	1	4	2
1,000	2	1	4	1
2,000	1	1	3	1
4,000	1	1	2	1
8,000	0	1	1	1
16,000	0	1	0	1

Fig. 10 The sound pressure levels in a stope may be predicted by adding the above correction factors to the rated levels for the drill in question. All levels must be measured at the positions defined as 3 and 4 in Fig. 1.

SOUND PRESSURE LEVEL CORRECTION FACTORS FOR DRIFTS FOR AIRLEG DRILLS OF TYPE B

Octave Band Mid-frequency	Correction Factors in dB re .0002 μbar									
	Cross Section Area (ft^2)									
	40	50	60	70	80	90	100	120	140	160
63	10	8	7	6	6	5	4	4	3	3
125	11.5	11	10	9.5	9	8.5	7.5	6	5	4
250	9	8	7	6	5	4	3.5	2	1	.5
500	9.5	7.5	6.5	5.5	5	4	3.5	3	2	1.5
1,000	12	10	8.5	7	5.5	4.5	3.5	3	2.5	2
2,000	6.5	5.5	4.5	3.5	3	2.5	2.5	2	1.5	1
4,000	5	4	3	2	1.5	1	1	.5	0	0
8,000	7	5	4	3	2	1.5	1	.5	0	0
16,000	2.5	2	1.5	1	1	1	.5	0	0	0

Fig. 11 The sound pressure levels in drift may be predicted by adding the above correction factors to the rated levels for the drill. All the levels must be measured at the positions defined as 3 and 4 in Figure 1.

drill. Measurements made underground have indicated that the actual increases are always affected by the floor conditions.

A set of correction factors is presented in Figure 10. These factors represent the increases over the free field levels of a type B airleg drill as measured in eight stopes. For comparative purposes, the SPL's as measured in stopes may be reduced to the levels the drill would produce in a free field environment by subtracting the appropriate correction factors from the levels observed in-situ.

SOUND LEVELS IN DRIFTS

As the acoustic conditions of drifts are reproducible, the detailed investigations in this paper were carried out in such areas. In comparison to stopes, during the drilling cycle drifts will usually exhibit a higher degree of symmetry, have more smoothly blasted walls, and contain less broken rock material piled on the floor.

The equations 4, 5 and 6 show that the acoustic characteristics of the drilling environment are described by the volume, bounding surface area, and the average absorption coefficient. The volume and surface area cannot be calculated because drifts are open ended and thus the length is not defined. There are some cases in which an effective length corresponding to a few sound wavelengths may be applicable, but a definition of this situation is not available. The question is left open by describing the drifts by their cross-section area. The volume and surface area are simply related to the cross-section area of square drifts when an effective length of drift is chosen.

The SPL's of the test drill have been measured in a large number of drifts (see Appendix II) and the increases over the drill rating levels are tabulated in Figure 11. These correction factors are given as average values and possess a tolerance limit of two decibels for all octave bands above 125 hertz. Errors will be incurred in measurements taken in very small drifts, i.e. cross-section less than 40 sq. ft., where the CAGI positions can no longer be maintained with respect to the walls.

Definite reverberancy and standing waves have been observed in all drifts. These effects are most marked in the 63 and 125 hertz octave bands with SPL variations of from 4 to 10 dB observed over a distance of less than 0.5 m. Smaller variations of the SPL have been observed in all octave bands up to the 8,000 hz. range. These variations are also caused by direct reflection of sound due to the slabby nature of the walls, large rock fragments lying on the floor, and hardware lying about the working place.

Operation of a drill at the face of a drift as shown in Figure 9 caused more reverberancy than the open drift especially when the cross-section area is less than 60 sq. ft. The increases were mainly in the lower octabe bands and no significant changes in the average levels could be shown above the 500 hz. band. Insufficient data have been obtained to predict confidently the increases in the 63 and 16,000 hz. octave bands.

RATING THE SOUND LEVELS OF ROCK DRILLS

Testing facilities were arranged at the Britannia Mine where drills were tested underground in a 10' x 10' drift located in chlorite schist and in a free field environment drilling into the same rock type. The latter testing station was an area located near the portal of a mine access drift where the sound levels were not influenced by surrounding walls. This location is judged to satisfy the CAGI designated requirements for SPL measurements of airleg type drills, but for the operation of stoper type drills the CAGI requirements cannot be met fully at this location. Since the stoper is a directive sound source, the SPL measurements at fixed points around it are markedly increased when there is a rock face close to the drill. This problem was recognized at the Britannia station by the poor reproducibility of SPL's produced by the stopers.

The SPL's measured in the 10' x 10' drift and in the free field area are defined as the rated levels for the rock drills. Tables 1 to 6 of Appendix I present ratings for some airlegs and stopers. All the operating conditions during testing were maintained as close to CAGI specifications as possible. In the course of these tests a variable not identified in the CAGI specifications was discerned.

The CAGI Test Code specifies 0.5 to 2 m. of steel exposed from a drill hole during testing provided that the drill is more than 1 m. from the face at all times. The graphs of Appendix III represent data gathered in the test drift described earlier. These graphs show that the SPL's produced when 0.5 m. of steel is exposed are significantly less than those produced when 1.0 m. is exposed. In order to make ratings reproducible the length of steel exposed was maintained at 0.75 to 1.0 m. despite penetration rates of up to a meter per minute. For the short time intervals in which such a reading was possible, taped records were found to be somewhat superior to SPL observations written in the field.

DERIVATION OF THE SOUND PRESSURE LEVEL CORRECTION FACTORS

The "scatter" of data plotted in the graphs of Appendix II warrants comment. These data points represent drills working in rocks ranging from chlorite schists to diorites and under operating air pressures of between 80 and 90 psi. If the noise produced by the drills could be shown to have a marked dependence on air pressure or on the rock type, some of the scatter could be explained.

The graphs of Appendix III present the results of the studies into the effect of compressed air supply pressure on the sound levels of some airleg drills. As the dynamic pressure increased from 80 to 90 psi the SPL's increased by about one decibel in each octave band. This change is too small to account for the scatter mentioned above.

An airleg drill of type B was tested in drifts in a chlorite schist rock (9' x 10'), in a mineralized dolomite (8' x 11'), and in a quartz diorite rock (8'6" x 10'). All the data points are plotted on the lower graphs of the Appendix II and illustrate no clear dependence on the hardness of the rock or the size of the drift. It was concluded that the rock type was not a significant variable in the tests.

A number of transformations were carried out on the decibel and cross-section scales of the graphs of Appendix II in an attempt to find an analytical function to predict the SPL's. Inverse and logarithmic transformations, functions of the form of equation 4, and simple polynomials were tried but none of these gave a suitable fit, consequently the points were plotted linearly as shown and graphical curve fitting was employed.

The SPL Correction Factors were obtained by subtracting the free field ratings from the levels predicted by the curves for a given cross-section area. Since the errors associated with the ratings are at least ±1 dB and the errors on the curves as drawn are also ±1 dB, the correction factors possess a total error of ±2 dB. This error has been used as the estimate of the tolerance limits quoted earlier. The factors quoted are for an air pressure of nominally 85 psi dynamic and 0.5 dB per 5 psi are added or subtracted when the corrections are applied to the observed levels.

IN-SITU COMPARISON OF ROCK DRILLS

The sound levels produced by rock drills are most readily measured when the drill is operating in the working place. This situation means that the data will indicate the SPL's under a special set of conditions and as such should not be used as a direct measurement of the efficiency of the drill's silencing devices. The correction factors presented in this paper can be selected to fit the conditions in the working place and subtracted from the measured SPL's, thereby reducing the levels to those the drill would produce in a free field. When the reduced SPL characteristics of the drill are plotted critical comparisons can be made with the levels produced by other drills of the same type and with the rated levels presented in Appendix I.

In Figure 12 the SPL's of three drills of type B producing from 114 to 118 dB were reduced to a common datum. It was found that all three drills were in good condition with efficient mufflers and would have produced about 111.5 dB had they been operating in a free field. The SPL in the 7' x 8' drift used in this example was 78% higher than the SPL in free field, in the 8' x 8' drift it was 65% higher and in the 9' x 11' drift the SPL was increased by 44% overall.

SILENCING THE ROCK DRILL

The major sources of noise from the percussive rock drill have been identified (2) as impact, exhaust and resonance.

PARAMETER	AIRLEG DRILL 1		AIRLEG DRILL 2		AIRLEG DRILL 3	
	SPL measured in 7' x 8' drift	SPL predicted for free field operation	SPL measured in 8' x 8' drift	SPL predicted for free field operation	SPL measured in 9' x 11' drift	SPL predicted for free field operation
Rock Type	Argillite		Dolomite		Chlorite Schist	
Air psi	95		80		90	
Water psi	140		140		80	
Measurement Position	3		3		3	
Overall SPL	118	111.4	116	111.3	114	111.3
SPL's by Octave Band						
63 hertz	110	103.5	103	98	100	98
125 "	106	94.5	102.5	92.5	101.5	94.5
250 "	110	101.5	107	100	103.5	100.5
500 "	106	98.5	109	102.5	103.5	100.5
1000 "	105	95	106	98	101	98
2000 "	109	103	108	103.5	105	103
4000 "	110	105.5	109.5	106.5	108.5	108
8000 "	110	105	107	104.5	104.5	104

Figure 12 The sound levels measured in a variety of working environments have been reduced to a common datum (free field) by application of the appropriate SPL Correction Factors.

Frequency	Source
40 - 100 hertz	Impact of piston and drill steel Impact of drill steel and rock
100 - 2000	Exhausting of air from the exhaust ports
2000 up	Resonance of parts of drill Resonance of drill steel

The graphs of Appendix III show that the three airleg drills, A, B and C are efficiently muffled. At an operating pressure of 90 psi the contribution to the overall SPL by the frequency components above and below the 2000 hertz octave band are:

Source of Noise	Drill A	Drill B	Drill C
Exhaust	110.5dB	109.5dB	106.5dB
Steel	112.5dB	113.5dB	111.5dB

These numbers indicate that the steel noise forms 62%, 70% and 76% of the total noise produced by drills A, B and C respectively. Efficient muffling has decreased the exhaust noises to such an extent that further silencing can best be achieved by solving the steel noise problem.

Simon (15) has shown that the drilling efficiency of a percussive rock drill is an inverse function of the mechanical impedance of the steel. As the amplitude of the stress waves in the steel is increased, the rate at which work can be done on the rock increases. An increase in the number of blows per minute will also increase the rate of work provided the thrust on the drill is increased proportionately. All of these steps call for an increase in the strength of the steel being used so that the mechanical impendance need not be increased. Silencing of the steel usually involves a sizable increase in its cross-section area and a decrease in drilling efficiency. Visnapuu and Jensen (16) were able to drop the steel noise by 6 dB but found that the penetration rate dropped by 28%.

Percussion drill designers have increased the penetration rate by increasing the frequency of drill steel blows, however this condition has accentuated the SPL of the 4,000 hz. octave band to the point where the maximum amplitude of the rock drill noise occurs in this band. There appears to be some correlation between the rate of penetration and the level observed in this band. If this SPL is reduced by 2 or 3 dB through manipulation of the steel itself the drilling rate is decreased very noticeably. Since these losses are not acceptable it is suggested that special earmuffs might be designed for drilling operations. These muffs would be similar to those worn by aircraft ground crew and would provide extra attenuation for frequencies between 2,000 and 10,000 hz. Such muffs would reduce effectively the noise hazard of percussion drilling provided complete operator acceptance could be obtained.

CONCLUSIONS

The CAGI-PNEUROP Test Code can be used as a guide for sound pressure level measurements in underground environments. The correlation of free field SPL's with underground SPL's has been achieved satisfactorily for a number of percussion rock drills. Sound levels in the working place can be predicted from a knowledge of the free field levels of these drills. Likewise the sound levels measured in the working place can be related to expected free field levels.

ACKNOWLEDGEMENTS

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APPENDIX I

THE RATED SOUND LEVELS OF SOME PERCUSSIVE ROCK DRILLS

TABLE 1 RATED LEVELS FOR AIRLEG A

Air Pressure = 95 psi.
Water Pressure = 85 psi.

Penetration = ≈ 35 ipm.
Muffler: Integral

Octave Band	Position 1		Position 3		Position 4	
	Free Field	Drift	Free Field	Drift	Free Field	Drift
linear	107	112	111.5	115	111.5	115
dBA	107	109	111	113	111	113
63	95	100	95	102	96	104
125	97	105	97	105	96	104
250	94	102	91	102	93	103
500	98	105	102	106	101	106
1,000	95	100	95	101	96	101
2,000	101	102	102	104	104	105
4,000	101	106	105	108	106	110
8,000	95	102	103	106	104	105
16,000	90	94	93	95	96	96

TABLE 2 RATED LEVELS FOR AIRLEG B

Air Pressure = 90 psi.
Water Pressure = 60 psi.

Penetration = ≈30 ipm.
Muffler: Integral

Octave Band	Position 1		Position 3		Position 4	
	Free Field	Drift	Free Field	Drift	Free Field	Drift
linear	108	113	113	114	112	114
dBA	107	112	112	113	111	113
63	90	102	97	104	97	103
125	94	104	96	105	95	104
250	95	103	101	102	100	105
500	97	105	100	105	100	104
1,000	95	103	98	103	96	101
2,000	100	104	104	105	102	105
4,000	101	105	108	108	107	109
8,000	100	103	107	104	105	105
16,000	88	95	98	98	98	98

TABLE 3 RATED LEVELS FOR AIRLEG C

Air Pressure = 90 psi.
Water Pressure = 80 psi.

Penetration = ≈ 30 ipm.
Muffler: Integral

Octave Band	Position 1		Position 3		Position 4	
	Free Field	Drift	Free Field	Drift	Free Field	Drift
linear	106.5	112	111.5	113	111	112.5
dBA	106	110	111	112.5	111	112
63	86	106	96	102	96	102
125	81	98	90	96	88	98
250	88	98	90	99	88	99
500	89	96	91	98	90	98
1,000	94	98	95	99	94	99
2,000	96	103	102	103	102	103
4,000	104	106	107	108	108	108
8,000	100	103	105	106	106	107
16,000	88	92	93	94	94	94

TABLE 4 RATED LEVELS FOR AIRLEG D

Air Pressure = 95 psi.
Water Pressure = 80 psi.

Penetration = ≈ 35 ipm.
Muffler: Integral

Octave Band	Position 1		Position 3		Position 4	
	Free Field	Drift	Free Field	Drift	Free Field	Drift
linear	108	113	111.5	115	111	114.5
dBA	107	110	111	113.5	110	113
63	95	95	102	102	101	106
125	100	103	97	104	96	104
250	94	105	100	107	101	106
500	98	101	99	103	101	102
1,000	95	103	100	102	98	102
2,000	101	104	107	106	104	107
4,000	101	106	110	108	106	108
8,000	95	104	107	106	104	106
16,000	90	98	95	98	96	97

TABLE 5 RATED LEVELS FOR STOPER B

Air Pressure = 85 psi.
Water Pressure = 60 psi.

Penetration = = 30 ipm.
Muffler: Integral

Octave Band	Position 1		Position 3		Position 4	
	Free Field	Drift	Free Field	Drift	Free Field	Drift
linear	110.5	113.5	109.5	113	110	113
dBA	107	109	108	110	108	110
63	105	109	104	109	104	107.5
125	103.5	101	101	101	101.5	103
250	99	100	97	102	98	102
500	100	101	97	101	97	101
1,000	98	101	95	98	95	99
2,000	101	103	100	104	100	103
4,000	100.5	105	103	105	103	105
8,000	99	100	101	102	101.5	101
16,000	94	94	94	94	95	95

TABLE 6 RATED LEVELS FOR STOPER C

Air Pressure = 90 psi.
Water Pressure = 80 psi.

Penetration = = 30 ipm.
Muffler: Integral

Octave Band	Position 1		Position 3		Position 4	
	Free Field	Drift	Free Field	Drift	Free Field	Drift
linear	111.5	113.5	112	113.5	112	113.5
dBA	110	112	110	112	110	112
63	103	103	103	108	104	106
125	97	101	102	101	102	103
250	97	104	103	104.5	103	105
500	97	102	96	101	96.5	99
1,000	102	103	100	102	100	102
2,000	103	105	101	103.5	101.5	103.5
4,000	107	109	106.5	109	106	108.5
8,000	105	104	103.5	105	104	106
16,000	96	96	97	97	96	97.5

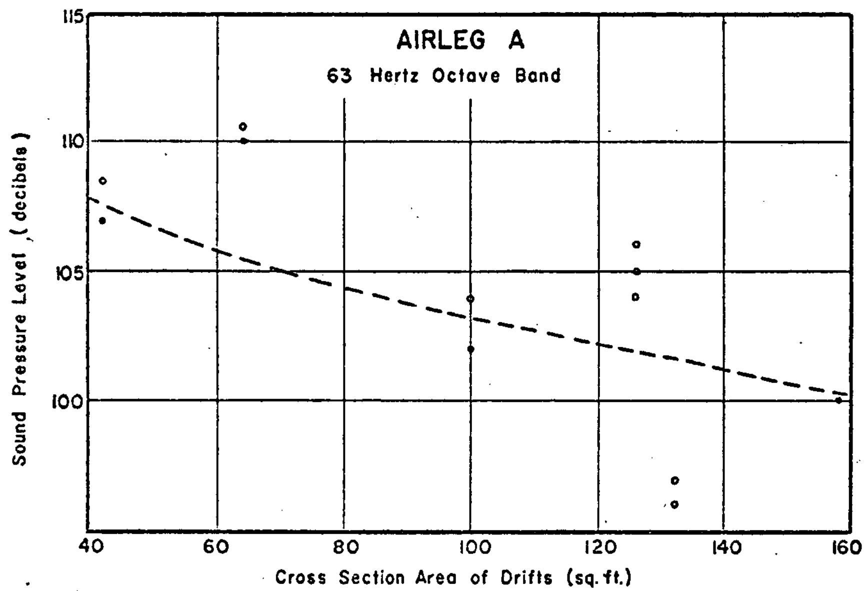
APPENDIX II

THE EFFECT OF DRIFT SIZE ON SOUND PRESSURE LEVELS

1. The data points represent readings taken at the positions designated 3 and 4 by the CAGI-PNEUROP Test Code.

2. Open circles o represent single data points. Closed circles • represent two or more coincident data points.

3. The observations were made in drifts with a width to height ratio between 0.6 and 1.4.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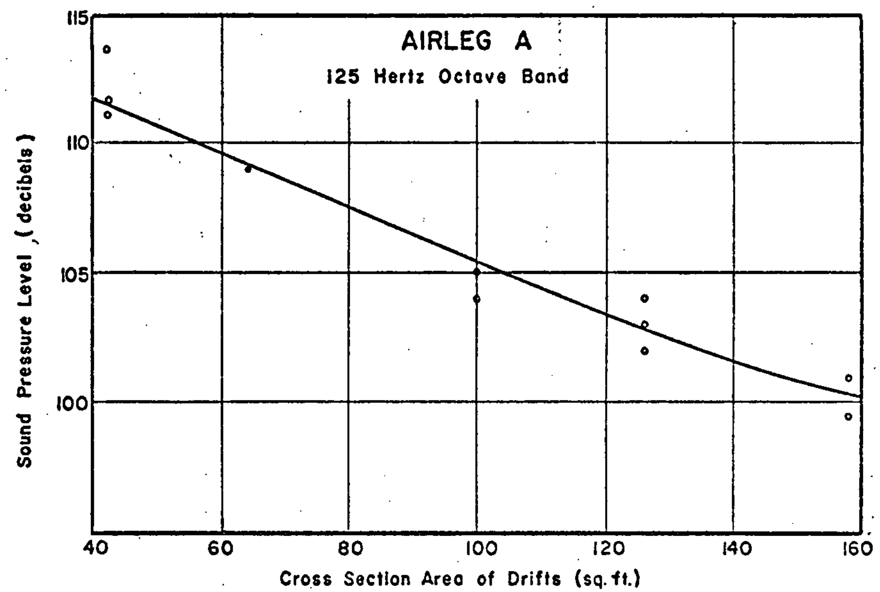
63 Hertz Octave Band
Sound Pressure Level (decibels)
Cross Section Area of Drifts (sq. ft.)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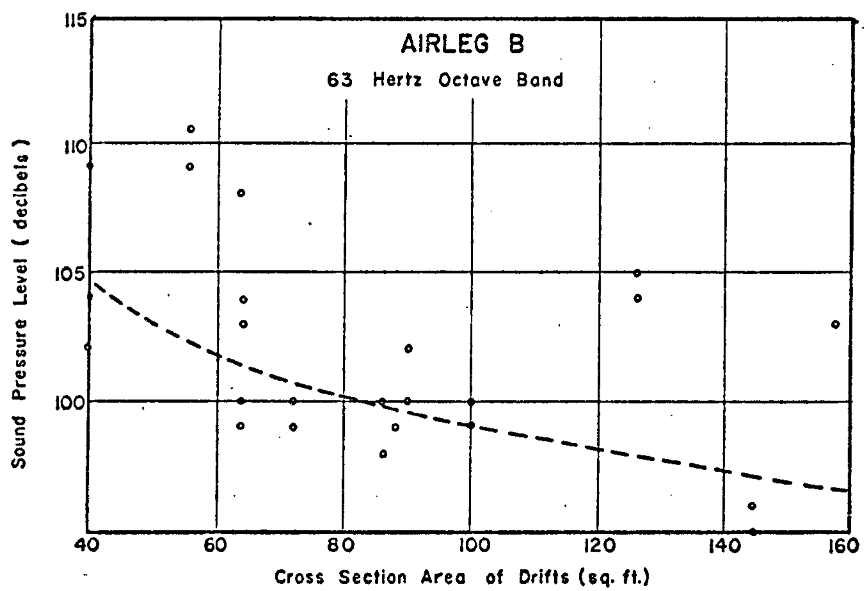
Sound Pressure Level (decibels)
Cross Section Area of Drifts (sq. ft.)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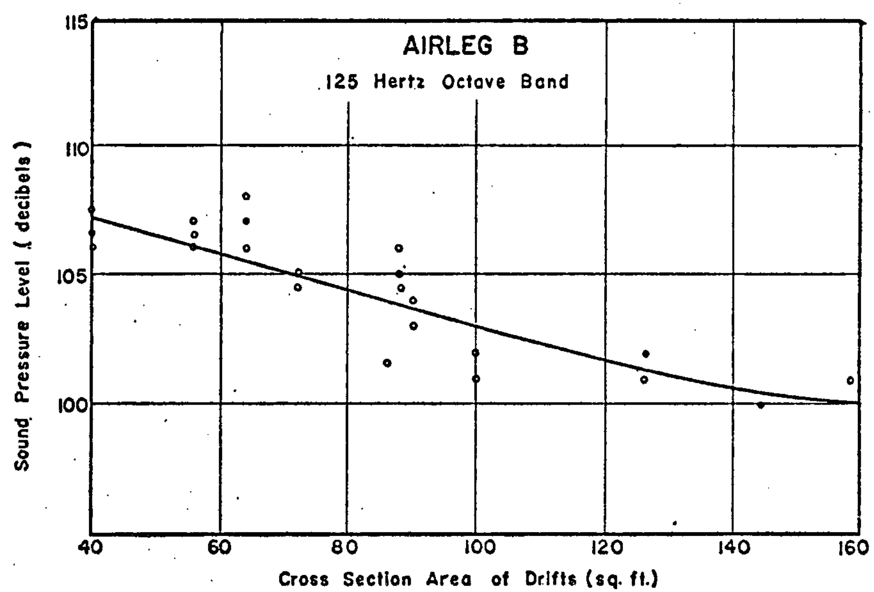
63 Hertz Octave Band
Sound Pressure Level (decibels)
Cross Section Area of Drifts (sq. ft.)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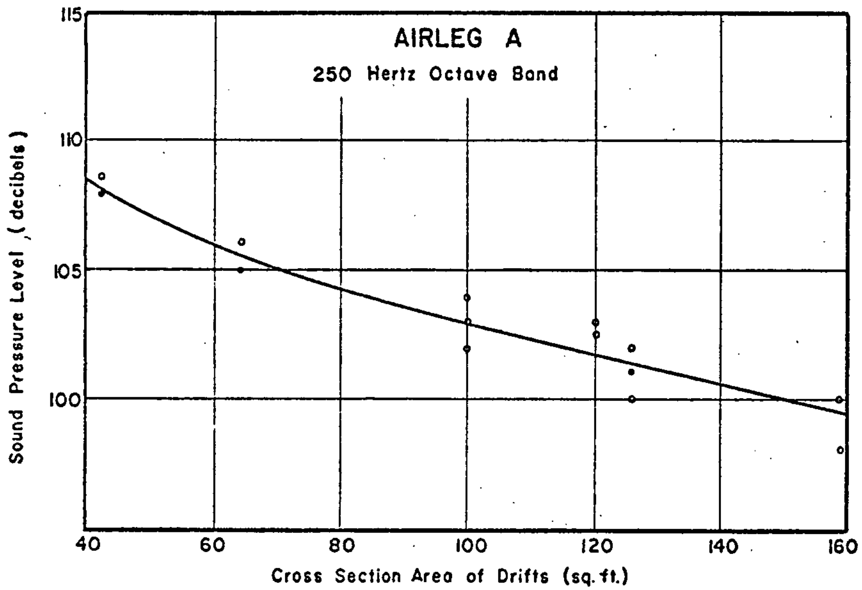
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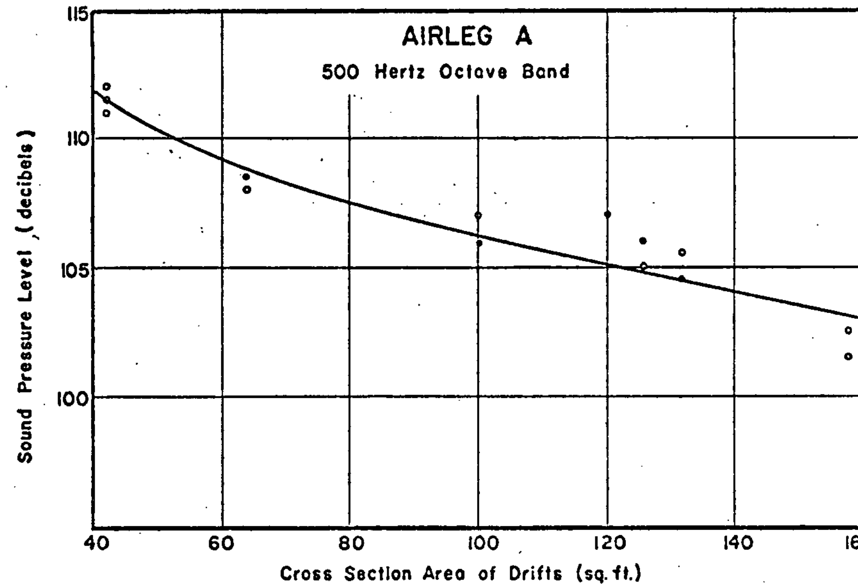
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Sound Pressure Level (decibels)
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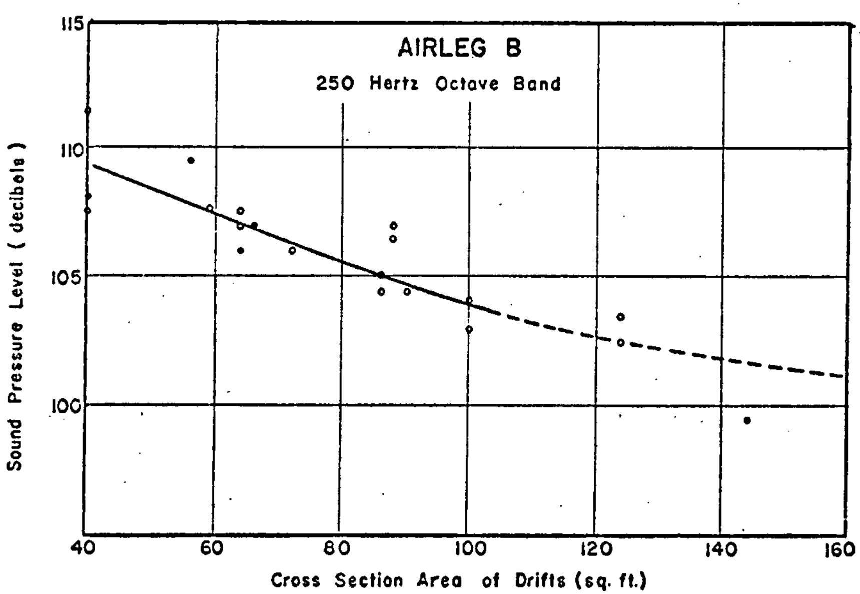
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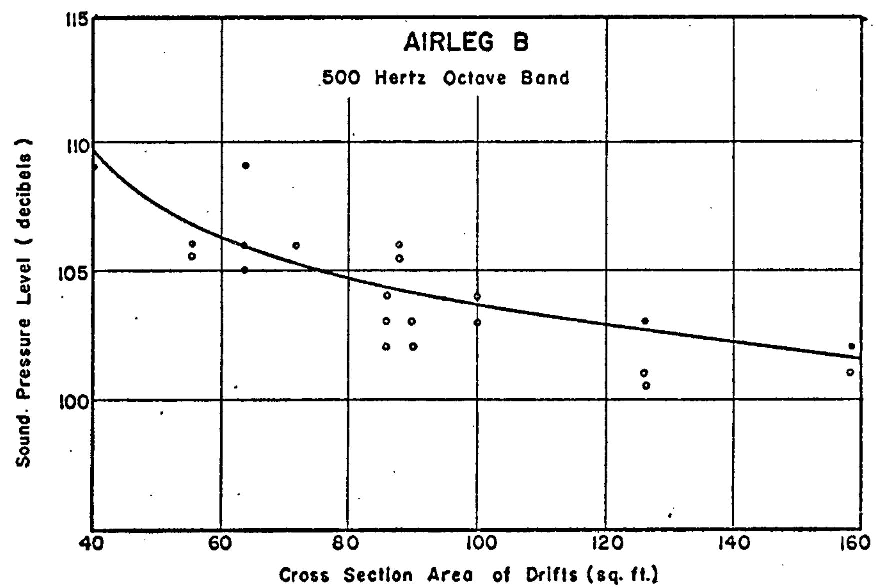
Sound Pressure Level (decibels)
Cross Section Area of Drifts (sq. ft.)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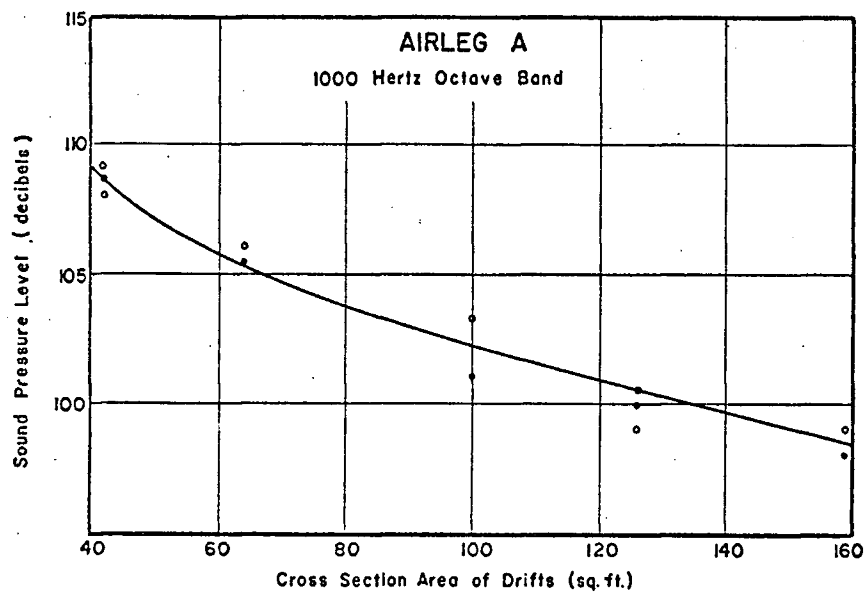
Sound Pressure Level (decibels)
Cross Section Area of Drifts (sq. ft.)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1000 Hertz Octave Band
Sound Pressure Level (decibels)
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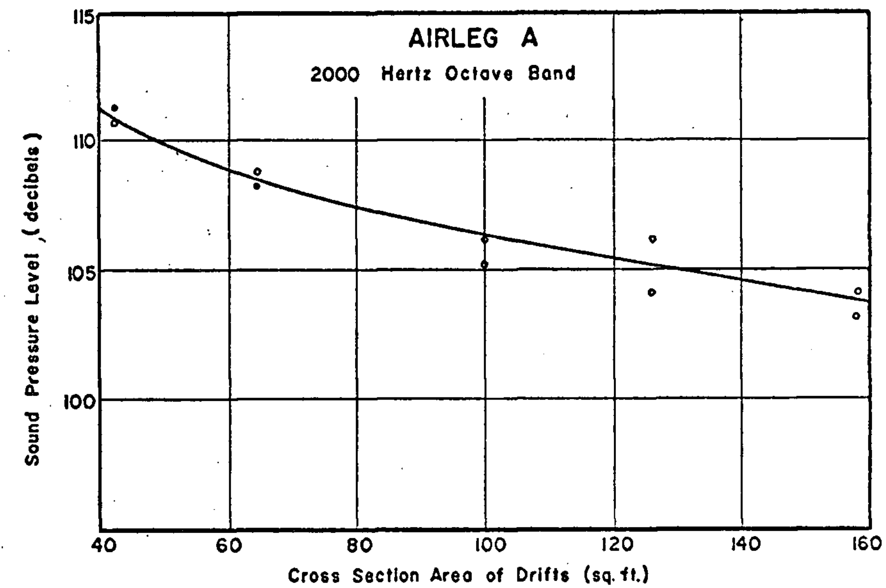
110
105
100
40
60
80
100
120
140
160
Cross Section Area of Drifts (sq. ft.)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2000 Hertz Octave Band
Sound Pressure Level (decibels)
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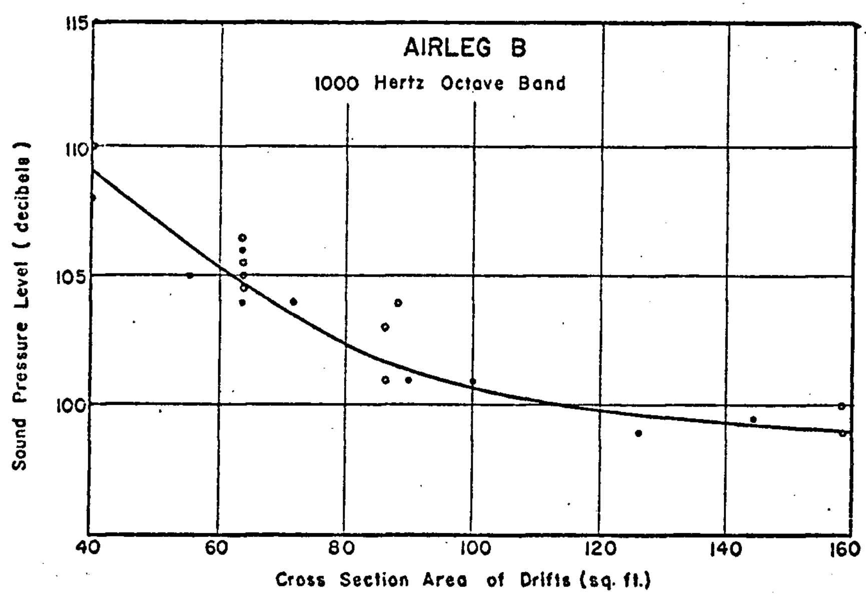
100
40
60
80
100
120
140
160
Cross Section Area of Drifts (sq. ft.)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1000 Hertz Octave Band
Sound Pressure Level (decibels)
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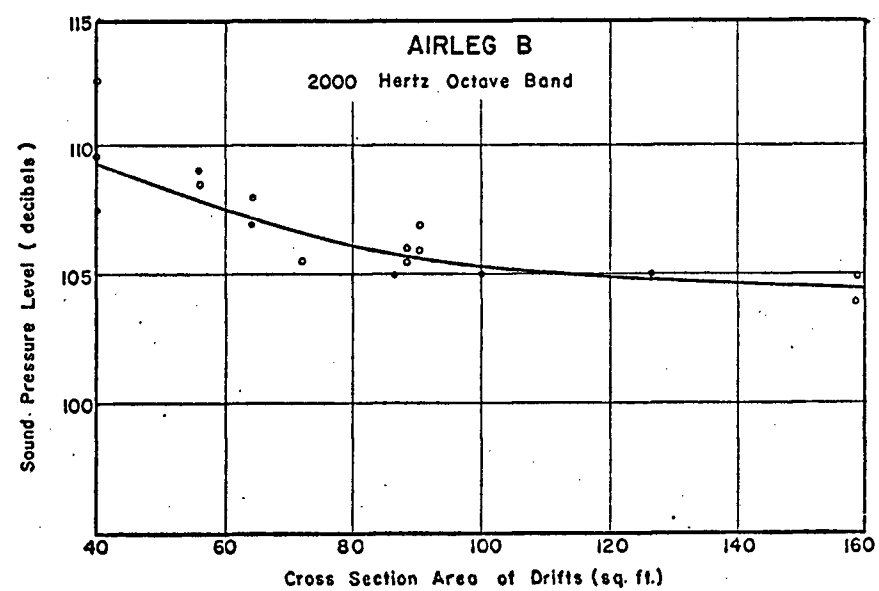
110
105
100
40
60
80
100
120
140
160
Cross Section Area of Drifts (sq. ft.)


AIRLEG B
2000 Hertz Octave Band
Sound Pressure Level (decibels)
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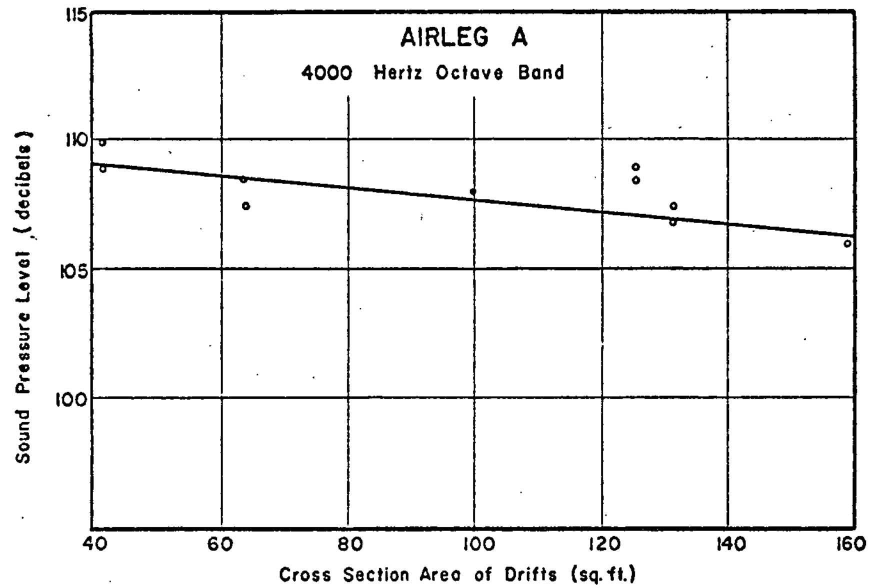
110
105
100
40
60
80
100
120
140
160
Cross Section Area of Drifts (sq. ft.)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4000 Hertz Octave Band
Sound Pressure Level (decibels)
Cross Section Area of Drifts (sq. ft.)
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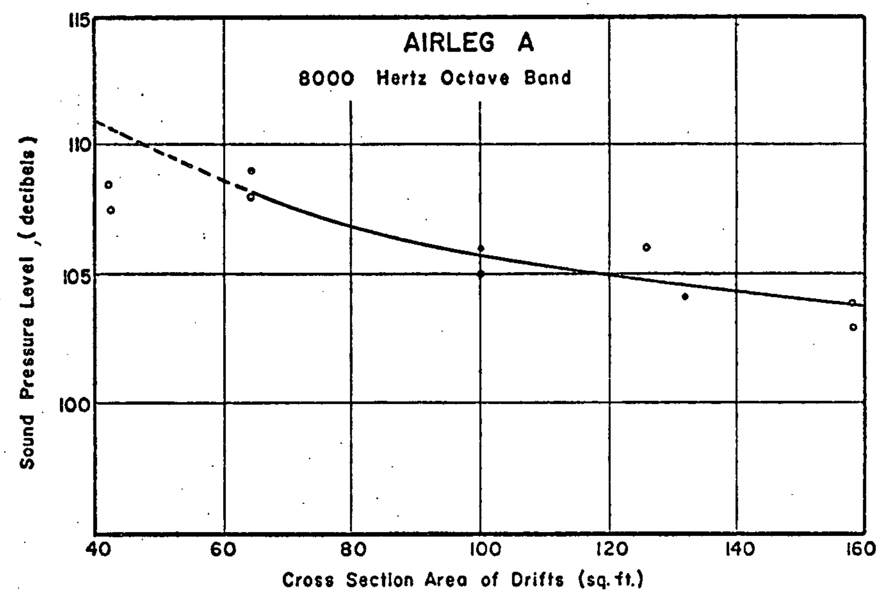
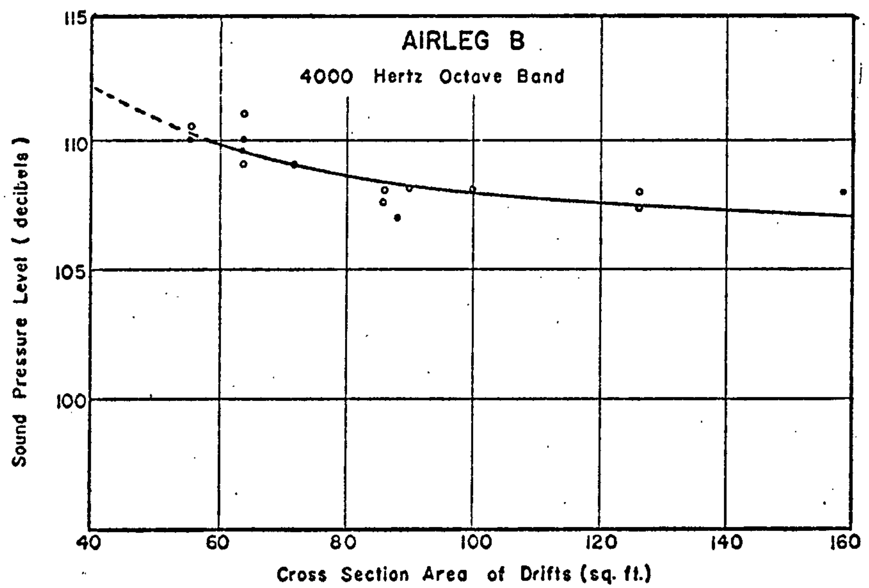
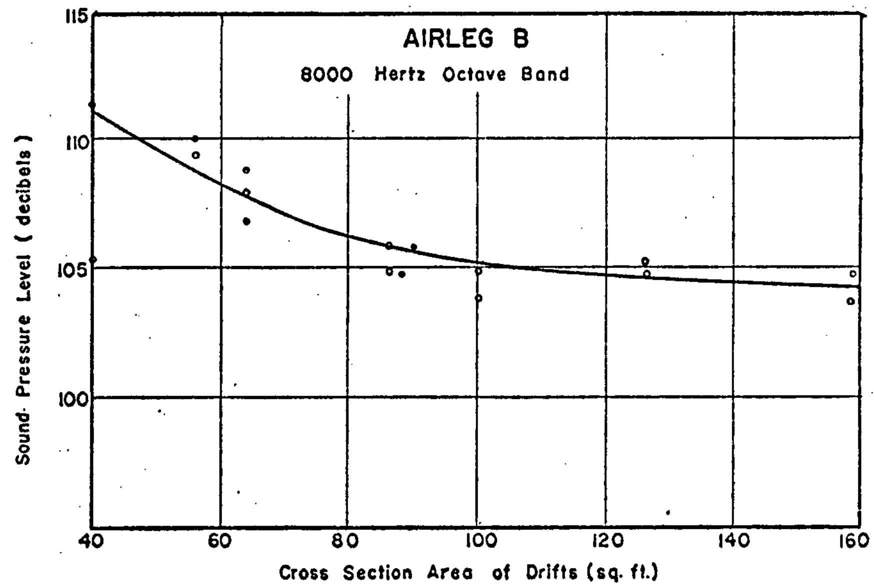
105
110
115
40
60
80
100
120
140
160


AIRLEG A
8000 Hertz Octave Band
Sound Pressure Level (decibels)
Cross Section Area of Drifts (sq. ft.)
100
105
110
115
40
60
80
100
120
140
160


AIRLEG B
4000 Hertz Octave Band
Sound Pressure Level (decibels)
Cross Section Area of Drifts (sq. ft.)
100
105
110
115
40
60
80
100
120
140
160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8000 Hertz Octave Band
Sound Pressure Level (decibels)
Cross Section Area of Drifts (sq. ft.)
100
105
110
115
40
60
80
100
120
140
160

APPENDIX III

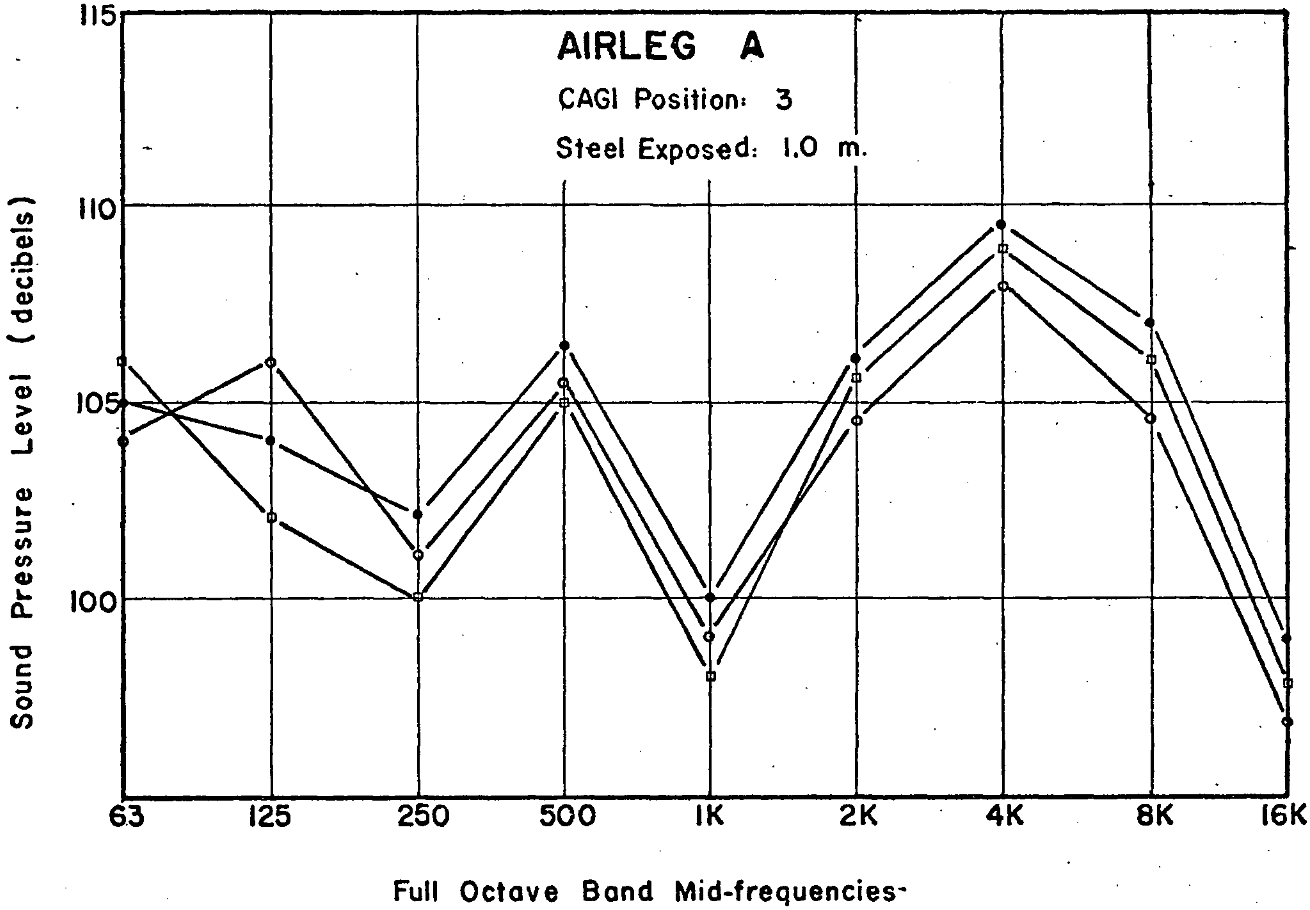
THE EFFECT OF OPERATING PRESSURE ON THE SOUND PRESSURE LEVELS

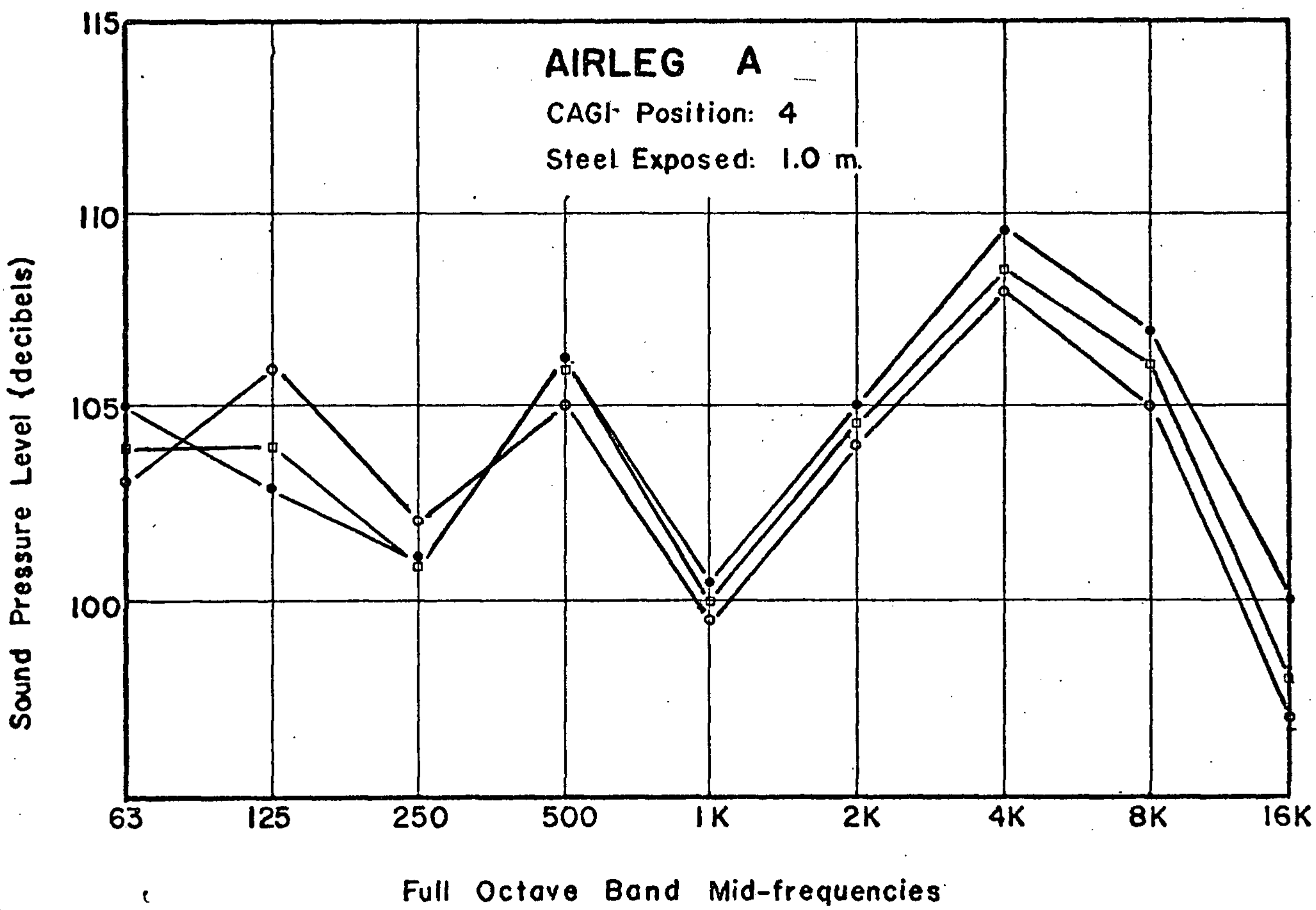
1. All observations were made in the 10' x 10' drift at Anaconda Britannia Mines.

2. The data points are ∘ 70 psi dynamic air pressure
   ▫ 80 psi
   • 90 psi

3. The overall SPL's for the graphs which follow are:

Dynamic Air Pressure (psi)	Graph A	Graph B	Graph C
70	114	112	103
80	114.5	113.5	110.5
90	114.5	114	112
70	113.5	113	110.5
80	114	114	111
90	115	115	112.5


AIRLEG A
CAGI Position: 3
Steel Exposed: 1.0 m.
115
110
105
100
Sound Pressure Level (decibels)
63
125
250
500
1K
2K
4K
8K
16K
Full Octave Band Mid-frequencies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CAGI Position: 4
Steel Exposed: 1.0 m.
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Sound Pressure Level (decibels)
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125
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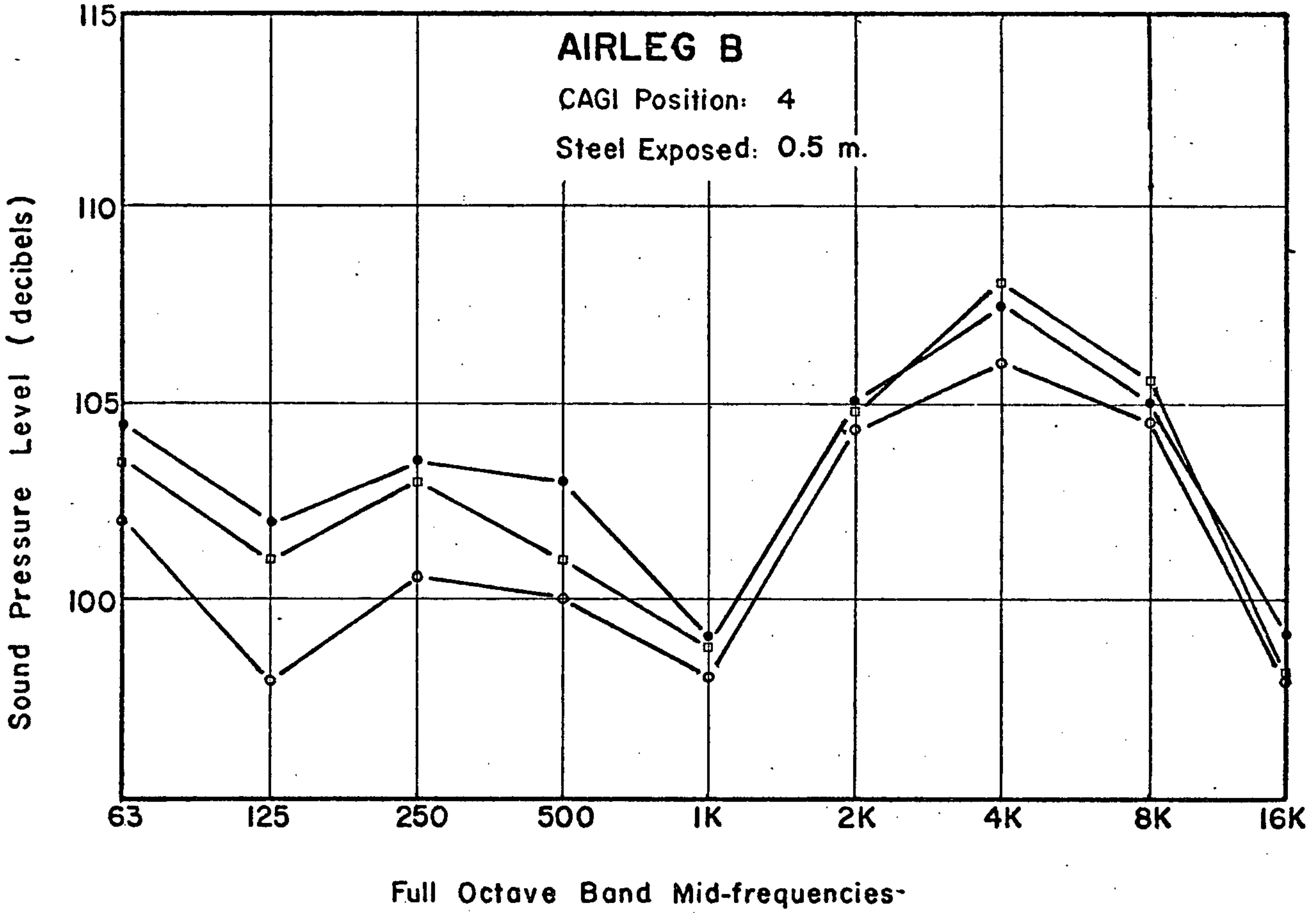
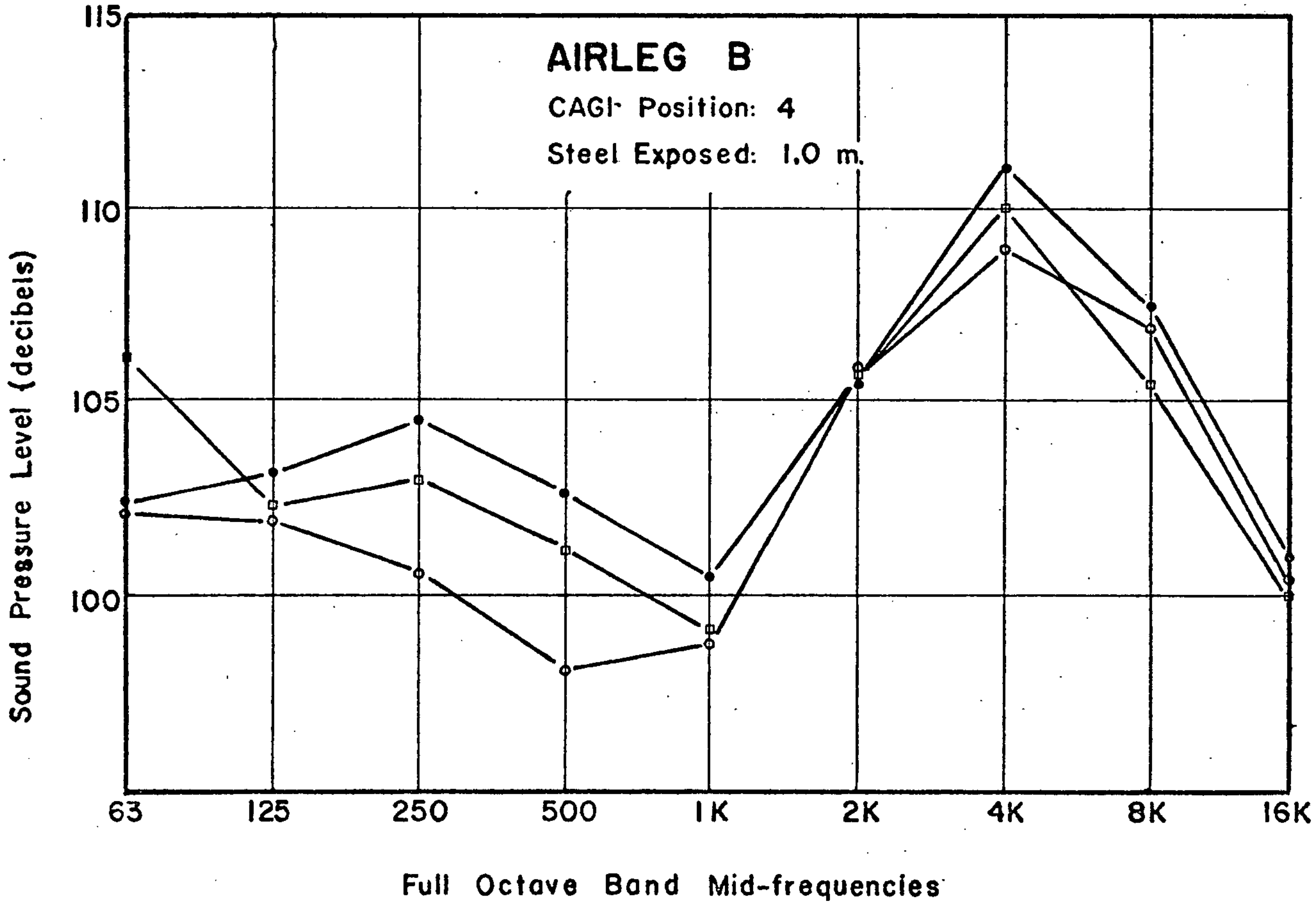
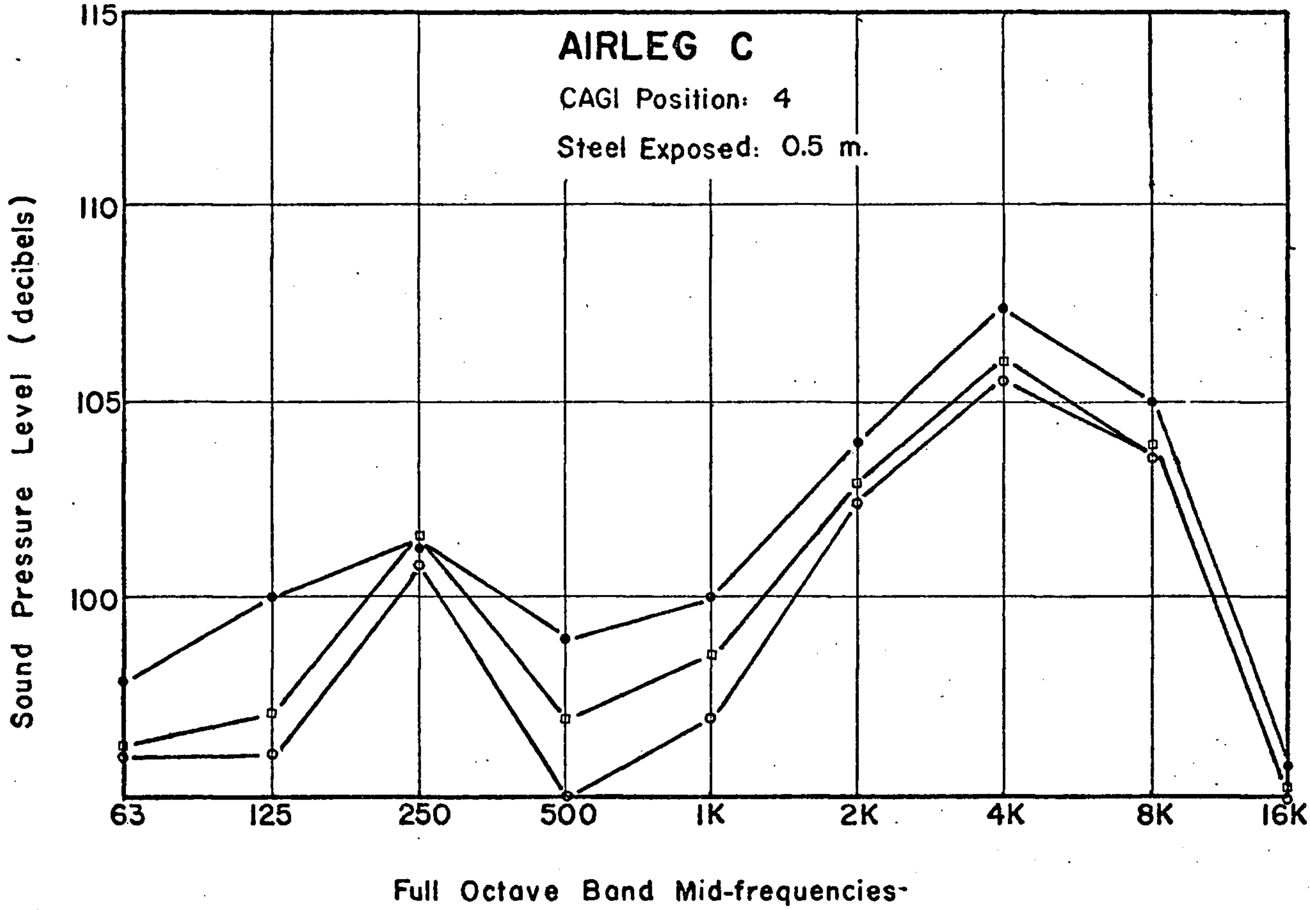
500
1K
2K
4K
8K
16K
Full Octave Band Mid-frequencies


AIRLEG B
CAGI Position: 4
Steel Exposed: 0.5 m.
Sound Pressure Level (decibels)
115
110
105
100
63
125
250
500
1K
2K
4K
8K
16K
Full Octave Band Mid-frequencies


AIRLEG B
CAGI Position: 4
Steel Exposed: 1.0 m.
Sound Pressure Level (decibels)
115
110
105
100
63
125
250
500
1K
2K
4K
8K
16K
Full Octave Band Mid-frequencies


AIRLEG C
CAGI Position: 4
Steel Exposed: 0.5 m.
Sound Pressure Level (decibels)
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100
63
125
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500
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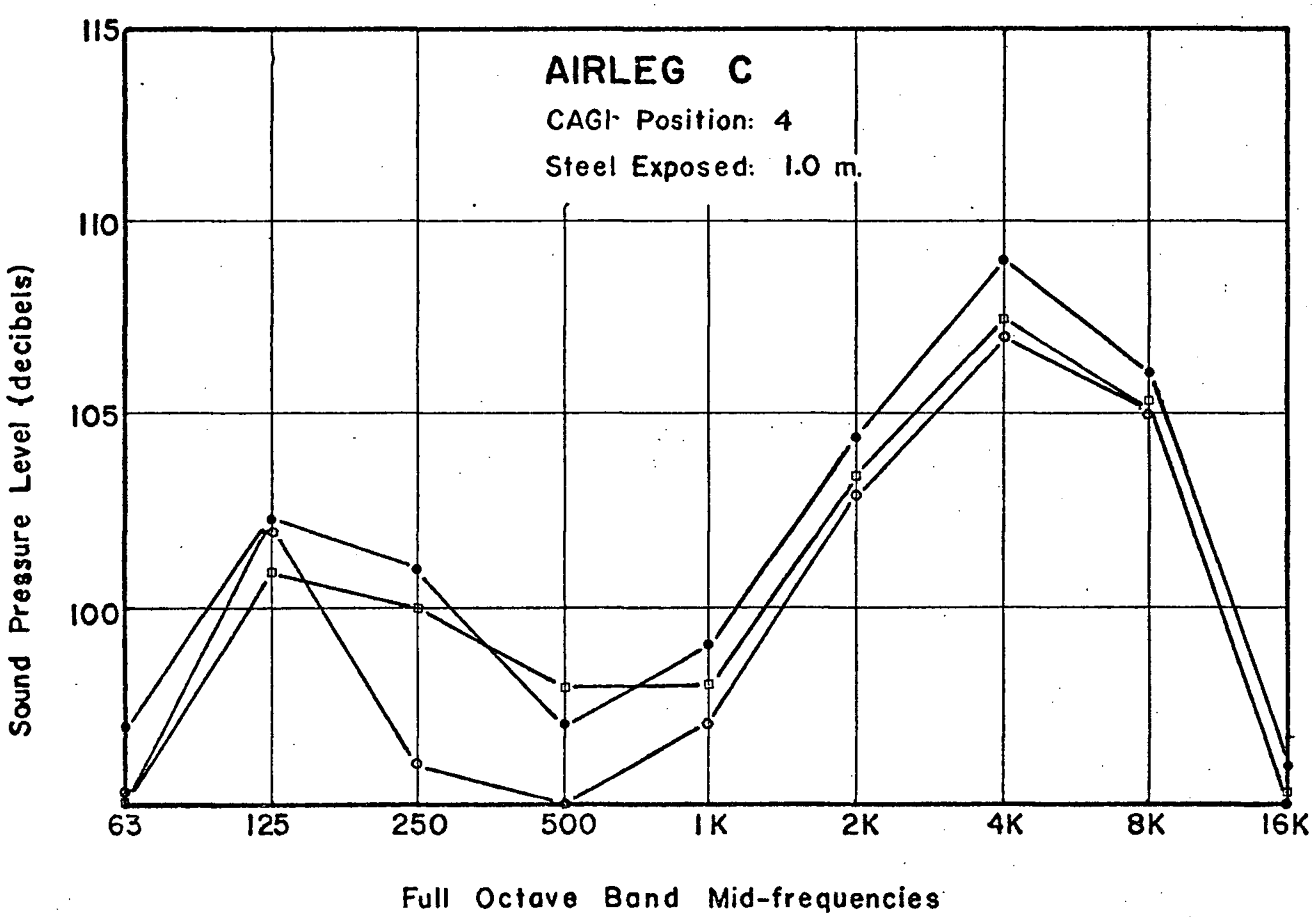
2K
4K
8K
16K
Full Octave Band Mid-frequencies


AIRLEG C
CAGI Position: 4
Steel Exposed: 1.0 m.
Sound Pressure Level (decibels)
115
110
105
100
63
125
250
500
1K
2K
4K
8K
16K
Full Octave Band Mid-frequencies