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Noise Reduction of a Pneumatic Rock Drill

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Noise Reduction of a Pneumatic Rock Drill

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NOISE REDUCTION OF A PNEUMATIC ROCK DRILL

by

Aarne Visnapuu [1] and James W. Jensen [1]

ABSTRACT

Experimental modifications have been made by the Bureau of Mines on standard pneumatic rock drills to reduce the noise of the air exhaust, drill steel resonance noise, and noise radiated by the drill body. A close-fitting case and muffler around the drill body, consisting of a metallic honeycomb skeleton filled with viscoelastic absorber on the inside and a durable outer shell, provide both exhaust and drill body noise muffling and absorption. Drill steel resonance noise is reduced by a constrained-layer treatment consisting of a tubular metal cover bonded to the ouside of the rod by a viscoelastic filler. Damping alloy components have been developed to reduce metallic resonance noise. Combined, these modifications have reduced the drilling noise level in granite from 115 dbA to 97 dbA. Data are presented on the individual and combined effects of these modifications on drilling noise and performance.

INTRODUCTION

The pneumatic rock drill is one of the most severe noise sources in the mining industry. A 1971 environmental noise survey in 21 coal mines by the Bureau of Mines revealed that pneumatic rock drilling for the installation of roof bolts exposed individuals to the highest sound levels observed, a range of 104 to 118 dbA (7).[2 3] The pneumatic drill is used worldwide and in hard rock mining, comparable noise levels are common.

The Federal Coal Mine Health and Safety Act of 1969, Public Law 91-173, states in section 206 that "on and after the operative date of this title the standards on noise prescribed under the Walsh-Healey Public Contracts Act... shall be applicable to each coal mine and each operator of such mine shall comply with them." The act further stipulates that "in meeting such standards under this (noise) section, the operator shall not require the use of any

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[1] Research physicist.

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

[3] Noise levels given in dbA are measured on a weighted scale that simulates response of the human ear.

protective device or system, including personal devices, which the Secretary or his authorized representative finds to be hazardous or to cause a hazard to the miners in such mine." Hence, the act is considered to be restrictive in the possible use of ear muffs and plugs to provide ear protection, and emphasis is placed on the reduction of operational noise to acceptable levels.

As part of the Bureau of Mines research program on coal mine noise problems under the act, the Rolla Metallurgy Research Center was assigned the task of modifying the rock drill to reduce its noise level to acceptable limits, as shown in table 1. The approach chosen to produce the prototype quiet drill was to start with existing drills and make such modifications and component substitutions as would be possible in a short period of time. Use of noise-suppressing materials, damping alloys, and innovative approaches and methods was to be stressed in fabrication of external covers and muffling devices and in modifying the internal drill mechanism.

TABLE 1. - Permissible noise exposure under the Walsh-Healey Public Contracts Act[1]

Sound level, dbA	Duration per day, hours	Sound level, dbA	Duration per day, hours
90	8	102	1-1/2
92	6	105	1
95	4	110	1/2
97	3	115	1/4
100	2	>115	0

[1]When the daily noise exposure is composed of 2 or more periods of different levels, their combined effect is to be used, rather than the individual effect of each. If the sum of the fractions C1/T1 + C2/T2 + ... + Cn/Tn exceeds unity, then the mixed exposure is considered to exceed the limit value. (Cn indicates the total time of exposure at a specific noise level, and Tn indicates the total time of exposure permitted at that level.)

Functional performance requirements and operator acceptance were major considerations in planning and making the modifications. From a functional standpoint, the prototype drill should operate without serious loss of drilling efficiency; it should neither overheat nor ice up to a point of reduced efficiency or complete stoppage. It should be rugged and durable enough to take the stresses of normal use without breakage and special maintenance. From an operator's standpoint, the added weight of modifications should be kept to a minimum. Projecting mufflers and other devices that could catch or break, or be broken off intentionally, should be avoided, there should be no interference with operating controls, and the modified drill must withstand the same severe treatment as the standard drill.

An Atlas-Copco BBC-16[4] feed-leg drill was selected for development of the prototype drill. This drill can be converted to a muffled version, the BBC-17, by substitution of a patented silencing exhaust cylinder for the standard exhaust cylinder. This releases the exhaust air through a ring of small holes into an expansion chamber, which according to the manufacturer reduces the exhaust noise by 75 percent. The drill weighs 59 pounds and has a piston diameter of 2.75 inches and a stroke of 2.125 inches. At an air pressure of 85 psi, the BBC-16 is rated at 2,300 impacts per minute, and the BBC-17 at 2,200.

This research and other earlier studies (2, 8) show that drilling noise is the sum of three major noise sources: Exhaust, drill steel resonance, and drill machinery noise. Exhaust noise is normally the most severe and is produced by the high-velocity cyclic release of spent compressed air to the atmosphere. Mixing of the high-velocity air with the relatively still atmosphere gives rise to broadband random noise, and the cyclic nature gives it the characteristic staccato sound. Drill steel noise results from the transverse and longitudinal resonance vibrations excited by the piston impacts on the steel shank. Drill machinery noise is produced by the metallic resonance excited by the piston striking the steel, and the moving and impacting parts inside the drill, and is then radiated to the surroundings by the drill body. It is the least offensive of the three noises and becomes apparent only when the exhaust noise and drill steel noise have been reduced to low levels.

Exhaust noise can be reduced two ways: By hoses to carry the expelled air away from the drilling site, and by muffling. Hoses are effective and have been used with more or less stationary equipment. In mining operations hand-held and feed-leg drills require freedom of movement in limited space, making weight and mobility critical factors. Design of noise reduction into the drill itself is most desirable. Mufflers, to be used effectively, should reduce exhaust noise by 20 db or more and should be lightweight, compact, durable, and not prone to freezing during operations. Mufflers of expansion (1) and reactive (4) types have been investigated for use on pneumatic drills. In this work the reactive type was selected for prototype development because it provided better noise reduction and design flexibility. Using the criterion that the method of suppressing the drill steel resonance noise should be an integral part of the steel, constrained-layer damping was selected as offering the best method for reducing noise from this source. For reducing drill body noise, two innovations were investigated. One was the use of a combination muffler cover, and the other was substitution of energy-absorbing-alloy components where possible to damp impact shock waves.

EXPERIMENTAL WORK

Experimental Facilities

Experimental drilling was conducted at two locations. The indoor site was in a large warehouse building that also housed the laboratory and noise

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[4]Reference to specific trade names does not imply endorsement by the Bureau of Mines.

analysis instrumentation. Granite blocks, approximately 3 feet on a side, were used as the drilling medium. The outdoor site was a level, cleared area approximately 100 feet from the warehouse. The granite block was set in the ground with the upper surface flush with the ground. Compressed air was provided from a remote compressor, and a ballast tank was installed at the test site to aid in pressure regulation.

The sound laboratory was instrumented with a portable sound level survey meter, a sound and vibration analyzer with graphic level recorder, sound level calibrators, an impact noise analyzer, a real-time spectrum analyzer, a digital integrator with X-Y plotter and dual-trace display oscilloscope, laboratory and portable tape recorders, and other accessories.

Drilling Noise Measurements

Most of the noise measurements involved in developing the prototype drill were taken at the indoor drilling site and at only 70-psi air pressure due to limitations in compressor capacity. The drill was operated in a vertical position into a granite block resting on the floor. The operator was positioned on a wooden platform above the rock and behind the drill, which was located over a cutout section on one side of the platform. The microphone pickup was located on the clear side of the platform and normally was positioned 1 meter from the geometric center of the drill. Normally, the front or exhaust port side of the drill faced the microphone, but the drill could be rotated so that any portion of the body pointed toward the microphone. The drills had two exhaust ports that directed the airblast to the sides, so the air did not blow directly on the microphone. The microphone could also be positioned above the drill. Each test was tape-recorded, and simultaneously a linear real-time spectral analysis was performed on the incoming signal. After each test the stored real-time spectrum was plotted on an X-Y recorder to provide the initial analysis of the test. Further analysis, such as 1/3-octave band, was made from the tape. The same procedure was used for vibration analysis by accelerometers.

Drilling noise measurements at the outdoor location were conducted at 90-psi air pressure according to the CAGI-PNEUROP[5] test code for pneumatic rock drills (5). The noise levels were measured at a distance of 1 meter in four directions horizontally from the geometric center of the drill and also at a position 1 meter above the geometric center of the drill. Data analysis was the same as for the indoor tests, except that no real-time spectral analysis was made during the test.

Drill Performance Measurements

The effects of the various drill and drill steel modifications on drill performance were evaluated on the basis of penetration rates in granite. Penetration rates were determined from vertical drilling distances for fixed time periods under specific thrust and operating pressure. The thrust was supplied

[5]Compressed Air and Gas Institute-European Committee of Manufacturers of Compressed Air Equipment.

by deadweight attachments to the drill. Drilling performance of steels with equal bit diameters was evaluated on the basis of penetration rates; performance of steels of different bit diameters was evaluated on the basis of granite removal rates. The latter are proportional to the rate of energy expended in removing the rock and offer a more suitable measure of drilling efficiency because the differences in bit diameters are compensated for.

Special Noise Measurements

To measure the specific noise components of the drill, special methods were devised. To isolate the noise from the drill mechanism alone, a short stub of drill steel, with the exposed section below the collar enclosed in thick-walled rubber tubing and sound-absorbent foam, was used to eliminate the drill steel noise. The stub was inserted into a lubricated, close-fitting hole in a large rubber block, and the drill was operated in the normal way for brief periods. This eliminated virtually all the drill steel noise. Addition of exhaust hoses eliminated the exhaust noise and permitted the drill machine noise radiated from the case to be measured and analyzed.

To measure and analyze drill steel noise, the drill body was encased in an absorber-barrier cover and the exhaust air was carried away by hoses.

Exhaust noise levels were for three drill configurations: (1) The drill was operated free running without steel in a suspended position; (2) to determine the exhaust noise level under load, the drill was operated with the stub on the rubber block so that the steel resonance noise was eliminated; and (3) the exhaust noise level was calculated from the difference in noise levels when drilling in granite without and with exhaust hoses.

DRILLING NOISE LEVELS

Table 2 summarizes representative noise levels observed in the laboratory when drilling in granite with the unmodified Atlas-Copco BBC-16 and 17 drills using standard 4-foot integral-chisel-bit and 4-foot detachable-bit rope-thread steels. The data show a variation from a high sound pressure level of 121 db to a low of 112 db at the 70-psi operating pressure. Variation in the corresponding A-weighted noise level was from 115 to 108 dbA. The noise levels of the drill and steel combinations of table 1 are shown in 1/3-octave bands in figure 1. From the curves in figure 1 it can be seen that the BBC-17 drill with the built-in muffler is considerably quieter than the BBC-16, and that most of the noise reduction is at the lower frequencies. Also it is apparent that the detachable-bit rope-thread steel is quieter than the integral-chisel-bit steel, with most of the noise reduction at higher frequencies.

The reduction in noise in changing from the BBC-16 drill with the chisel-bit steel to the BBC-17 with the rope-thread steel is representative of what can be achieved by judicious selection of available standard equipment. While the reduction in noise is significant, the lowest level is still extremely high and the drill and steel combination that produced it may not be practical

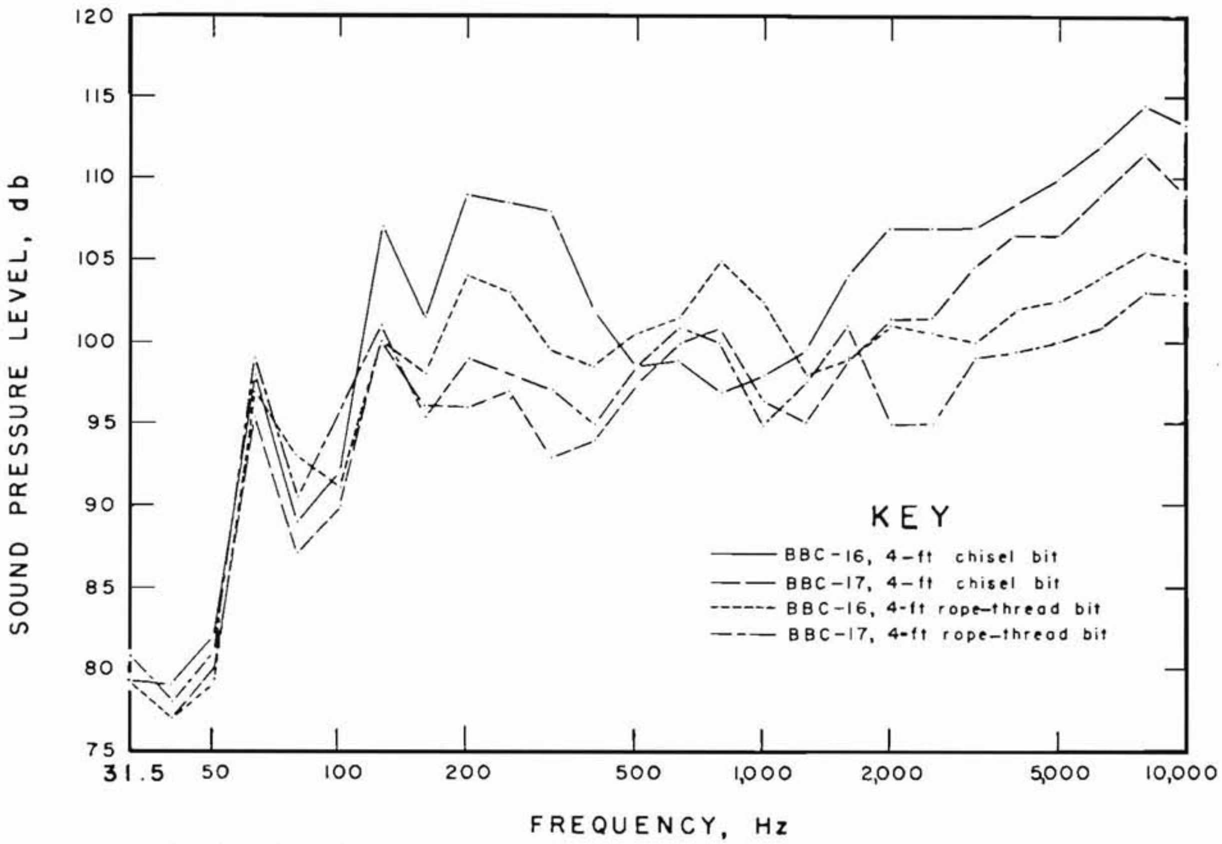

FIGURE 1. - One-third-octave-band noise levels for standard drills and steels.

in actual use. It is evident that noise levels of these typical drill and steel combinations need further reduction.

TABLE 2. - Drilling noise levels in granite, standard BBC-16 and BBC-17 drills, 4-ft integral chisel bit and 4-ft detachable-bit rope-thread steels, indoor drilling site, 70-psi air pressure

Drill	Steel	Noise level db	Noise level dbA
BBC-16....................	4-ft chisel................	121	115
BBC-17....................	.....do....................	117	112.5
BBC-16....................	4-ft rope..................	116	113.5
BBC-17....................	.....do....................	112	108

Exhaust noise of the BBC-16 ranged from 116 to 120 db (112 to 114 dbA). The corresponding noise levels for the BBC-17 were 108 to 112 db (107 to 110 dbA), confirming that the integral muffler conversion is effective in reducing the exhaust noise level of the BBC-16 drill as advertised.

The integral-chisel-bit steels produced a sound pressure level of 115 to 117 db (112 to 113 dbA). Tones at the frequencies of transverse vibrations of the steel dominated the sound frequency spectrum, as shown in the narrow-band, constant-bandwidth plot of the noise spectrum in figure 2. The noise of the detachable-bit rope-thread steels was not as intense at 107 to 109 db (105 to

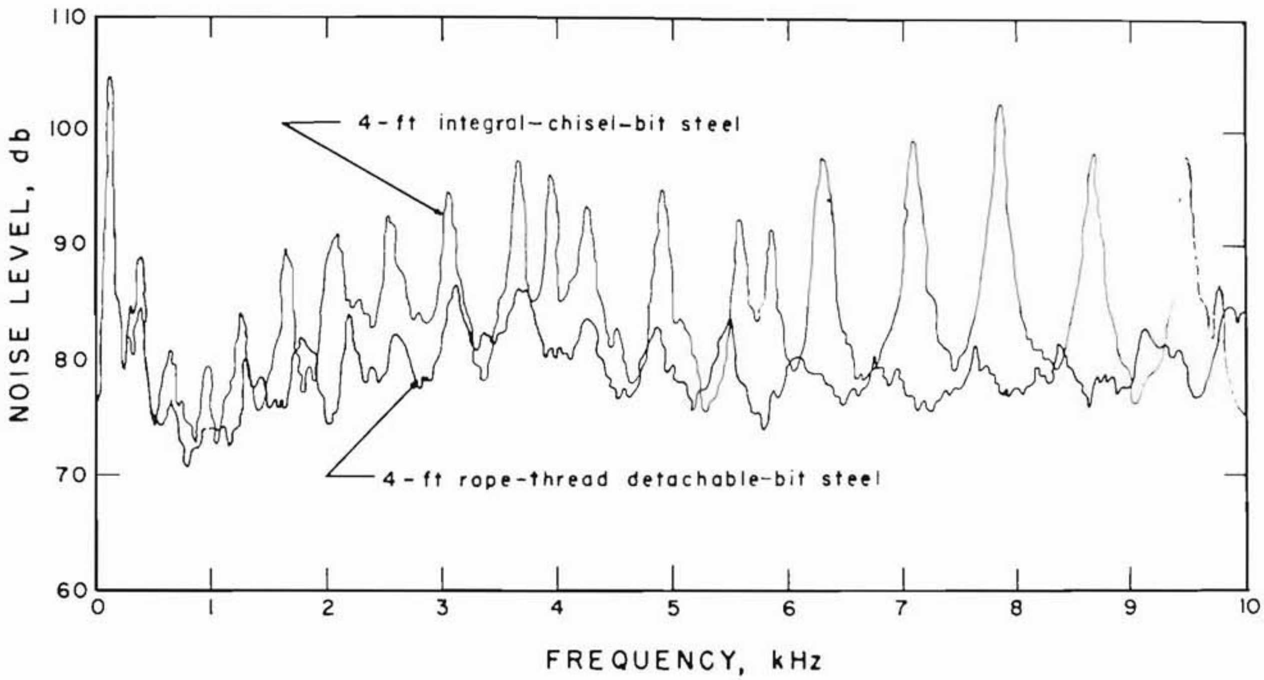

FIGURE 2. - Noise spectrum of standard 4-ft drill steels.

106 dbA) and was muted, as indicated by the absence of sharp transverse resonance peaks in the lower curve of figure 2.

Noise radiated by the drill body was observed to be considerably lower, ranging from 101 to 105 db (96 to 100 dbA).

MODIFICATIONS AND INNOVATIONS

It is apparent that successful sound reduction can be realized only if the noise contribution from each source is reduced to a level considerably below that of the final total level, because of the way sound levels combine (10). Ultimately even the drill body noise must be reduced to produce a prototype drill that is "quiet" in operation.

Exhaust

A study to compare the merits of expansion and reactive types of mufflers was made to determine which should be incorporated into the prototype. The expansion muffler was based on the work of Barth (1), modified for adaptation to the BBC-17 drill. The reactive muffler was of the Pi type[6] made according to the design data of Chester, DeWoody, and Miller (4). The test results, summarized in table 3, showed that the reactive type was more effective in reducing the exhaust noise from this drill, apparently because the shape of the drill did not permit construction of an expansion chamber cavity as long

[6]A Pi-type reactive muffler consists of two expansion chambers with a connecting pipe.

as in the original design, whereas with the reactive muffler the shape of the cavity was not a factor as long as essential volume was provided. Based on these test results, the reactive-type muffler was selected for the prototype.

TABLE 3. - Comparison exhaust noise from BBC-17 drill operated on rubber pads with resonant chamber and Pi-type muffler under same experimental cover, 70-psi air pressure

Muffler type under cover	Noise level	
	db	dbA
No muffler or cover..................................	112	110
Resonant chamber..................................	109	99
Pi-type reactive..................................	98	95

A muffler cover was designed in which the exhaust from the drill vents first into an open air space between the drill body and cover and then to the atmosphere. It was decided to start with the BBC-17 drill to take advantage of the lower exhaust noise level of this machine. Advantages of adding this type of muffler cover to the BBC-17 are (1) the outer surface can be made to conform to the general shape of the drill to avoid excessive bulk and protrusions, (2) the design maximizes the air volume of the muffler, (3) contact of cold expelled air with heated parts of the drill body would tend to counteract freezing of the exhaust and heating of the drill, (4) the muffler cover would act as an absorber for the drill body noise, and (5) it could be removed readily for drill servicing.

The cover enclosing the reactive muffler must meet a number of stringent requirements. It should be a good barrier, rigid and light weight, with the surfaces hard and durable to withstand rigors of rough usage. It should conform well to the mating surface of the drill to avoid noise sources from small air leaks and should be thermally conductive to help prevent icing on the inside.

Numerous materials and methods were tested to find the combination with the desired properties, and two covers were constructed according to the following design. A sheet of 1/2-inch-thick, flexible aluminum honeycomb with a foil thickness of 0.0019 inch was cut and shaped around the drill to which were attached clay buildups of the resonance chambers for the reactive mufflers. The honeycomb cells were then filled with viscoelastic material, either a liquid rubber, Devcon Flexane 80, or a pour-in-place syntactic polyurethane foam, Emerson and Cuming Eccofoam VIP. The outer surface of one cover was coated with commercial plastic aluminum, reinforced by expanded aluminum metal sheet. The other cover was coated with fiberglass built up to four reinforced layers. The first cover weighed 9.5 pounds, whereas the latter weighed 6 pounds. Mating surfaces of the two cover halves, and of the cover to the drill, were formed during pouring of the liquid filler, and made very tight joints when the cover halves were clamped together. Two exhaust tubes, 10 inches long and 5/8 inch ID, were installed at the lower front end of the case to complete the reactive muffler.

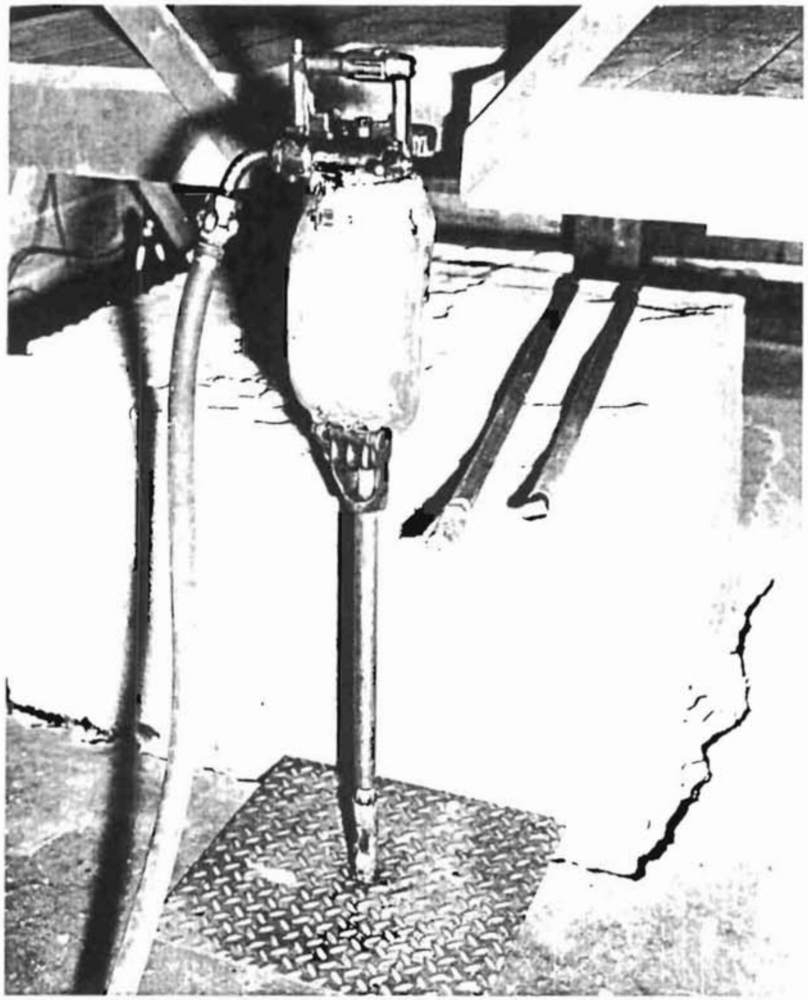

FIGURE 3. - Plastic-aluminum-outer-surface muffler cover on Atlas-Copco BBC-17 drill.

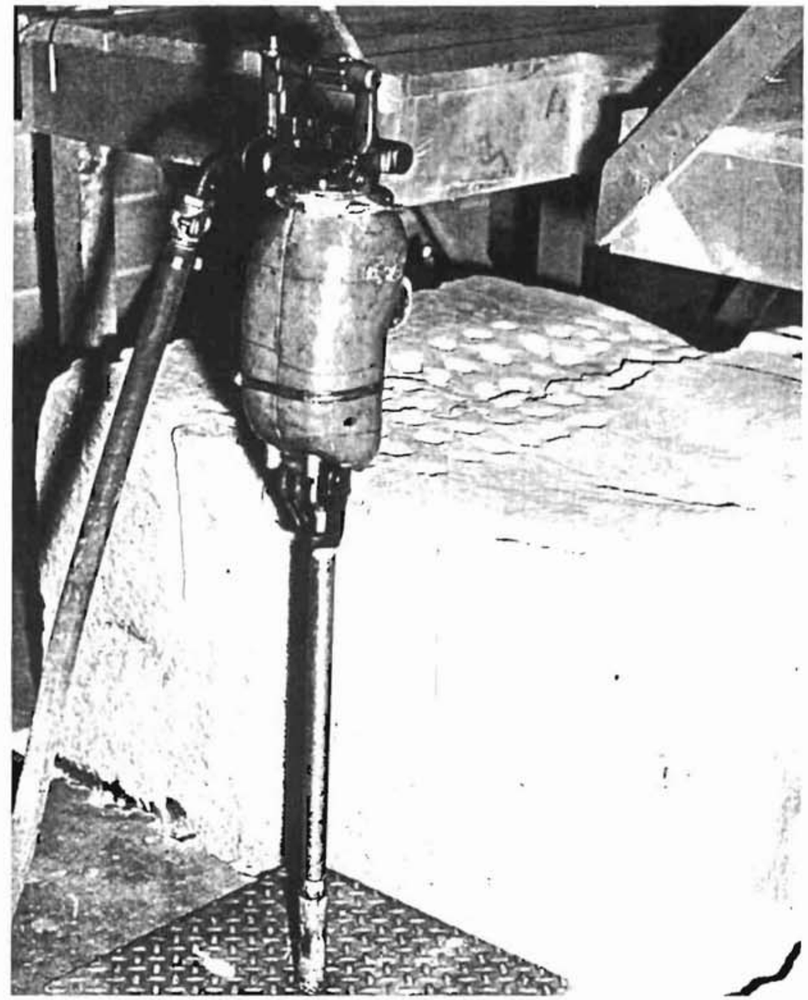

FIGURE 4. - Fiberglass-outer-surface muffler cover on Atlas-Copco BBC-17 drill.

Figure 3 shows the muffler cover made with the plastic aluminum outer surface, and figure 4 shows the muffler cover with the fiberglass outer surface. Figure 5 shows the aluminum-putty-surface muffler cover being attached to the drill.

Noise levels under free-running conditions with these two muffler covers are compared with levels with the bare BBC-16 and 17 drills in table 4.

TABLE 4. - Free-running-rock-drill noise levels, standard drills without and with muffler covers, indoor test site, 70-psi air pressure

Drill	Muffler cover	Noise level	
		db	dbA
BBC-16........	None..............................	120	115
BBC-17........	None..............................	112	109
BBC-17........	Urethane rubber-aluminum putty.....	96	92.5
BBC-17........	Syntactic polyurethane-fiberglass..	96	92

Drill Steel

The constrained-layer damping system developed in this research consists of a thin-walled tubular metal cover bonded to the drill steel by viscoelastic material that adheres well to both. This makes the noise suppression treatment into an integral part of the drill steel, not removable or detachable.[7] The bonding material must be strong enough to withstand the violent vibrations in drilling, yet compliant enough to absorb the steel vibrations without transmitting them to the outer cover.

Constrained-layer-damped steels were prepared by slipping the metal tube over the drill steel,

FIGURE 5. - Installation of plastic-aluminum-outer-surface muffler cover on Atlas-Copco BBC-17 drill.

[7] Jensen, J. W., and A. Visnapuu (assigned to U.S. Department of the Interior). Constrained Layer Damper and Noise Suppressor for a Rock Drill Steel. U.S. Pat. 3,842,942, Oct. 22, 1974.

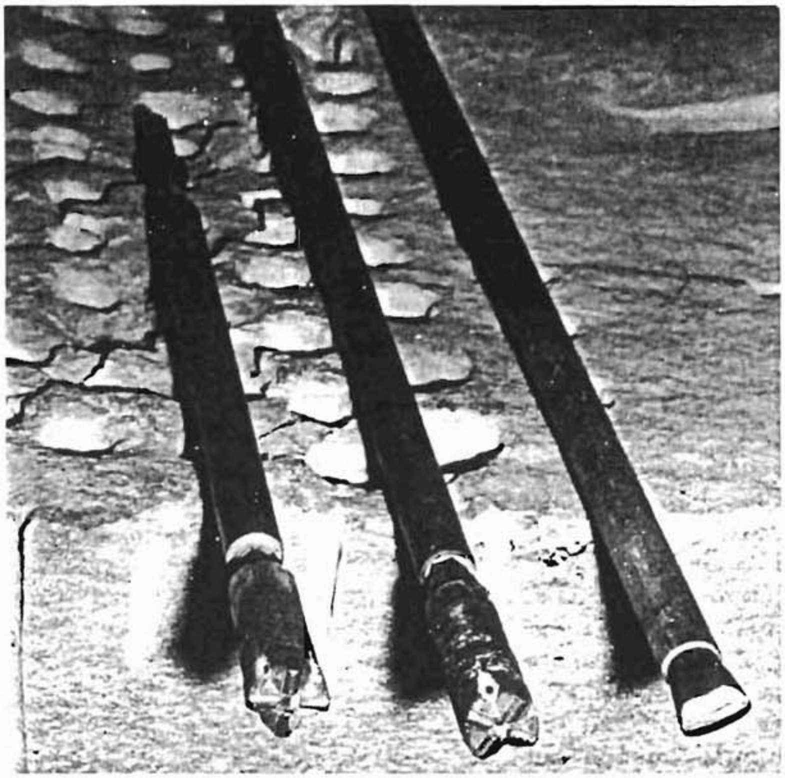

FIGURE 6. - Detachable-bit rope-thread and integral-chisel-bit drill steels with constrained-layer damping covers.

centering the steel in the tube, and then filling the space between the tube with liquid viscoelastic filler. After the filler cured, 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. Three finished constrained-layer-damped drill steels are shown in figure 6. Representative noise reduction resulting from constrained-layer treatment of chisel bit steels can be obtained from table 5 by comparing the data in columns 1 and 3, and 2 and 4, respectively.

TABLE 5. - Summary of drilling noise measurements, four rotation chucks in a new and a worn BBC-17 drill, no drill case cover, exhaust hoses attached, 70-psi air pressure

BBC-17 drill	Drill steel	Drilling medium	Average observed noise level, db and (dbA) with indicated rotation chuck			
			Steel (worn)	Steel (new)	Mn-Cu alloy	Sonoston alloy
Worn.......	4-ft steel chisel bit.	Granite...	116.5 (111.3)	115.0 (109.3)	113.8 (107.5)	113.2 (108.5)
New........	.....do...............	...do.....	117.3 (111.7)	113.2 (109.7)	114.7 (108.8)	112.7 (107.3)
Worn.......	4-ft damped chisel bit	...do.....	106.3 (102.2)	104.8 (101.5)	102.5 (99.3)	101.8 (98.3)
New........	.....do...............	...do.....	104.8 (100.2)	104.0 (99.8)	103.0 (98.5)	101.5 (97.7)
Worn.......	Tool stub.............	Rubber pad	100.5 (97.7)	97.2 (97.5)	98.2 (95.7)	97.7 (95.2)
New........	.....do...............	...do.....	102.0 (99.5)	99.7 (97.5)	99.0 (97.2)	97.7 (95.7)

Drill Body

Two methods were developed to suppress the drill body noise. One was the combination muffler cover that encased most of the drill body, and the other was energy-absorbing alloy components substituted where possible to damp impact shock waves.

Alloys composed of manganese and copper are noted for their ability to damp vibration, and in mechanical strength they are comparable to mild steel (6). The energy they absorb is converted to heat, and they lose their damping capacity above 125° C. Miller (8) substituted a manganese-copper piston in a drill and reduced the noise, but the piston expanded on heating and jammed, and also lost its damping capacity.

In this investigation the use of damping alloy substitute components such as the rotation chuck, air valve, back end, and piston was further explored.

The rotation chuck proved to be the most effective noise suppressor of the damping-alloy substitute components. Its function is to transmit rotation to the drill steel, and it encases the volume in which the piston strikes the end of the steel. Stresses on the chuck are not as severe as on the percussion train and other components in the drill, and substitution of a damping alloy can be tolerated. It was postulated that the damping alloy surrounding the piston-steel impact point would absorb much of the shock and noise transmitted to the drill case through the chuck.

Two experimental rotation chucks, one of Sonoston and the other of binary alloy (73 Mn-27 Cu), were cast and fabricated for the BBC-16 and 17 drills. The Sonoston alloy (3) was developed in England and consists (in percent) of 54 Mn, 37 Cu, 4.25 Al, 3 Fe, and 1.5 Ni. The ingot was machined roughly to the dimensions of the chuck and then was heattreated 4 hours at 450° C before final machining. The cast binary-alloy ingot was hot-forged to 3-inch-diameter rod from which the chuck was rough machined. Final aging was for 2 hours at 450° C before finish machining.

The effectiveness of the alloy chucks in reducing the drilling noise was compared in a series of drilling tests using each of the two alloy chucks, a new steel chuck, and a worn steel chuck in two BBC-17 drills; one drill was new, and the other was moderately worn. The drills were provided with exhaust hoses, but no covers were used on the drill bodies. They were operated at an air pressure of 70 psi and a constant thrust of 200 pounds. Standard and constrained-layer-damped steels and the steel stub were employed in the tests. Tests were made on a random schedule to give 3 tests in each of the 24 combinations of variables. The results are summarized in table 5, where the average sound pressure levels and A-scale noise levels for each experimental drilling condition are given. In figure 7 the 24 average A-scale values of noise levels in table 5 are plotted as bar graphs, arranged in two sets that group the observations for the new and used drills. Each bar is shaded to show the level observed for each of the three drill steels used. It is evident that the worn chuck is noisiest in all cases, and the prevailing trend in general is for the noise level to decrease stepwise as the worn chuck is

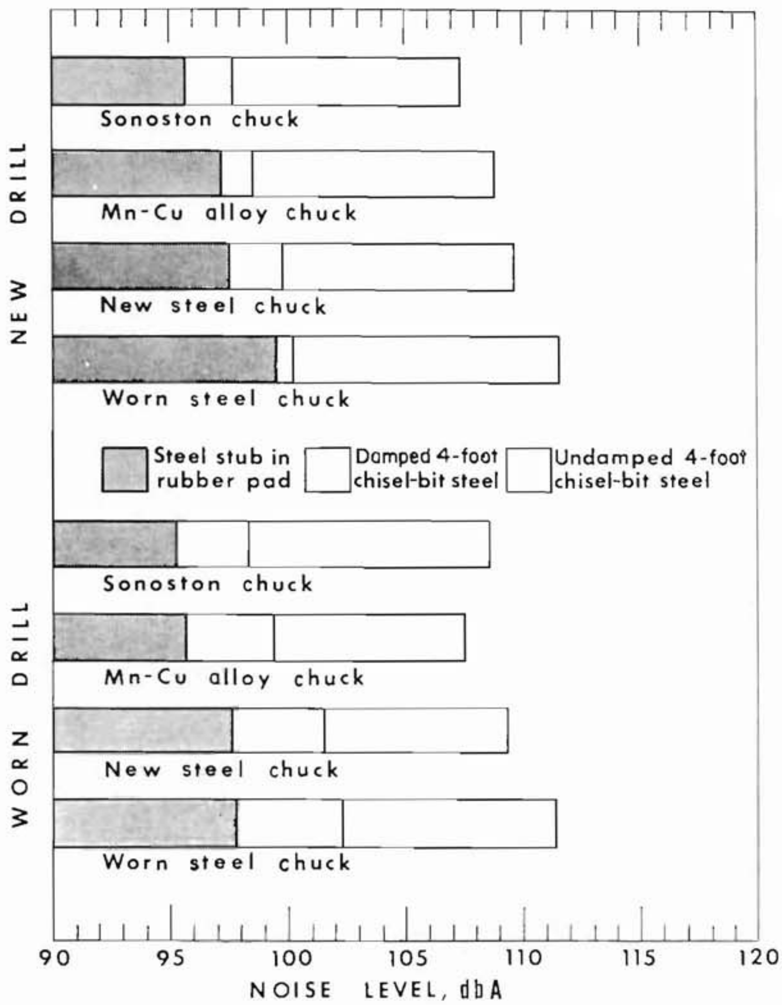

FIGURE 7. - Variations in noise level obtained by changing rotation chucks in a new and a worn BBC-17 drill. No drill case, exhaust hoses attached, 70-psi air pressure.

replaced in succession with the new steel, manganese-copper alloy, and Sonoston chucks. This trend is observed most consistently in tests employing the drill steel with constrained-layer damping.

Other efforts to utilize damping alloys were not effective in reducing the noise. Substitution of Sonoston and manganese-copper air valves in the BBC-17 drill produced no observable reduction in overall noise under free-run, simulated drilling on the test pad, or when drilling in granite. A Sonoston damping alloy back end for this drill did not reduce the noise from this area of the drill. Mechanical impacting tests on damping alloy blocks confirmed the assumptions of Miller (8) that this type of material is inadequate for piston construction.

RESULTS WITH COMBINED MODIFICATIONS

Laboratory Noise Tests (Indoor)

The prototype drills with the combination muffler-drill body covers, constrained-layer-damped chisel-bit drill steel, and Sonoston alloy rotation chuck operated at a sound pressure level of 102 db and 99 dbA, compared with a sound pressure level of 121 db and 115 dbA for the unmodified BBC-16 and chisel-bit steel. Table 6 summarizes the stepwise reduction in noise as various modifications were added to the standard drill until it was converted to the prototype. The summary in table 6 represents data acquired at the indoor test site over the period of drill development.

TABLE 6. - Summary of indoor test site drilling noise levels, singular and combined drill modifications, average of three drilling tests in granite, 70-psi air pressure

Test	Sound level		Drill	Muffler cover	Rotation chuck	Drill steel (chisel)
	db	dbA				
1	121.3	115.0	BBC-16	None.............	Steel............	Standard.
2	116.5	112.0	BBC-16	None.............	.....do...........	Damped.
3	117.3	113.5	BBC-17	None.............	.....do...........	Standard.
4	110.2	106.5	BBC-17	None.............	.....do...........	Damped.
5	117.5	111.0	BBC-17	Aluminum.........	.....do...........	Standard.
6	104.2	99.5	BBC-17	.....do..........	.....do...........	Damped.
7	115.2	109.0	BBC-17	.....do..........	Alloy.............	Standard.
8	102.7	98.5	BBC-17	.....do..........	.....do...........	Damped.
9	115.2	111.0	BBC-17	Fiberglass.......	Steel.............	Standard.
10	104.7	102.0	BBC-17	.....do..........	.....do...........	Damped.
11	114.2	109.0	BBC-17	.....do..........	Alloy.............	Standard.
12	102.3	99.0	BBC-17	.....do..........	.....do...........	Damped.

The effectiveness of selected singular and combined modifications in reducing drilling noise, listed in table 6, is further illustrated in figures 8, 9, and 10, where the 1/3-octave-band noise spectra are compared. Figure 8 compares the noise spectrum of the original standard drill and chisel-bit steel (test 1) with the final prototype (test 8). The effect on the noise spectrum in changing from the standard steel rotation chuck (test 6) o the Sonoston alloy rotation chuck (test 8) is demonstrated in figure 9. Most of the noise reduction appears to be above 400 Hz in this case. Figure 10 shows noise reduction resulting from the use of a constrained-layer-damped chisel-bit steel (test 8) in place of the standard chisel-bit steel (test 7). The decrease of noise is most pronounced at the higher frequencies.

Laboratory Noise Tests (Outdoor)

In addition to the drilling noise and performance evaluation conducted concurrently with the prototype development, a final, comprehensive noise and performance evaluation of the modified drills and drill steels was made in comparison with standard drills and drill steels. Drilling noise was measured outdoors in conformance with the CAGI-PNEUROP test code for pneumatic rock drills. All the tests were conducted at an operating air pressure of 90 psi and an applied thrust of 290 pounds, which was determined to give maximum penetration rate at the 90-psi pressure. Forty drill and drill steel combinations were tested, each twice, on a random schedule, for a total of 400 noise measurements.

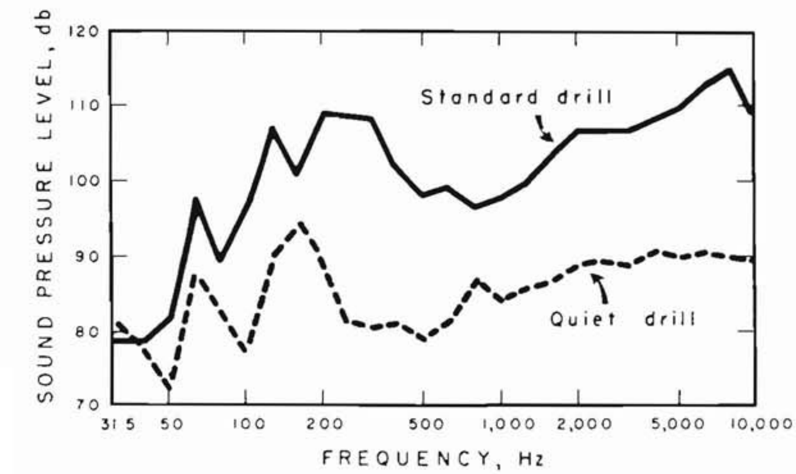

FIGURE 8. - One-third-octave-band noise levels of standard and prototype drills.

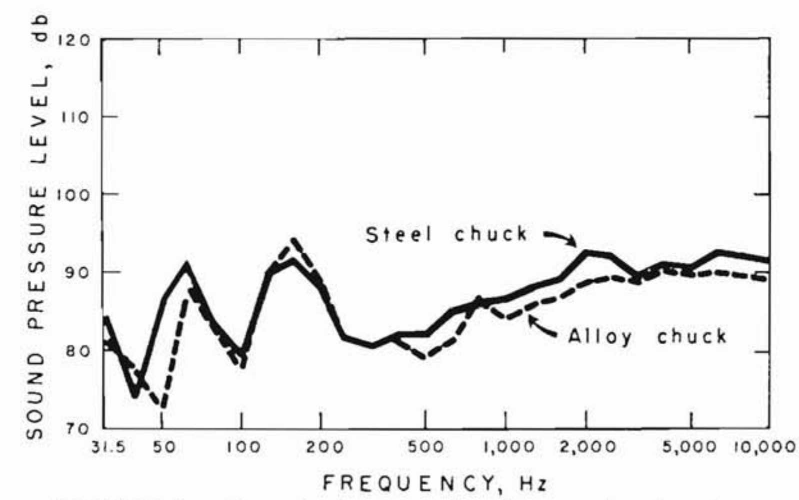

FIGURE 9. - One-third-octave-band noise levels of prototype drill with standard steel, standard and Sonoston alloy rotation chucks.

Table 7 summarizes drilling noise as a function of progressive drill modification using 4-foot integral-chisel-bit and 4-foot detachable-bit rope-thread steels and their constrained-layer-damped versions. Starting with an unmuffled BBC-16 drill, noise levels are listed for the same drill with the BBC-17 integral muffler conversion, for the BBC-17 drill with the VIP-fiberglass add-on muffler cover, and for the latter with an alloy rotation chuck. These noise measurements amplified and confirmed some of the previous findings. The data in table 7 show similar results to those in table 6 for operation at 90 psi under the CAGI-PNEUROP test conditions.

Exhaust and drill body noise reduction obtained by the use of the muffler cover on the BBC-17 drill is shown by the difference in noise readings between columns 2 and 3 using the constrained-layer-damped steels. For the standard steels the steel resonance noise predominates, and the overall noise reduction is not as great. The effectiveness of the constrained-layer treatment on reducing drill steel resonance noise is shown by the noise differences between the standard and treated steels in column 3. Column 4 shows that a further reduction of 1 db in operating noise is obtained by the alloy rotation chuck.

TABLE 7. - Average drilling noise in granite, selected drill and steel combinations, CAGI-PNEUROP test code, 90-psi air pressure

Drill steel type	Drill and noise level, db and (dbA)			
	BBC-16	BBC-17	BBC-17 with VIP-fiberglass muffler cover	BBC-17 with VIP-fiberglass muffler cover and Sonoston rotation chuck
4-ft chisel, standard.	118 (115)	114 (111)	113 (108)	108 (107)
4-ft chisel, 1-3/8-inch OD, full-length steel tube, VIP filler..............	116 (112)	110 (107)	101 (98)	100 (97)
4-ft rope, standard, 1-3/4-inch bit.......	118 (114)	112 (109)	106 (102)	104 (102)
4-ft rope, 1-3/8-inch OD, full-length steel tube, VIP filler, 1-3/4-inch bit.......	116 (112)	110 (107)	101 (98)	100 (97)

Noise levels for a selection of standard and damped drill steels are summarized in table 8. These measurements were made with the modified BBC-17 with the VIP-fiberglass muffler cover to minimize the exhaust and drill body noise. The data show that the 4-foot steels were the loudest; for them, maximum noise reduction is obtained by the addition of a full-length constrained-layer damper. The fully damped 4-foot chisel-bit and rope-thread steels operated at equal noise levels, whereas of the standard steels the rope-thread type with the detachable bit is considerably quieter. Partial constrained-layer dampers added to these steels were also very effective, reducing the noise level to within 2 to 3 db of the full constrained-layer treatment. No significant noise reduction resulted from the addition of full-length constrained-layer dampers to the 2-foot rope-thread steels. This is attributed to the fact that the detachable bit acts as an effective damper for the shorter steels. Similarly, the 4-foot standard rope-thread steels are considerably quieter than the standard 4-foot integral-chisel-bit steels.

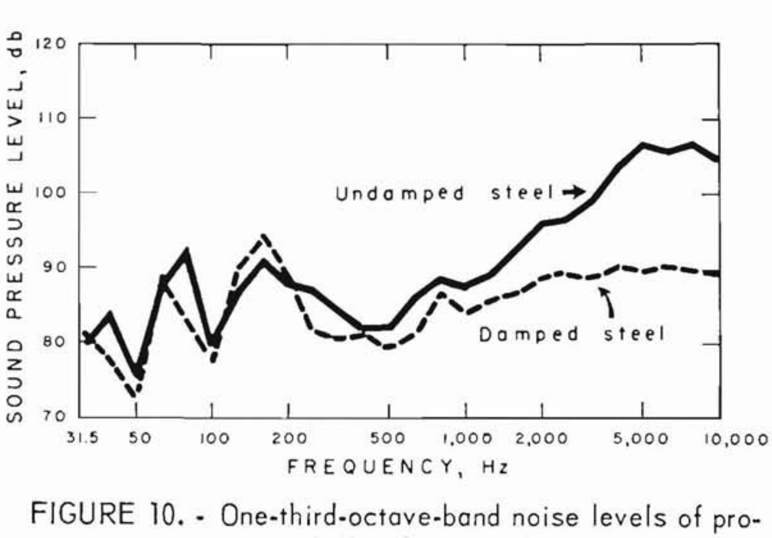

FIGURE 10. - One-third-octave-band noise levels of prototype drill with standard- and constrained-layer-damped 4-ft integral-chisel-bit drill steels.

TABLE 8. - Drilling noise in granite, selected drill steels, CAGI-PNEUROP test code, BBC-17 drill with VIP-fiberglass muffler cover, 90-psi air pressure

No.	Constraining treatment	Campaign A		Campaign B	
		Bit diam, inches and type	Noise level, db and (dbA)	Bit diam, inches and type	Noise level, db and (dbA)
	4-FT CHISEL-BIT STEEL				
1	None.......................	1-5/8, chisel.	113 (108)	NAp	NAp
2	1-3/8-inch OD, 13-inch long steel sec., clamped on top, rubber filler.	...do....	104 (101)	NAp	NAp
3	Two 1-3/8-inch OD, 12-inch long steel sec. on top and bottom, VIP filler.	...do....	105 (101)	NAp	NAP
4	One 1-3/8-inch OD, 12-inch long steel sec. on top, VIP filler.	...do....	106 (104)	NAp	NAp
5	1-3/8-inch OD, full length steel tube, VIP filler.	...do....	101 (98)	NAp	NAp
6	1-3/8-inch OD, full length steel tube, Flexane 30 filler.	...do....	101 (98)	NAp	NAp
	4-FT ROPE-THREAD STEEL				
7	None.......................	1-3/4, 4 point.	106 (102)	2-1/8, 4 point.	108 (104)
8	1-3/8-inch OD, 13-inch long steel sec., clamped on top, rubber filler.	...do....	104 (100)	...do....	103 (100)
9	1-1/2-inch OD, full length steel tube, VIP filler.	...do....	100 (97)	...do....	102 (98)
10	1-3/8-inch OD, full length steel tube, VIP filler.	...do....	100 (98)	...do....	102 (98)
11	1-1/4-inch OD, full length steel tube, VIP filler.	...do....	102 (99)	...do....	102 (98)
12	1-1/2-inch OD, full length Al tube, VIP filler.	...do....	102 (98)	...do....	102 (98)
	2-FT ROPE-THREAD STEEL				
13	None.......................	1-3/4, 4 point.	103 (99)	2-1/8, 4 point.	105 (101)
14	1-3/8-inch OD, full length steel tube, VIP filler.	...do....	102 (99)	...do....	103 (100)
15	1-3/8-inch OD, full length steel tube, Soundcoat filler.	...do....	103 (99)	...do....	104 (100)
16	1-1/2-inch OD, full length Al tube, VIP filler.	...do....	104 (100)	...do....	104 (101)

NAp Not applicable.

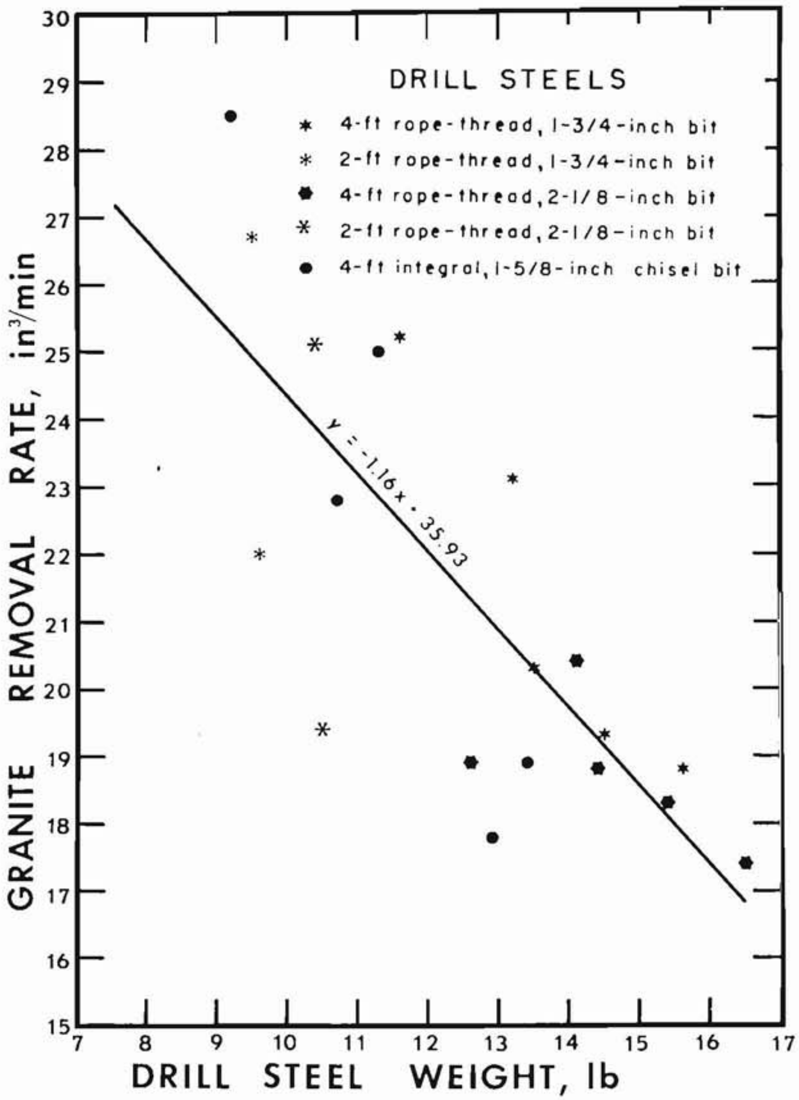

FIGURE 11. - Dependence of granite removal rate on total drill steel weight, BBC-17 drill with VIP fiberglass muffler cover.

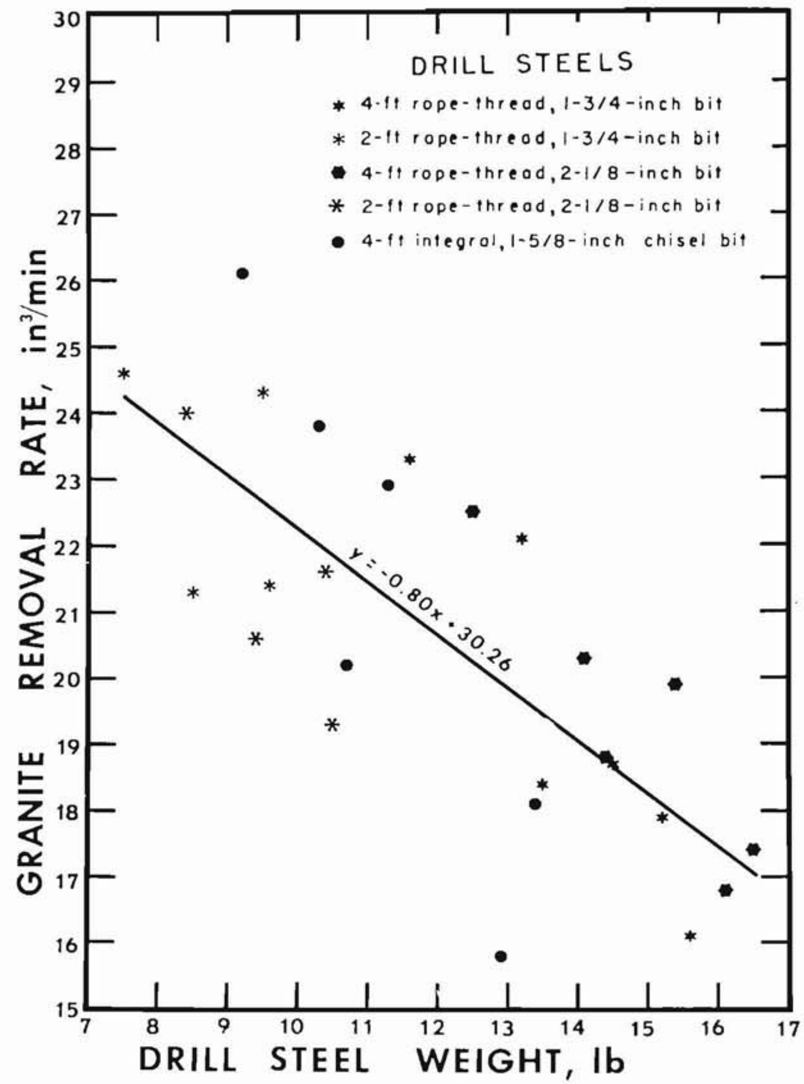

FIGURE 12. - Dependence of granite removal rate on total drill steel weight, BBC-17 drill.

A definite increase in noise level due to higher operating air pressure was observed for all drill and drill steel combinations tested at 90- and 70-psi air pressure. Noise levels at 90-psi air pressure averaged 3 to 4 db higher than those at 70 psi, as shown in table 9.

TABLE 9. - Drilling noise in granite, 90- and 70-psi air pressure, CAGI-PNEUROP test code, 4-ft. standard and fully constrained chisel-bit steels

Drill	Steel	Noise level, db and (dbA)	
		90 psi	70 psi
BBC-16..................	4-ft standard chisel.....	118 (115)	116 (111)
Do.....................	4-ft constrained chisel..	116 (112)	114 (108)
BBC-17..................	4-ft standard chisel.....	114 (111)	113 (108)
Do.....................	4-ft constrained chisel..	110 (107)	107 (103)
BBC-17 with VIP-fiberglass muffler cover	4-ft standard chisel.....	113 (108)	111 (107)
Do.....................	4-ft constrained chisel..	101 (98)	97 (94)
BBC-17 with VIP-fiberglass muffler cover and Sonoston chuck.	.....do.................	100 (97)	96 (92)

Performance Evaluation

Drilling performance tests were conducted to determine the effect of drill modifications and steel damping treatments on drilling efficiency. The tests were made with selected drill steels using the BBC-17 drill with and without the VIP-fiberglass muffler cover. The results for the 45 drill and drill steel combinations are compiled in table 10, which shows for both drills the total drill steel weight, the measured penetration rate into the rock, and the rate of rock removal for each drill steel-drill bit combination.

The data on drilling rates show evidence of measurable loss in drill performance because of the use of the muffler cover and the constrained-layer damping on the drill steels. In figures 11 and 12, granite removal rate is plotted against total drill steel weight for the damped and undamped drill steels listed in table 7, divided as to whether the muffler cover was or was not employed, respectively. The scatter inherent in a test of this type is understandably great, but the trend is evident and there is statistical evidence that the muffler cover may reduce drilling rate 10 or 12 percent if a very light drill steel is used. With long, heavy drill steel the cover probably has insignificant effect on drilling rate. The results showed that the influence of drill steel weight on drilling rate is linear, and that there would be a calculable loss of efficiency when a constrained-layer damper was applied to a drill steel for noise suppression.

TABLE 10. - Penetration rates for selected drill steels, BBC-17 and BBC-17 with VIP-fiberglass muffler cover, 290-lb thrust, 90-psi air pressure, Gray Georgia granite

Constraining treatment, number from table 8	Total steel and bit wt, lb	Penetration rate, in/min		Granite removal rate, in^3/min	
		BBC-17	BBC-17, muffler cover	BBC-17	BBC-17, muffler cover
4-FT CHISEL-BIT STEEL, 1-5/8-INCH-DIAMETER BIT					
1	9.2	13.7	12.6	28.5	26.1
2	10.7	11.0	9.7	22.8	20.2
3	11.3	12.0	11.1	25.0	22.9
4	10.3	NA	11.5	NA	23.8
5	12.9	8.6	7.6	17.8	15.8
6	13.4	9.1	8.7	18.9	18.1
4-FT ROPE-THREAD STEEL, 1-3/4-INCH-DIAMETER 4-POINT BIT					
7	11.6	10.5	9.7	25.2	23.6
8	13.2	9.6	9.2	23.1	22.1
9	15.2	NA	7.4	NA	17.9
10	15.6	7.8	6.7	18.8	16.1
11	14.5	8.0	7.8	19.3	18.8
12	13.5	8.4	7.7	20.3	18.4
2-FT ROPE-THREAD STEEL, 1-3/4-INCH-DIAMETER 4-POINT BIT					
13	7.5	NA	10.2	NA	24.6
14	9.5	11.1	10.1	26.7	24.3
15	9.6	9.2	8.9	22.1	21.4
16	8.5	NA	8.9	NA	21.4
4-FT ROPE-THREAD STEEL, 2-1/8-INCH-DIAMETER 4-POINT BIT					
7	12.5	5.3	6.3	18.9	22.5
8	14.1	5.7	5.7	20.4	20.4
9	16.1	NA	4.7	NA	16.8
10	16.5	4.9	4.9	17.4	17.4
11	15.4	5.2	5.6	18.3	19.9
12	14.4	5.3	5.3	18.9	18.9
2-FT ROPE-THREAD STEEL, 2-1/8-INCH-DIAMETER 4-POINT BIT					
13	8.4	NA	6.8	NA	24.0
14	10.4	7.1	6.1	25.1	21.6
15	10.5	5.5	5.4	19.4	19.3
16	9.4	NA	5.8	NA	20.6

NA Not available.

DISCUSSION

Two versions of the prototype muffler cover, installed on the BBC-17, are pictured in figures 3 and 4. Figure 3 shows the 9-pound aluminum cover, and the 6.5-pound fiberglass cover is pictured in figure 4. Both versions of the prototype drill present a clean and smooth appearance, although both are somewhat bulkier than the standard drill. There are no appendages to interfere with normal use of the drill or to break off. The cover does not interfere with the operating controls or with the air and water couplings at the top of the drill, and it can be readily removed for servicing the drill. For these reasons operator acceptance of the prototype drill should be favorable.

Constrained-layer treatment was demonstrated to be an effective method for reducing drill steel noise. This method does not alter the integrity of the steel rod and would not in any way weaken the rod and cause premature failure. Conversely, it could prolong steel life by reducing fatigue damage from transverse resonance vibrations and steel flexing. For the 4-foot, and presumably for longer, drill steels, constrained-layer dampers can play an essential role in noise reduction. This is especially true for the integral-chisel-bit steels, which without damping treatment operate at extremely high noise levels. In comparison, the standard rope-thread steel is 6 db quieter because the detachable bit acts as a damper for steel resonance, but it also operates at the quietest level with a full constrained-layer damper. With partial constrained-layer dampers, both types of steel operate at noise levels that are only 2 to 3 db higher than those of the fully treated steels. No significant reduction in noise was realized for the 2-foot detachable-bit rope-thread steels by the use of full-length constrained-layer damping treatment. The low level of steel resonance noise in this case is attributed to the detachable nature of the bit, which acts as an effective damper for the short rod. Since the drilling rate is dependent inversely on the steel weight, the use of partial covers or short detachable-bit steels where practical appears to offer a method of obtaining significant reduction in noise level with minimal loss of drilling efficiency.

Comparison of noise levels between tests at 70 and 90 psi (table 8) indicates that the 20-psi increase in air pressure causes an increase of about 4 dbA in noise level. Bureau of Mines data on the relationship between penetration rate and operating air pressure (9) show that in hard-rock drilling the increase in air pressure from 70 to 90 psi increases the rate by approximately 50 percent. For the prototype drill the 20-psi reduction caused the noise level to fall from 97 to 92 dbA. Under Walsh-Healey limits, an operator could work twice as long with air at 70 psi (6 rather than 3 hours) and be in compliance, and possibly could drill more than twice as much footage as in 3 hours at 90 psi.

The average 2-db noise reduction obtainable with the damping alloy rotation chucks under all drilling conditions where the exhaust noise is not a factor is of enough significance to merit serious consideration in industrial drill production.

CONCLUSIONS

The noise levels of the common hand-held or air-leg pneumatic rock drills operating at an air pressure of 90 psi can be reduced from 115 dbA to 97 dbA by modifications that do not change the basic configuration or utility of the drill. Drill exhaust and mechanical noise radiated by the drill body were reduced by a combination muffler cover that increased the drill weight by only 10 percent. Drill steel resonance noise was reduced by full or partial constrained-layer dampers around the steel and by use of damping alloy rotation chucks. Although these drill and steel modifications result in some loss in drilling performance, they cannot be avoided if noise reduction is the primary goal. These modifications have left the basic drill configuration, airhose requirements, controls, and operating methods of the drill unchanged, and it appears that any further noise reduction would require enclosing the complete drill and steel in an air bag or similar device. The exhaust noise with these modifications is approximately 90 dbA, and a further reduction in exhaust noise would not have a noticeable effect on the overall noise level. Requirements that the drill cover must be rugged and durable, yet light in weight and not bulky, limit the design and materials that can be used. Drilling performance can be improved by the use of partial-length constrained-layer dampers at an increase in noise level, and a possible compromise between drilling performance and noise levels could be made here.

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