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The Bureau of Mines Noise-Control Research Program—A 10-Year Review

By William W. Aljoe, Thomas G. Bobick,
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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel	lb/ft^2	pound per square foot
dBA	decibel, A-weighted	kHz	kilohertz
dB/Hz	decibel-second per cycle	mi/h	mile per hour
ft	foot	min	minute
ft•lbf	foot pound (force)	μm	micrometer
ft•lbf/min	foot pound (force) per minute	ms	millisecond
ga	gauge	pct	percent
h	hour	rev/min	revolution per minute
h/d	hour per day	s	second
Hz	hertz	ton/h	ton per hour
in	inch	yd^3	cubic yard
in/s	inch per second	yr	year
lbf	pound (force)		

THE BUREAU OF MINES NOISE-CONTROL RESEARCH PROGRAM—A 10-YEAR REVIEW

By William W. Aljoe,[1] Thomas G. Bobick,[1] Gerald W. Redmond,[2] and Roy C. Bartholomae[3]

ABSTRACT

This report summarizes the Bureau of Mines noise-control research program from 1972 to 1982. Each segment of the mining industry--underground coal, underground hardrock, surface mining, and processing plants--has different noise-control problems because of vast differences in working procedures, equipment, and workplace design. The Bureau has identified the most serious noise problems in each segment and has developed strategies for attacking these problems.

This publication points out the need for noise control in the mining industry, discusses Federal regulations governing worker exposure to noise, and describes the Bureau's overall approach to mining noise-control research. It traces the history of noise overexposure in each segment of the mining industry and discusses the major noise sources. It provides detailed information on noise-control research efforts in the Bureau's major areas of emphasis, including the results of these efforts. Finally, the report discusses the Bureau's future role in research on mining noise control, emphasizing the need to expend more effort on long term in-house investigations into the noise problems that have been identified in past programs as the most serious ones.

INTRODUCTION

Noise exposures of workers in the mining industry often exceed those specified under Federal noise regulations. Because of the severity and diversity of this problem, the Bureau of Mines has conducted a wide variety of noise-control research efforts. This report summarizes the Bureau's noise-control research program during the 1972-82 period, giving an overall picture of the Bureau's activities in this area and its major accomplishments. Further details on the projects described in this publication can be found in the reports included in the reference list or by contacting the authors of this report at the Bureau's Pittsburgh Research Center.

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PART 1.--GOVERNMENT INVOLVEMENT IN MINING NOISE CONTROL

THE MINING NOISE PROBLEM

Noise is often regarded merely as a nuisance; however, it is also a widespread occupational health problem. In the mining industry, the noise problem is especially serious because overexposure can cause permanent hearing loss. The extent and severity of the noise problem in mining was revealed in a 1976 study by the National Institute for Occupational Safety and Health (NIOSH) (25).[4] This study found that underground coal miners had measurably worse hearing than the national average population; for example, the median hearing threshold of retired miners was 20 dB greater than that of the general population (fig. 1). Figure 2 shows that, at age 60, over 70 pct of all miners had a hearing loss greater than 25 dB, and about 28 pct had a hearing loss greater than 40 dB. Miners experience greater hearing impairment than most other industrial workers because of their work-related overexposure to noise. Because this hearing loss occurs gradually over many years, the individual is not aware of it until he or she notices difficulties in communicating with other people or an inability to hear safety signals in the workplace.

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

FEDERAL NOISE REGULATIONS PERTAINING TO MINING

The Federal Government regulates the noise exposure of miners under the Federal Mine Safety and Health Act of 1977 (Public Law 95-164). This act, which supersedes the previous Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173), covers surface and underground operations of metal and nonmetal mines as well as coal mines. The Code of Federal Regulations (CFR) defines permissible noise exposures for all mine workers in

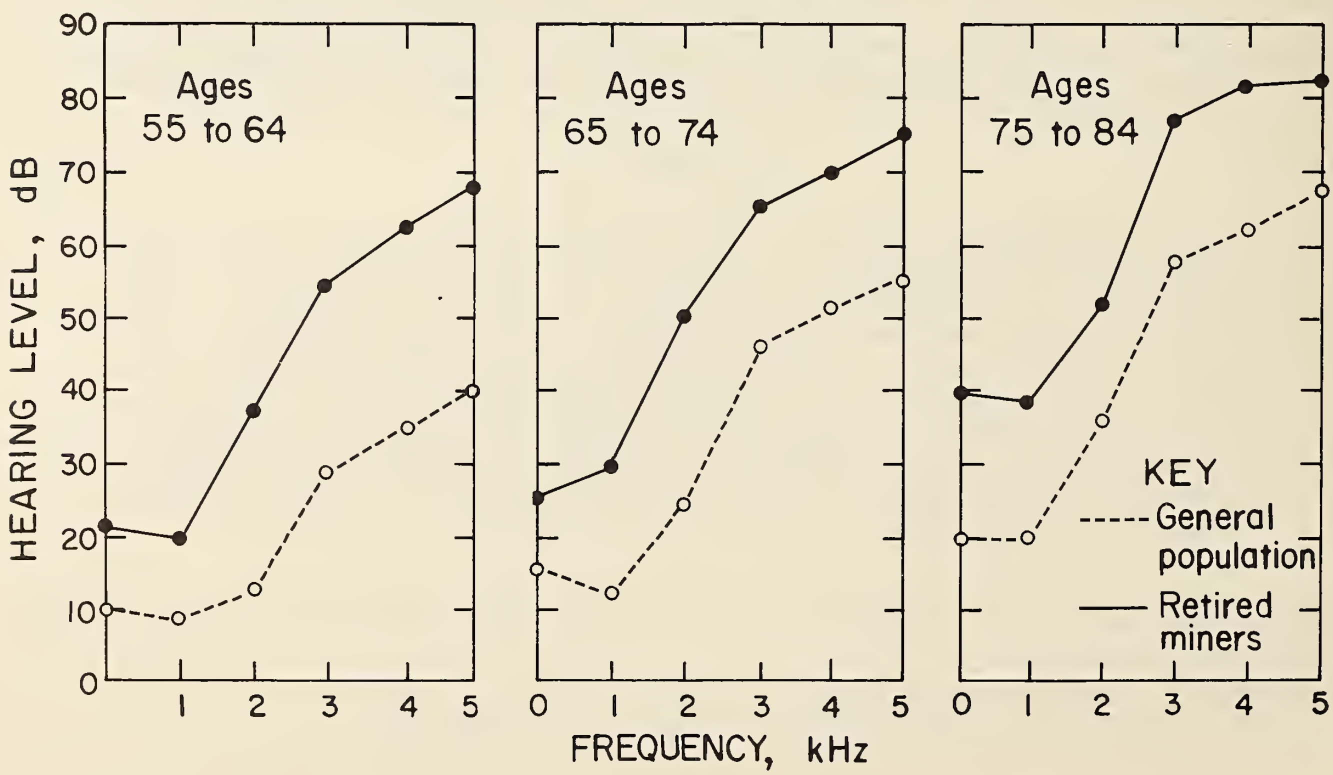


FIGURE 1. - Hearing thresholds of retired miners.

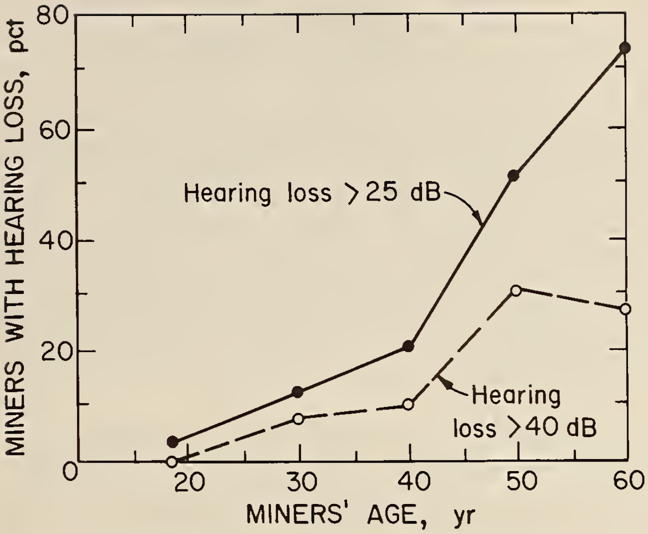


FIGURE 2. - Hearing loss among miners.

terms of noise dose, which includes both the level and duration of the noise.[5]

[5]Mining noise regulations are contained in the following sections of 30 CFR: 55.5-50 (surface metal and nonmetal mines), 56.5-50 (sand, gravel, and crushed stone), 57.5-50 (underground metal and nonmetal), 70.500 through 70.511 (underground coal), and 71.800 through 71.805 (surface coal).

Noise level is measured in decibels,[6] using a sound level meter, and the A-weighted decibel (dBA) is the unit of measure used in the regulations. The A-weighting scale takes into account the fact that the human ear is more responsive to high-frequency sounds (1,000 to 5,000 Hz) than to low-frequency sounds (below 1,000 Hz). Table 1 shows the typical A-weighted noise levels of everyday events.

Table 2 gives the relationship between noise level and allowable exposure time per day for mining operations. Exposure

[6]The decibel is a dimensionless relationship between two quantities, defined as 20 times the logarithm of the ratio of a measured quantity to a reference quantity. When measuring noise, the sound pressure is the quantity of interest, and the sound pressure level (SPL) is defined as

$$20 \log_{10} \left(\frac{\text{measured sound pressure}}{\text{reference sound pressure}} \right) \text{dB}.$$

The standard reference sound pressure used in the United States is 4.32×10^{-7} lb/ft^2. Further discussion of the SPL can be found in reference 18 or in any standard textbook on noise control.

TABLE 1. - Typical noise levels of various sounds, A-weighted decibels

Noise source	Noise level	Subjective evaluation
Jet engine	140	Deafening.
Pneumatic chipping	[1]130	Do.
Underground pneumatic percussion drill	120	Intolerable.
Automatic punch press; hand grinding	110	Do.
Bulldozer (at operator's position)	105	Very loud.
Auto horn (at 10 ft)	100	Do.
Construction site in urban area	90	Do.
Busy street; school cafeteria	80	Loud.
Loud radio; stenographic room	70	Do.
Restaurant; department store	60	Moderate.
Average office; quiet conversation	50	Quiet.
Residential area at night	40	Faint.
Quiet residence (inside)	30	Do.
Background in TV studio	20	Very faint.
Rustle of leaves	10	Do.

[1]Threshold of pain.

TABLE 2. - Allowable noise exposure time per day

Noise level, dBA	Allowable exposure time, h
90	8
92	6
95	4
97	3
100	2
102	1.5
105	1
107	.75
110	.5
115	≤.25

to noise levels less than 90 dBA is not regulated. It is evident from table 2 that the higher the noise level, the shorter the allowable exposure time is. At 90 dBA, the maximum allowable exposure time is 8 h/d; every 5-dBA increase in noise level reduces the maximum allowable exposure time by half. Exposure to continuous noise levels higher than 115 dBA is not permitted by law.

In practice, compliance with noise regulations is determined by measuring each worker's noise exposure index (NEI), which includes both the noise level and the exposure time at each level. NEI is defined as

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} + \cdots ,$$

where C_1, C_2, etc., are the actual times the worker was exposed to each noise level above 90 dBA, and T_1, T_2, etc., are the allowable exposure times (table 2) for the noise levels to which the worker was exposed. A worker is overexposed, or out of compliance, when the NEI value exceeds 1. NEI values are often expressed as a percent of the allowable noise dose, i.e., actual NEI value × 100 pct. For example, table 3 shows that during an 8-h shift, a worker is exposed to noise for 2 h at 89 dBA, 2 h at 90 dBA, 2 h at 95 dBA, and 2 h at 100 dBA. The NEI for this worker is

$$\frac{2}{8} + \frac{2}{4} + \frac{2}{2} = 0.25 + 0.5 + 1.0$$

$$= 1.75 \times 100 \text{ pct} = 175 \text{ pct}.$$

Thus, the worker is out of compliance with Federal noise regulations (because the NEI exceeds 100 pct).

The NEI measures only the worker's exposure to continuous noise; it does not include "impulse" or "impact" noise, which takes place over too short a time to be included in NEI calculations. Impulse or impact noise is defined as a sound that (1) reaches its peak level within 35 ms after initiation and (2) decreases to at least 20 dB below its peak level within 500 ms after reaching the peak level (535 ms after initiation) (24). If the impulses recur at intervals less than 1 s apart, the noise is classified as continuous. All of the Bureau's noise-control research efforts have dealt with continuous noise because this is by far the most prevalent type of mining noise.

TABLE 3. - Illustrative calculation of worker NEI during 8-h shift

Noise level, dBA	Allowable exposure time (T), h	Actual exposure time (C), h	Dosage [(C/T) × 100], pct
89	Unlimited	2	0
90	8	2	25
95	4	2	50
100	2	2	100
Total	NAp	NAp	[1]175

NAp Not applicable. [1]NEI.

THE BUREAU OF MINES APPROACH TO MINING NOISE CONTROL

Because noise affects large numbers of workers in all segments of the mining industry the Bureau has become involved in many different aspects of noise control. The objective of the Bureau's noise-control research efforts is to investigate techniques that would, if adopted, help bring the mining industry into compliance with Federal noise regulations.

Because the mining noise problem is so widespread, the Bureau must define those areas in which it can appropriately be involved. Three criteria must be met before the Bureau will investigate a specific noise problem: (1) The problem must result in serious worker overexposure and risk of hearing loss; (2) it must affect a large number of mine workers; and (3) the mining industry itself must be incapable of solving the problem because of insufficient financial resources or technical expertise. For example, the Bureau is conducting long-term basic studies into all the major noise-generating mechanisms of the coal-cutting process; this requires a level of effort and technical expertise that equipment manufacturers cannot provide. Conversely, the Bureau is not heavily involved in acoustical booth technology because these structures are commercially available and can be improved through efforts by the private sector. However, the Bureau has become involved in specific areas where acoustical booth technology is especially difficult to apply, such as in portable mineral processing plants.

An important aspect of the Bureau's approach to noise control is its emphasis on engineering controls for the major noise sources in the mining workplace. Although Federal noise regulations specify the use of both engineering and administrative (e.g., job switching) controls as the primary means of addressing mining noise problems, Bureau research has shown that engineering controls can often be more effective. For example, job switching during any given day would be nearly impossible in many mines because of long, nonproductive travel times between noisy and quiet workplaces. In addition, serious safety hazards could result if inexperienced workers were switched into noisy jobs that require high levels of skill. Finally, if an engineering control can be applied successfully to the noise source, administrative controls will be unnecessary and the solution will generally be more permanent.

At first glance, personal hearing protectors (earplugs, earmuffs, etc.) seem to be a relatively cheap, simple solution to almost any noise problem. However, Federal regulations state that hearing protectors should be considered as only a secondary noise-control treatment in situations where engineering or administrative controls cannot be used. Reasons for this include the following: (1) Earplugs and earmuffs do not usually provide the same degree of protection in the mining workplace as they do in the laboratory or in other types of workplaces; (2) miners often refuse to wear hearing protectors because they are uncomfortable, annoying, or cumbersome (especially earmuffs); and (3) hearing protectors can prevent miners from hearing warning signals such as "roof talk" (the noise that often precedes a roof fall) or backup alarms on moving equipment. Although the Bureau is still conducting research into the potential effectiveness of hearing protectors in the underground mining environment, they are viewed as only a temporary solution to a problem that requires the use of engineering controls.

Unfortunately, the mining environment often prohibits the use of standard engineering noise-control techniques common to other industrial workplaces. In most cases (especially underground), the mining workplace is very confined, and it changes constantly because it is controlled primarily by local geology rather than by engineering design. Physical conditions are usually quite severe (e.g., wet floors and sloughing roof and ribs), thus restricting the use of standard acoustical materials such as sound-absorbing foam panels. Another reason treating the mining workplace would be impractical is that many miles of mine tunnels would have to be treated. Surrounding the noise source with an acoustical enclosure is another standard engineering noise-control technique that cannot usually be employed because the most severe mining noise sources are often large mobile machines such as continuous miners and jumbo drills.

Engineering noise controls in mining can be as simple as adding sound-absorbing material to the inside of a bulldozer operator's cab, or as complex and demanding as redesigning the inner workings of percussion drills to produce less noise while maintaining the same drilling power. The two basic engineering noise-control strategies are (1) to install noise-control treatments on existing mining equipment (the retrofit approach) and (2) to design inherently quieter mining equipment.

The retrofit approach is usually preferred if a straightforward noise-control technique can be employed, and it is especially desirable in the capital-intensive mining industry. If a retrofit noise-control treatment is successful, it can often allow timely and relatively inexpensive compliance with Federal noise regulations. An acoustical cab for a bulldozer operator is one example of a successful application of the retrofit approach. However, even in this simple case, careful application of the noise-control treatments is essential for optimum noise reduction. Unfortunately, the retrofit approach is not appropriate for many existing pieces of mining equipment.

In some cases, engineering noise controls can be incorporated into the machine design without affecting overall performance. For example, the manufacturer of an underground load-haul-dump (LHD) vehicle can easily install vibration-isolation mountings (a noise-reducing feature) on the engine and transmission of a newly built machine. Even though this treatment requires only minor dimensional changes in the original vehicle design, it could not be accomplished through the retrofit approach. The redesign approach is especially advantageous when the manufacturer has already decided to change its equipment for production puropses; noise-control technology would then constitute only a fraction of the redesign cost.

Cost-effectiveness is of primary importance in any approach to mining noise control. The Bureau considers an engineering noise-control technique to be cost-effective if it (1) does not reduce production or productivity, (2) costs relatively little to install, (3) does not increase long-term maintenance costs, and (4) does not introduce new hazards into the mining environment. The total amount of noise reduction is also important to the cost-effectiveness of any noise-control program. That is, a low-cost "quick-fix" approach may not be the best way to treat a noisy machine if a more expensive long-term research and development program can result in a much quieter, more efficient machine design. The Bureau has consistently sought the most cost-effective engineering approaches to mining noise problems and has therefore used both retrofit and redesign techniques in its research.

PART 2.--OVERVIEW OF THE BUREAU'S NOISE-CONTROL RESEARCH

Historically, the amount of mechanization in mines has determined the extent of worker overexposure to noise. This part of the report reviews the history of mechanization in the four major segments of the mining industry (underground coal, underground hardrock, surface mining, and mineral processing) and identifies the most serious "noise offenders" in each segment. The Bureau research programs designed to control noise from these "noise offenders" are described briefly in the following sections; part 3 discusses in detail some of the more successful Bureau research programs.

UNDERGROUND COAL MINING

When the first commercial U.S. underground coal mines were developed in the 18th century, the three major unit operations--extraction, haulage, and roof support--were performed manually. The coal was cut from the solid bed using hand tools such as picks and bars, then shoveled into baskets, boxes, carts, or wheelbarrows and dragged by workers or animals to the outside or to the foot of a shaft. Roof supports were emplaced with hand tools. Obviously, none of these manual extraction, hauling, and roof support methods generated much noise.

Underground coal mining operations started to become mechanized in the late 1800's with the development of punching machines and chain-type cutters to undermine the coal seam before blasting. Other early mining machines were coal and rock drills, electric and compressed-air locomotives, and gathering-arm-type loading machines. Still, very few workers were overexposed to noise because few mining operations were mechanized.

Full mechanization, and the noise associated with it, emerged in the 1920's when gathering-arm-type loading machines became more common. Rubber-tired and crawler-mounted machines for cutting and hauling coal away from the face reduced the number of workers underground, but those who remained were exposed to increasing amounts of machine-generated noise. The desire for increased coal production led to the development of larger, faster-moving machines with greater mechanical power; unfortunately, the noise associated with these machines also increased tremendously.

The final development contributing to increased noise in the coal mining environment came just after World War II, when the introduction of the tungsten carbide cutting bit enabled coal mining machinery to cut both rock and coal. With the tungsten carbide cutting bit, the three noisiest machines in present-day coal mines--the continuous miner, the longwall shearer, and the air-powered "stoper" roof drill--became possible. These three machines commonly produce noise levels that result in violations of Federal noise regulations (5).

Figure 3 shows the noise levels and operating times of most of the noise-producing machines in today's underground coal mines. This illustration shows that at least one noise offender is present in each major unit operation (extraction, haulage, and roof support). Therefore, the Bureau has conducted research programs in all three of these areas.

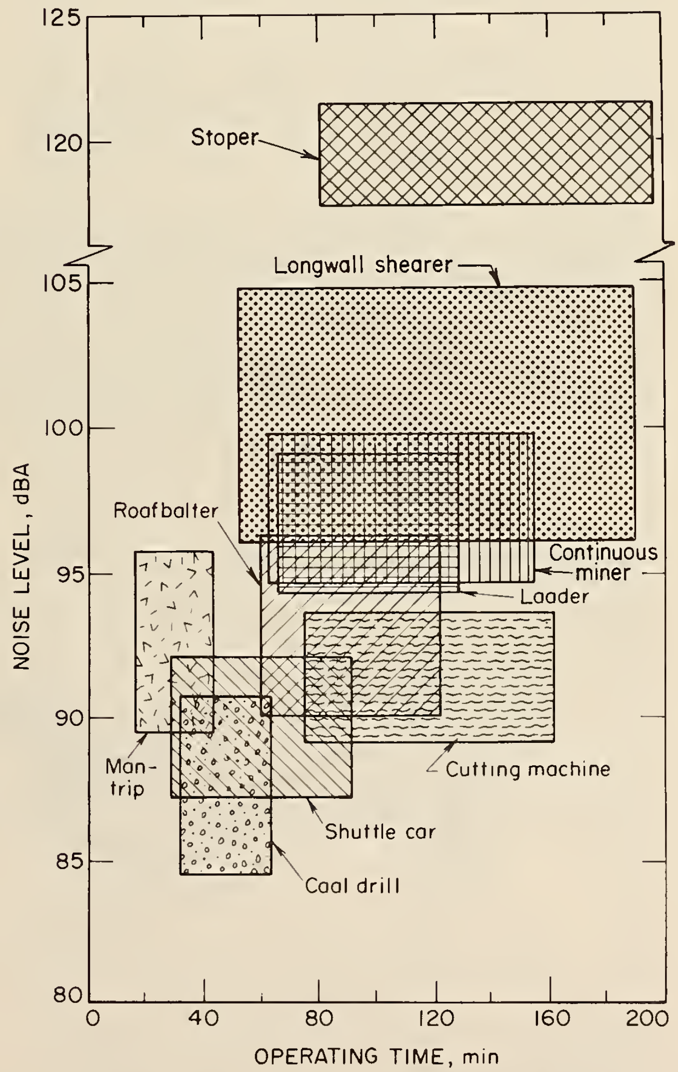


FIGURE 3. - Noise levels and operating times of underground coal mining machines.

Coal Extraction Methods

Continuous Mining

Figure 4 illustrates five different noise-producing mechanisms on continuous mining machines:

1. Face-radiated noise - When the bits on the rotating cutting drums strike and break the coal or rock, noise radiates from the coal or rock face.

2. Cutting head noise - Cutting bit vibration is transferred to the drums, the boom holding the drums, and the rest of the machine structure. These vibrating components often generate a very complex noise pattern.

3. Gathering head noise - After the coal or rock is cut from the face, it falls onto a pan called the gathering head, beneath the cutting drums. Rotating arms or discs on this pan force the broken material into the mouth of a conveyor that carries it to the rear of the miner. Gathering head noise results from various impacts involving the rotating arms or discs, the pan, and the broken material.

4. Conveyor noise - The conveyor consists of a continuously moving chain to which a series of flights are attached. The chain and flights move at the bottom of a metal trough. Scraping and impacts involving the chain, flights, trough, and broken material cause a great deal of noise.

5. Motor and drive-train noise - The motors and drive train supplying power to the cutting drums, gathering head, conveyor, and other machine components generate noise both internally (gear noise) and externally (vibration imparted to machine structures).

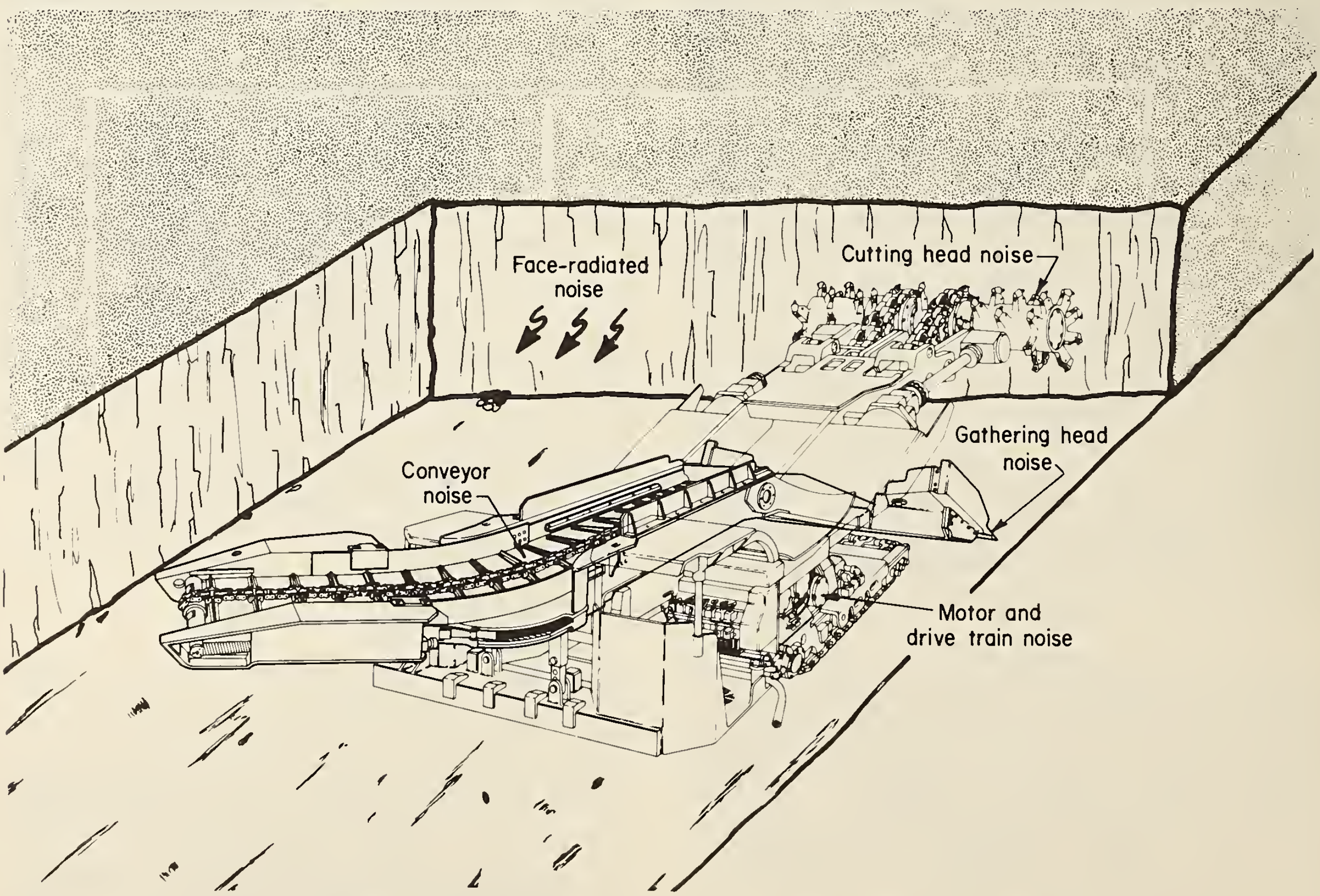


FIGURE 4. - Noise sources on continuous mining machines.

Laboratory research sponsored by the Bureau (see part 3) has indicated that face-radiated noise could be reduced, without harming production, if the bits on the miner cutting head moved at a slower speed while penetrating deeper into the coal face (1, 3). Unfortunately, present continuous miner designs are not adaptable to the Bureau's slow, deep-cutting technique. More research is needed to evaluate the potential noise reduction that can be obtained using slow, deep-cutting miners.

Cutting head noise can be reduced by preventing the transfer of cutting bit vibration to the cutting drums and to other machine components. The Bureau is presently investigating the merits of completely redesigning the cutting drum of the miner to reduce vibration transfer. Preliminary laboratory studies have shown a potential for significant noise reduction, but full-scale tests with a continuous miner equipped with an "isolated cutting drum" are needed to verify the laboratory predictions. It appears that this approach (isolating the cutting drum) may be applicable to a wide variety of coal- and rock-cutting machines because vibrational energy is absorbed close to its source--the interface between the cutting bits and the coal or rock.

Cutting head noise can also be reduced by limiting the vibration of the cutting drums and other structural components of the continuous miner. In one Bureau project (27), the noise radiated from the cutting heads of a low-coal auger-type miner was reduced by about 10 dBA by enlarging the auger core, stiffening the helix surrounding the core, and damping its vibration with sand. (This project is discussed in detail in part 3.) Mine operators can easily modify their augers in the same manner with the aid of detailed fabrication instructions provided by the Bureau (28). This reduced-noise auger can also be obtained from the auger manufacturer.

When the continuous miner is cutting and loading coal, the gathering head is usually less noisy than the cutting head or the conveyor. Although the impact of the rotating gathering arms on the pan generates significant noise when the miner is "running empty," this is not one of its major operating modes. Therefore, the Bureau has directed most of its efforts toward controlling cutting noise and conveyor noise rather than gathering head noise. Although disc-type gathering devices may be quieter than gathering arms, because they eliminate arm-to-pan impacts, no data exist to verify their potential for reducing of gathering head noise.

Conveyor noise can be reduced by (1) smoothing discontinuities between various sections of the trough, (2) isolating the chain and flights from the trough, and (3) structurally damping the large metal panels of the trough. A recent Bureau project (16) showed that conveyor-generated noise could be reduced by about 10.5 dBA through these techniques. However, this work was done in an aboveground test facility, using only the conveyor portion of the continuous miner (no cutting heads, gathering arms, drive train and motors, etc.). (For more details, see part 3.) Further testing on operating continuous miners is necessary to determine the overall noise reduction and durability of conveyor noise-control treatments.

Motor and drive train noise is usually not as loud as cutting and conveyor noise, but it tends to increase as components of the drive system deteriorate. This noise would probably be negligible if systems with smaller motors and shorter, simpler drive trains were used. Bureau research has not been directed toward control of this noise source.

Conventional Mining

Although the number of coal mines using the conventional mining system has decreased since the advent of the continuous miner, many smaller mines continue to use this system. In conventional mining, coal is blasted rather than cut from the face, and mechanized coal extraction procedures include (1) undercutting the face with chain-type cutting machines, (2) drilling holes for explosives with machine-mounted coal drills, and (3) loading the coal into shuttle cars with gathering-arm-type loading machines.

As indicated in figure 3, the loading machine (or loader) is the noisiest machine used in conventional mines. Since loader noise is due primarily to conveyor noise and gathering head noise, control of loader noise includes the same conveyor-quieting techniques as have been described for continuous miners. In fact, controlling loader noise is somewhat simpler than controlling miner noise because there is no coal-cutting noise.

The Bureau has not conducted noise-control research directed specifically toward conventional coal mining equipment, except for research on chain conveyors. The two major reasons for this are (1) the decreasing number of conventional mines as compared to continuous and longwall mines and (2) the relatively low noise levels of coal cutters and face drills compared with the noise levels of continuous miners and longwall shearers (fig. 3).

Longwall Mining

Although longwall mining systems were almost nonexistent in the United States prior to 1965, they now produce about 10 pct of all domestic coal mined underground. A continued increase in the use of these systems is expected in the future; therefore, the Bureau is now attempting to identify and develop the fundamentals that will be necessary to control all major noise sources in longwall mining. Figure 3 shows that the longwall shearer operator is often exposed to more noise than the continuous miner operator. Approaches to longwall noise-control have been somewhat similar to those for continuous miners because both mining systems utilize rotary cutting heads and chain conveyors. Part 3 describes the basic coal-cutting and chain conveyor research applicable to both continuous and longwall mining systems. However, design differences between the actual hardware in the two systems have necessitated separate Bureau efforts in both areas (42-43).

Haulage Methods

Because more coal miners work in the face area than in any other single location, the Bureau has concentrated on reducing the noise produced by face equipment. However, underground coal-haulage equipment also generates substantial noise, and the Bureau has addressed some of the problems in this area.

Face Haulage

Continuous miners and loading machines load coal into shuttle cars or some type of continuous face-haulage system. Shuttle car noise is usually not as loud as continuous miner and loader noise (fig. 3), so the shuttle car operator is exposed to the most noise while loading coal. Although operators may also experience noise levels slightly above 90 dBA while unloading the shuttle car, they usually spend more time tramming than loading and unloading combined. Since tramming is a relatively quiet procedure (less than 90 dBA), overexposure of shuttle car operators is minimal.

Conveyors are undoubtedly the greatest source of face-haulage noise. Continuous coal-haulage systems in the face area usually contain one or more conveyors, or "bridges," mounted on a self-propelled carrier vehicle. The bridge carrier operator either rides on this vehicle or walks and/or crawls beside it while loading coal. Conveyor noise-control treatments developed for continuous miners could also be used to benefit bridge carrier operators.

Secondary and Main Mine Haulage

Shuttle cars and continuous face-haulage systems usually transfer coal to belt conveyors or locomotive-drawn rail cars that haul the coal out of the mine. Electrically driven motors are the primary noise sources in belt-conveyor systems, but they do not usually contribute to worker overexposure. Likewise, the Mine Safety and Health Administration (MSHA) has not identified a serious overexposure problem among operators of electrically powered haulage locomotives.

Personnel Haulage

In the early days of coal mining, when coal was mined and transported by hand or animals, men usually walked or crawled to the face areas. When electrical power was introduced into the mines, personnel-haulage vehicles were developed. Typical of these is the rail-mounted "mantrip" or "portal bus" that carries workers from the mine portal to the face areas.

Because mantrips operate for only 15 to 45 min per shift, they are not a primary cause of noise overexposure; however, they commonly produce noise levels ranging from 90 to 95 dBA and can contribute significantly to the total daily noise dose experienced by face workers. Mantrips generate noise primarily through (1) interaction between the wheels and rails and (2) operation of the electric motor and drive train.

Bureau research programs aimed at controlling mantrip noise have been quite successful. (See part 3.) Noise levels have been reduced to below 90 dBA on two different mantrip vehicles. First, a mantrip was equipped with retrofit noise-control treatments on its wheels, passenger compartments, and motor enclosure (17). Similar noise-control techniques were then used by a mantrip manufacturer to produce an "inherently quieter" vehicle at its factory (15).

Roof Support Methods

Wooden posts, crossbars, and cribs were the original forms of coal mine roof support and were usually emplaced by hand. Roof bolts, the most common means of roof support in present-day coal mines, were first used extensively in U.S. coal mines in the mid-1940's. Holes must be drilled into the mine roof to install roof bolts, and two basic methods are used to drill roof bolt holes--handheld pneumatic percussion ("stoper") drills and machine-mounted electric rotary drills.

Stoper drills are by far the loudest machines used in coal mines today, commonly producing noise levels of about 120 dBA (fig. 3). Because Federal regulations do not allow continuous noise levels above 115 dBA, any continuous operation of a stoper drill would cause the operator to be overexposed. For this reason, the reduction of stoper drill noise was one of the Bureau's first high-priority areas of noise-control research. Part 3 includes a detailed description of the Bureau's stoper noise-control program.

The noise-generating mechanisms of stoper drills are basically the same as those of jumbo-mounted pneumatic percussion drills used in hardrock mines. (The operating mode of jumbo drills is discussed in some detail under the heading "Hardrock Extraction Methods" in the next section.) Although stopers are smaller and lighter than jumbo drills, the three major noise sources are the same--drill-body vibration, drill-steel vibration, and air-exhaust noise. Figure 5 shows a typical stoper drill and the location of these noise sources.

Two basic approaches to stoper noise control were investigated--retrofit techniques and complete redesign of the stoper drill. Although the redesign approach was more difficult and expensive than the retrofit approach, it resulted in a quieter, more efficient drilling machine. However, the retrofit treatments were also effective because they reduced noise substantially and did not require modification of the drill itself. The retrofit treatments reduced noise levels at the operator's position ranged from 102 to 106 dBA, reflecting an 11- to 14-dBA reduction versus noise levels of untreated stopers (38). The redesigned

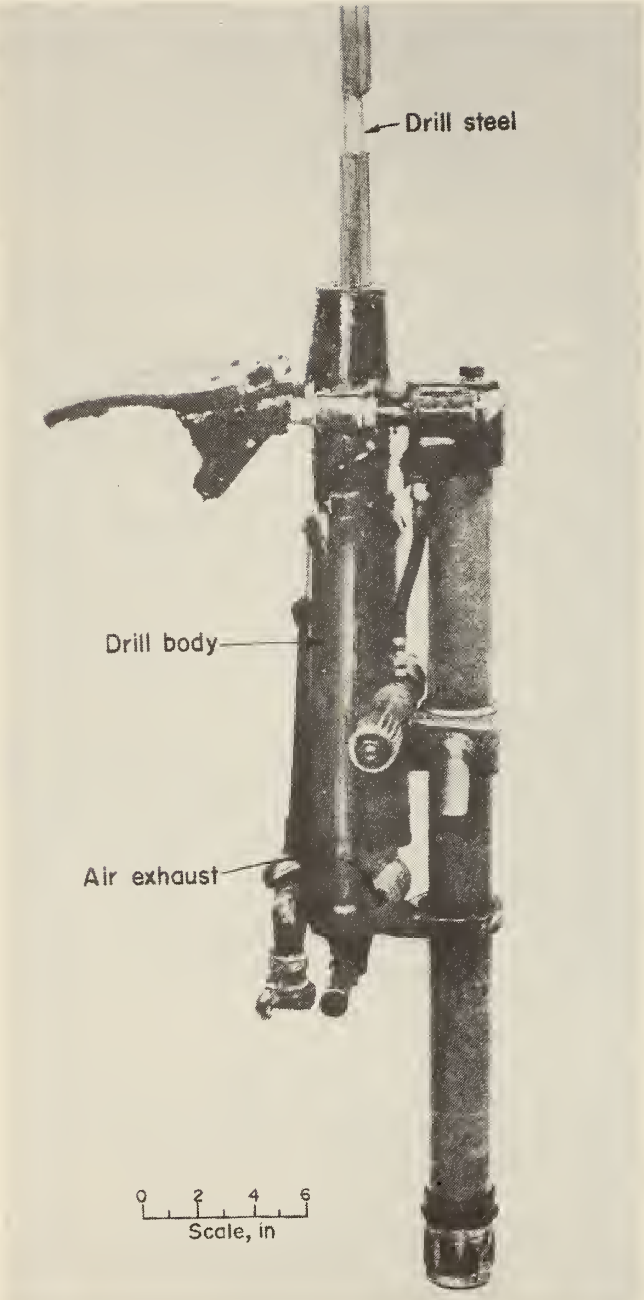


FIGURE 5. - Noise sources on typical coal mine stoper drill.

("quiet") stoper reduced operator noise levels to about 98 dBA, reflecting a 22-dBA reduction in noise versus that of standard drills (13). A smaller, lighter version of the "quiet stoper" produced noise levels of 102 to 105 dBA and was more readily accepted by drill operators.

Figure 3 shows that rotary roof-bolting machines can produce noise levels from about 90 to 95 dBA; this occurs while drilling the roof and tightening the bolt. However, these two operations comprise only 55 pct of the time spent by the bolter in the face area and only 20 pct of an 8-h shift. Based on these data, MSHA estimated that only 5 pct of all rotary roof bolter operators would be out of compliance with Federal noise regulations (5). For this reason, noise-control programs for rotary roof bolters have not been initiated by the Bureau.

UNDERGROUND HARDROCK MINING

Extraction, haulage, and roof support are unit operations that are common to both coal and hardrock mines. However, underground hardrock mining systems and equipment are quite different from those used in coal mines for the following reasons: (1) In most cases, explosives must be used for hardrock extraction because the rock is much too hard for continuous-type mining and cutting machines. (Exceptions are "soft" ores such as salt, potash, and trona.) (2) Hardrock ore bodies are more irregular than coal seams and require more complex mine layouts. (3) Diesel-powered equipment is more prevalent in hardrock mines than in coal mines.

Bureau studies in the mid-1970's (26) identified the major noise sources in underground hardrock mines, and research since that time has included efforts to control these sources. Because underground hardrock mines use such a wide variety of equipment types, Bureau research has addressed only the most serious noise offenders in these mines.

Hardrock Extraction Methods

Since the 16th century, hardrock ores have been freed from the earth by blasting. For more efficient blasting, holes are drilled into the rock mass, and explosives are placed in the holes. Although the types of explosives and drilling techniques used have changed substantially through the years, the basic principles of drilling and blasting have not. Increased noise associated with underground ore extraction is due primarily to the increased power of modern drilling machines.

Early miners found that the most effective way to bore a hole in rock was to place a hard, pointed object against the rock surface and strike the object with a hammer. At first this was done manually, but attempts were made throughout the 1800's to mechanize the process. The first mechanically powered rock drills were steam-driven; but they weighed several thousand pounds and were very cumbersome, so they were unacceptable commercially. Compressed air proved to be a better power source; in 1861, the Mont Cenis Tunnel in the French Alps marked the first successful commercial application of pneumatic rock drills. Improvements in pneumatic rock drill design continued throughout the late 1800's, including John George Leyner's development of a self-rotated striking tool (drill steel) with a hollow core to allow the passage of air or water for flushing the hole.

Metallurgical improvements in the 20th century have permitted the development of high-strength rock drill components that impart tremendous amounts of energy to the rock face. Modern drills commonly deliver 30 blows per second to the face at about 200 ft•lbf per blow--approximately 360,000 ft•lbf/min.

Often, percussion drills are most effective when mounted on a self-propelled vehicle called a jumbo. Figure 6 shows the major components of a typical jumbo drill system. The jumbo vehicle supports from one to three hydraulically powered booms that position the drill against the rock face. In operation, the drifter (drill body) generates a series of impulsive blows upon the steel by means of a rapidly oscillating piston, which is driven by either a pneumatic or hydraulic power source. With each blow, a stress wave moves from the drifter through the steel and bit into the rock, which shatters under the tungsten carbide cutting edges of the bit. After each blow, the steel and bit rotate slightly to bring the cutting edges of the bit into contact with fresh rock surface. The feed, a chain- or screw-drive mechanism within a channel, supports the drifter and moves it forward as drilling progresses; and this forces the bit against the rock. The centralizer wraps around the drill steel and keeps it from wandering sideways at the start of drilling. The chips and dust produced during drilling are flushed from the hole by either compressed air or water that flows through the center of the steel and out through

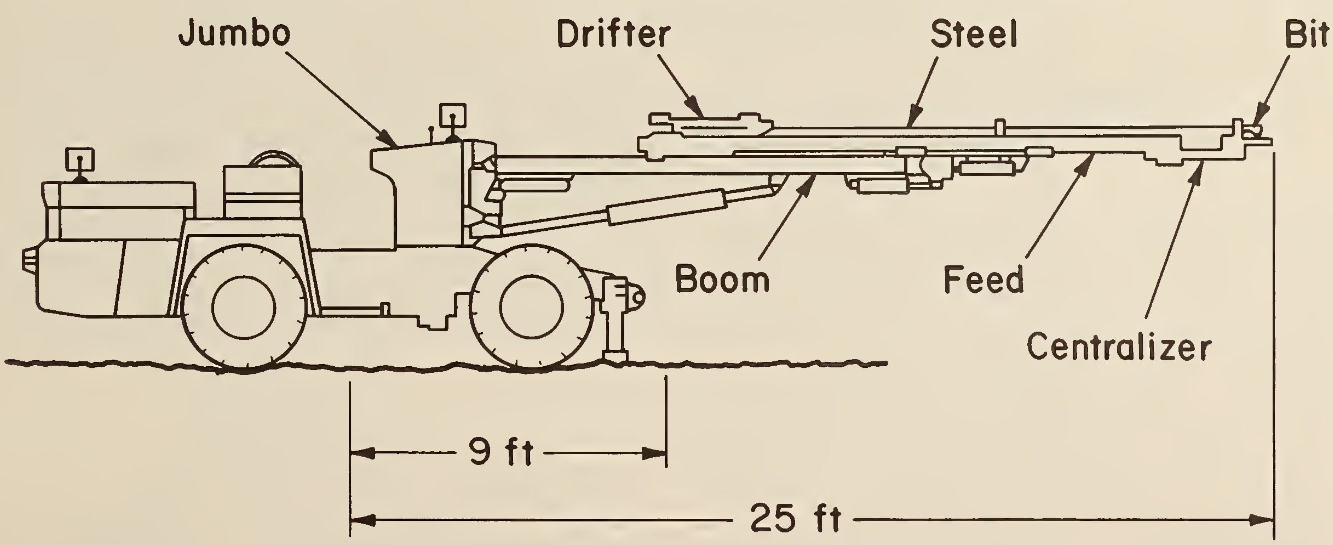


FIGURE 6. - Major components of a jumbo drill rig.

ports in the bit. The drill operator stands on a platform on the jumbo vehicle, just behind the booms.

Figure 7 shows the noise-generating mechanisms of jumbo-mounted pneumatic percussion drills. These mechanisms can be placed in two broad categories: exhaust noise and vibration of mechanical components. Exhaust noise, drifter-body vibration, and drill-steel vibration outweigh the other noise sources shown in figure 7; therefore, the Bureau has focused its efforts on ways to control these sources.

A straightforward approach for controlling exhaust noise is to channel it away from the operator through ductwork. A second approach is to attach a baffle-type muffler directly to the exhaust port(s) of the drifter. A third is to place the drifter inside an acoustical enclosure. These approaches are effective in reducing noise, but all share a common problem: freezing. The rapidly expanding exhaust air cools quickly, and the moisture in the air condenses on the inside surfaces of the ductwork, muffler, or enclosure; after a short time, perhaps only a few minutes, ice begins to accumulate, inhibiting the flow of exhaust air and causing the drill to stall. The Bureau presently has an in-house test setup designed to investigate the muffler-freezing problem in more detail. Also, as described in part 3, ice-inhibiting enclosures for two different jumbo drills were developed under two recent Bureau contracts. The enclosures reduced both the exhaust noise and the noise generated by vibration of the drifter body.

The vibrating drill steel often generates more noise than any other component of the jumbo rig. To address this problem, the Bureau is investigating several different drill-steel noise-control techniques. The two contracts mentioned above explored the "shroud-tube" concept, whereby a tube-shaped acoustical enclosure completely surrounded the drill steel. One contract (11) produced a form-fitting shroud-tube that closely surrounded the drill steel, like a sheath. The tube diameter was slightly smaller than the cutting bit diameter, allowing the tube to enter the hole as

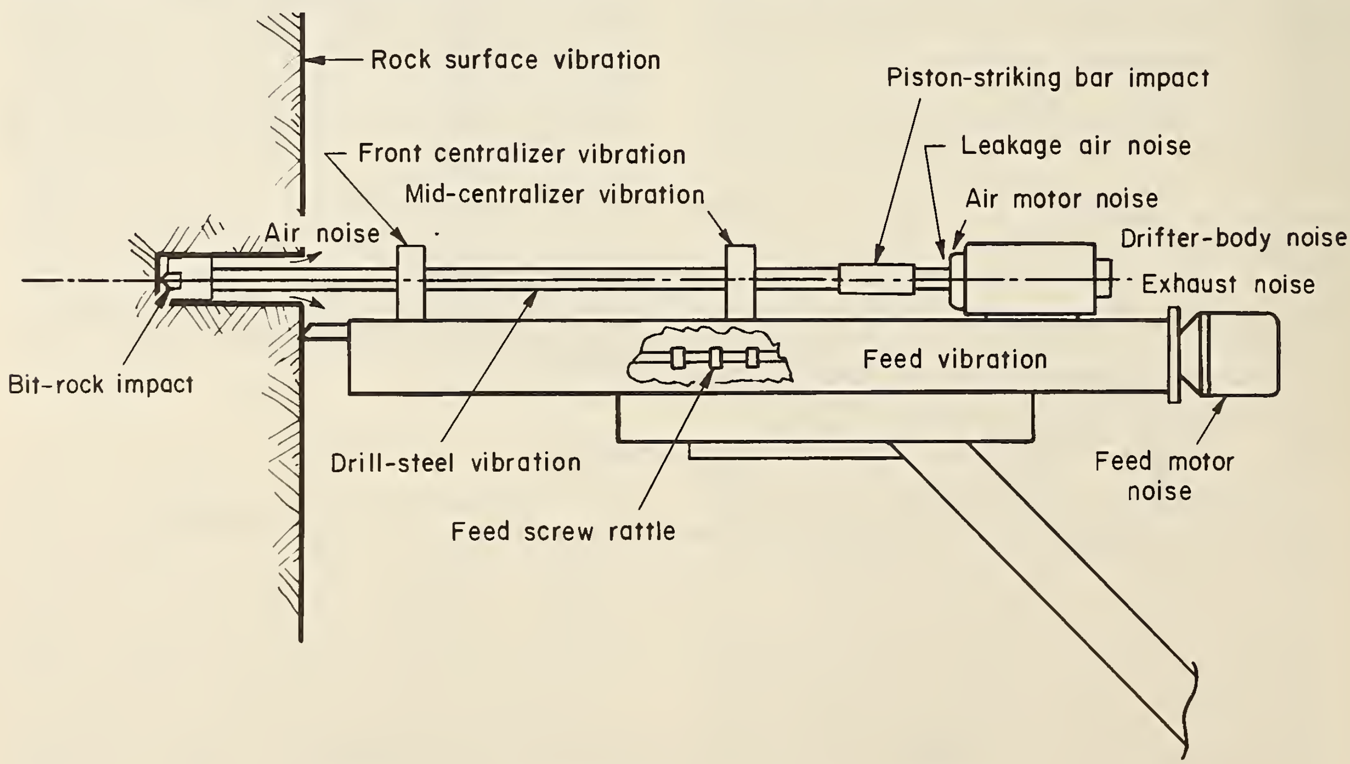


FIGURE 7. - Noise sources on jumbo-mounted drills.

drilling proceeded. The Bureau is now testing this "in-the-hole" shroud-tube design to determine its long-term durability and acoustical effectiveness. A large-diameter springlike shroud tube was developed under the second contract and is now being field-tested by the contractor (14). This "spring shroud" is located between the drifter body and the front centralizer (fig. 7) and is fully extended before drilling begins. As the hole is drilled, the drifter body moves closer to the front centralizer, and the spring shroud collapses around itself. Unlike the form-fitting shroud tube described above, the spring shroud does not enter the drill hole; it covers only the portion of the drill steel that is outside the hole. Noise generated by the drill steel that is within the hole is attenuated by the rock mass.

Handheld hardrock drills are also used for underground ore production, especially in tight quarters where jumbo-mounted drills cannot fit. Handheld drills are smaller and less powerful than jumbo-mounted drills, but the operating principles are the same except for the feed mechanism. Instead of a chain- or screw-type feed, handheld hardrock drills utilize air-powered cylinders called feedlegs, which are similar to the feedlegs used on coal mine stoper drills (fig. 5). Handheld hardrock drills are similar in design and construction to coal mine stopers, but must deliver more energy per blow to the bit because they drill in harder rock. The same basic noise-control treatments are required for both types of handheld drills; however, adapting coal mine stoper noise controls to hardrock drills is not a simple task because of the higher energy requirements. A prototype quiet handheld hardrock drill is now being developed under Bureau contract (8).

Haulage Methods

As in coal mines, man- or animal-powered carts were the first step toward mechanization of underground ore haulage in hardrock mines. Although air- and steam-powered loading and hauling vehicles were used in the 1800's, they were gradually replaced with diesel-powered machines. The diesel engine provides a safe, efficient, compact, and highly mobile power source and has been applied in the last 50 yr to many different types of underground hardrock mining equipment. It is by far the most popular source of power for today's underground hardrock haulage machines.

Recent Bureau studies revealed that a wide variety of diesel-powered loading and hauling machines are now used in underground hardrock mines (26). Most of these machines generate noise levels above 95 dBA at the operator's position, and operate long enough to cause overexposure. The noisiest machines in terms of operator overexposure are LHD machines, followed by ore trucks, ram haulers, tractor-trailer units, front-end loaders, skid-steer loaders, and shuttle cars. All of these machines share the following noise sources: (1) engine airborne noise (emanating directly from the engine or block structure); (2) engine structureborne noise (engine vibration radiated through the structure of the machine); (3) auxiliary-component noise--airborne and structureborne noise from the transmission, drive train, and hydraulic system; (4) noise generated by the cooling system fan; (5) exhaust noise--airborne noise from the outlet and structural radiation from the exhaust piping (or shell); and (6) air-intake noise--airborne noise from the intake and structural radiation from the intake piping.

The Bureau directed its initial noise-control research efforts toward LHD vehicles because many LHD operators are overexposed to noise and because the LHD is one of the most common machines in underground hardrock mines. Also, compared with other machines, the LHD is more difficult to treat for noise control; its structure is more complex, it places greater visual demands on the operator, and it is not designed to accommodate an acoustical cab (e.g., for underground ore trucks and surface haulage equipment). It was apparent that if the noise-control treatments developed for LHD's were successful, they could be modified and applied to other diesel-powered machines. As described in part 3, the Bureau is presently involved in both retrofit (22) and "factory-integration" (41) approaches to LHD noise control.

Roof Support Methods

Roof support in underground hardrock mining followed about the same evolutionary path as in coal mining--wooden posts and timbers, installed manually, were gradually replaced by mechanized roof-bolting systems. Handheld and jumbo-mounted percussion drills are used to drill the holes for roof bolts; in addition, diesel-powered machines (shotcrete machines, roof bolters and scalers, transit mixers and placers, etc.) are sometimes used in the roof support systems of underground hardrock mines. Because the diesel engine of the roof support machine is the primary noise-generating mechanism, the results of the Bureau's LHD noise-control program could be applied. However, the Bureau has not directly addressed the control of noise produced by roof support machines (other than percussion drills) because they do not contribute to widespread worker overexposure.

SURFACE MINING

Surface mining, like underground mining, involves excessive levels of equipment-generated noise. One of the first powered surface mining machines was a steam-driven "spoon dredge" developed in England in 1796. The need for faster railroad construction in the mid-1800's was responsible for the development of today's large mining shovels. Steam power gave way to internal-combustion and diesel engines, and finally to electric power shortly after 1900.

Ironically, the largest and most powerful surface mining machines--shovels and draglines--are not responsible for widespread overexposure to noise because (1) they are comparatively few in number, and (2) they often have factory-installed noise-controlled operator cabs. Instead, mobile diesel-powered machines such as bulldozers and front-end loaders have been identified by the Bureau as the primary noise offenders in surface mining operations (table 4) (9, 40). Even though these machines have about the same noise sources (fig. 8) as their underground counterparts, the LHD vehicles, the Bureau's approach to noise control has been much different. Since underground equipment must operate in a very confined environment, it is very difficult to design and install an acoustical cab that does not interfere prohibitively with operator movement and vision. However, this is not true of surface mining equipment, so for this equipment the acoustical cab approach was pursued as the most cost-effective means of reducing operator overexposure.

TABLE 4. - "Noise offenders" in surface mining operations

Equipment type	Pct of total overexposed operators
Bulldozers	48
Front-end loaders	15.5
Haulage trucks	8.5
Draglines	8
Scrapers	5.5
Overburden drills	2
Highway trucks	.5
All others	12

Although several types and models of surface mining equipment now have factory-installed acoustical cabs, many older bulldozers and front-end loaders do not. Therefore, the Bureau developed acoustical cab retrofit treatments for two popular models of each of these two machines (6-7). Although each model of bulldozer and front-end loader requires a slightly different retrofit package, the same basic procedures can be used on all models. Part 3 describes the results of these retrofit treatments.

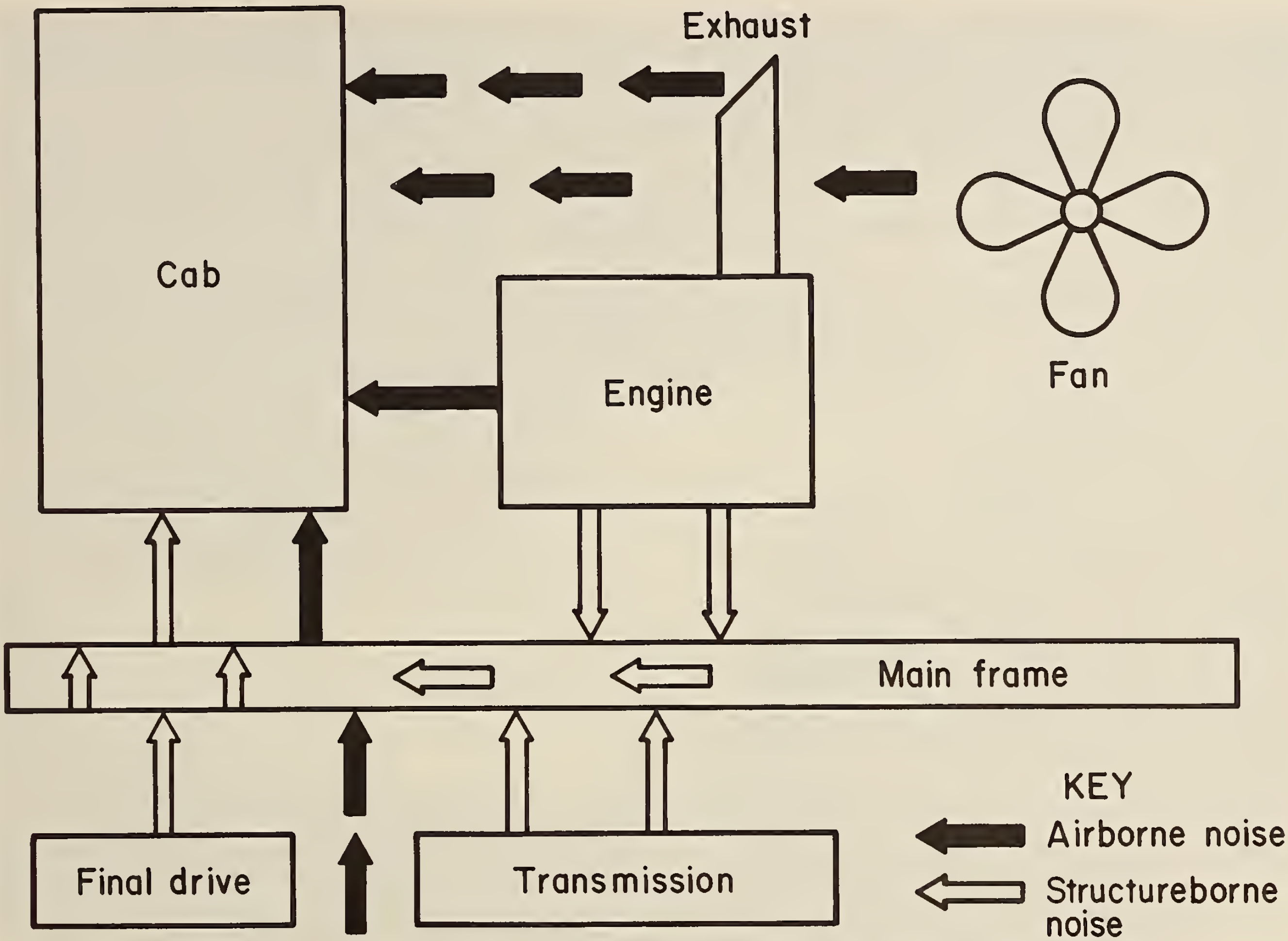


FIGURE 8. - Noise sources of mobile, diesel-powered surface mining equipment.

PREPARATION AND PROCESSING PLANTS

Almost all substances extracted from mines must undergo some form of processing to become a usable product. Mineral processing predates recorded history; "De Re Metallica," written in 1556 by Georgius Agricola, reveals the existence of equipment and techniques such as picking tables, smelting furnaces, sieves, crushers, and other items, all still used in one form or another. The noise associated with coal and mineral processing plants became much greater as more powerful energy sources, especially electric power, replaced wind and water as the primary driving forces behind mineral processing equipment.

All preparation plants contain equipment that performs one of three primary functions: crushing (size reduction), screening (size separation), and dewatering. In addition, many plants contain equipment that separates valuable constituents (coal or ore) from waste material through differences in their densities, physical properties, chemical properties, and/or magnetic properties. These machines come in a wide variety of shapes and sizes, and the flow of material through each preparation plant is different. Figure 9 shows the overall layout of the grinding mill area in a typical taconite (iron ore) processing plant. Each piece of equipment generates noise; furthermore, the mere transfer of material through the plant generates noise as the result of impacts between stationary components--chutes, bins, hoppers, etc.--and the moving material. Fluid movement, such as air flowing through a size-separation or dewatering device, also generates noise.

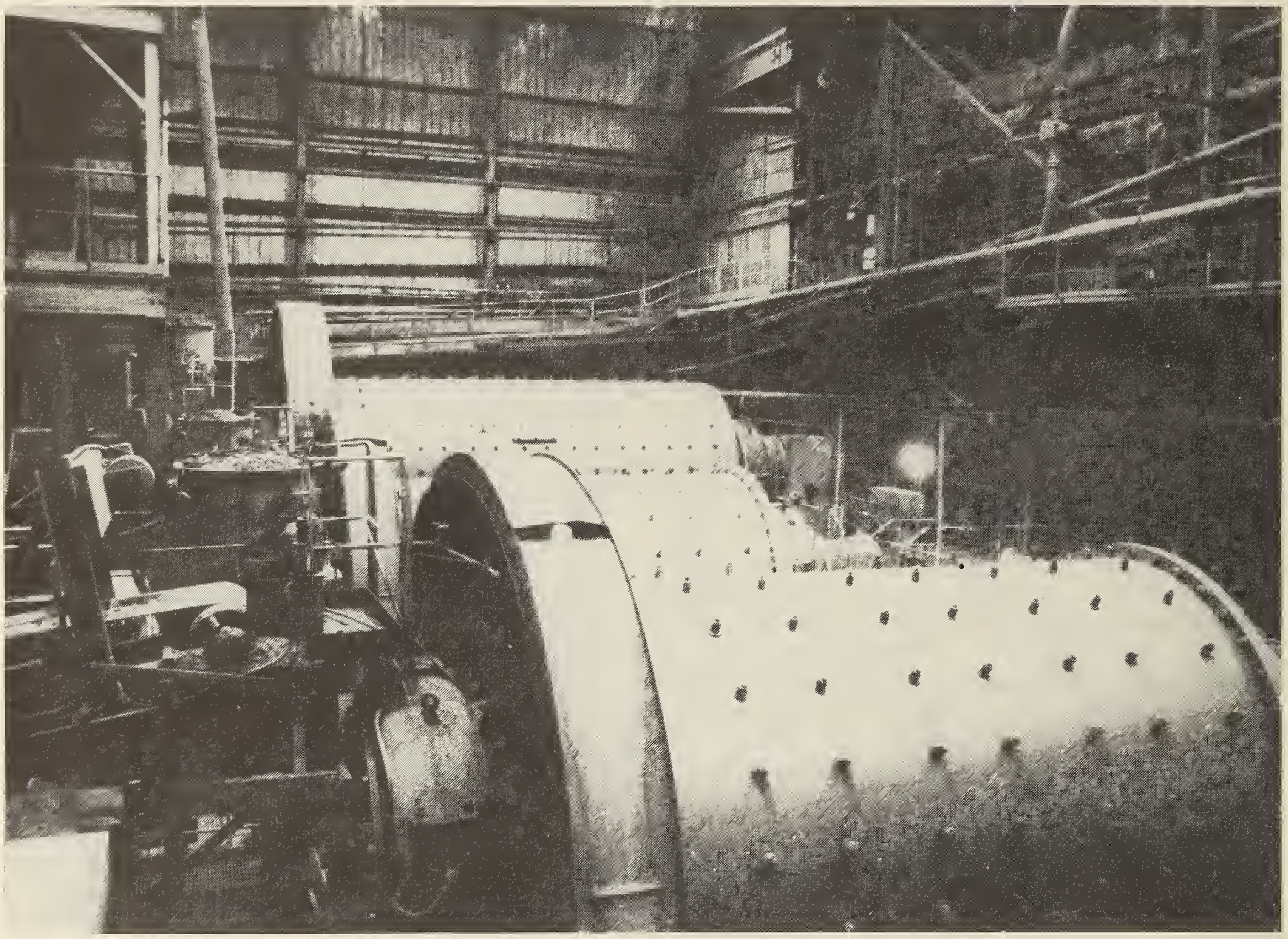


FIGURE 9. - Grinding mills in taconite processing plant.

Noise exposures of preparation plant workers depend mostly on their proximity to noise-producing equipment. Stationary workers have specific job stations that may or may not be close to a loud noise source. The noise exposures of stationary workers are relatively easy to measure compared to those of mobile workers--mechanics, samplers, cleanup workers, supervisors, etc.--who move throughout the plant during their normal working day. (Note the walkways in figure 9.) Consequently, the approach for reducing worker overexposure may be different for each type of worker. Acoustical booths and/or engineering noise controls are often better for stationary workers, while hearing protectors and/or administrative controls may be better for mobile workers.

Regardless of the nature of worker overexposure, however, engineering noise control of preparation plant equipment, if feasible, is the best long-term solution to the problem. The Bureau has therefore identified the most serious noise offenders in coal and mineral processing plants and has investigated means to control them. Noise generated by crushing devices can be controlled effectively by surrounding either the operator or the entire crusher with an acoustical barrier. Screening noise can be controlled by enclosing the area of the plant containing the screens or by using screen decks made of nonmetallic, energy-absorbing materials. Chutes and bins can be lined with rubber or other energy-absorbing materials to reduce the severity of impacts caused by moving material;

damping materials can also be added to reduce the vibration of chute and bin panels. An acoustical operator booth can be the most cost-effective solution, especially in small, portable mineral processing plants.

Part 3 describes the Bureau's preparation plant noise-control programs in more detail. A related study dealing with the screening efficiency of nonmetallic screen decks is also described in part 3.

PART 3.--RESULTS OF SELECTED RESEARCH PROGRAMS

This part of the report describes in detail the results of selected Bureau noise-control research projects. As in part 2, noise-control projects for underground coal mining are discussed first, followed by projects involving underground hardrock mining, surface mining, and preparation and processing plants. The final section of part 3 discusses the results of recent Bureau research into the potential effectiveness of personal hearing protectors in the mining environment.

UNDERGROUND COAL MINING

Part 2 reviewed the Bureau's underground coal mining noise-control research programs in terms of the three unit operations involved--extraction, haulage, and roof support. Here, the results of four specific Bureau noise-control research programs are discussed in detail, again in terms of unit operations: (1) coal cutting (extraction), (2) chain conveyors (material haulage), (3) mantrip vehicles (personnel haulage), and (4) stoper drills (roof support). Although several other projects dealing with underground coal mining noise have been conducted by the Bureau, the results of these four programs appear to have the most potential for impact on the industry.

Coal Cutting

Two major projects concerned with coal-cutting noise have been completed thus far; one was a series of extensive laboratory studies into the mechanics of the coal-cutting process, and the other was the development of reduced-noise cutting heads for auger-type continuous miners. The results of these programs are now being used in current Bureau research into the reduction of coal-cutting noise and will continue to influence the direction of this research.

Laboratory Studies (1, 3)

Early Bureau experiments revealed that an in-depth scientific understanding of the coal-cutting process was needed to devise an effective method for controlling coal-cutting noise. The three components of coal-cutting noise are (1) fracture noise, which is produced by the movement of air to fill the voids resulting from the formation of cracks in the coal; (2) face radiation, the vibratory response of the coal face itself; and (3) cutting head vibration, which results from the transfer of cutting forces from the bits to the rotating head assembly. The three basic goals of the laboratory studies were to (1) identify the dominant component of coal-cutting noise (fracture, face radiation, or cutting head vibration); (2) determine the magnitude of coal- and shale-cutting forces; and (3) show how the coal- and shale-cutting noise level can change due to machine operating parameters such as depth of cut, cutting speed, bit style, etc.

Noise of Coal Fracture and Face Radiation

One of the most important tools used in the laboratory studies was a gravity-powered "linear cutting apparatus" (LCA). The three major components of the LCA (fig. 10) were a sliding carriage capable of holding a small sample block of coal, a vertical guide mast on which the sample carriage was mounted, and an instrumented cutting bit on a pedestal. To operate the LCA, the coal sample carriage was raised above the instrumented bit and released; the falling coal sample then

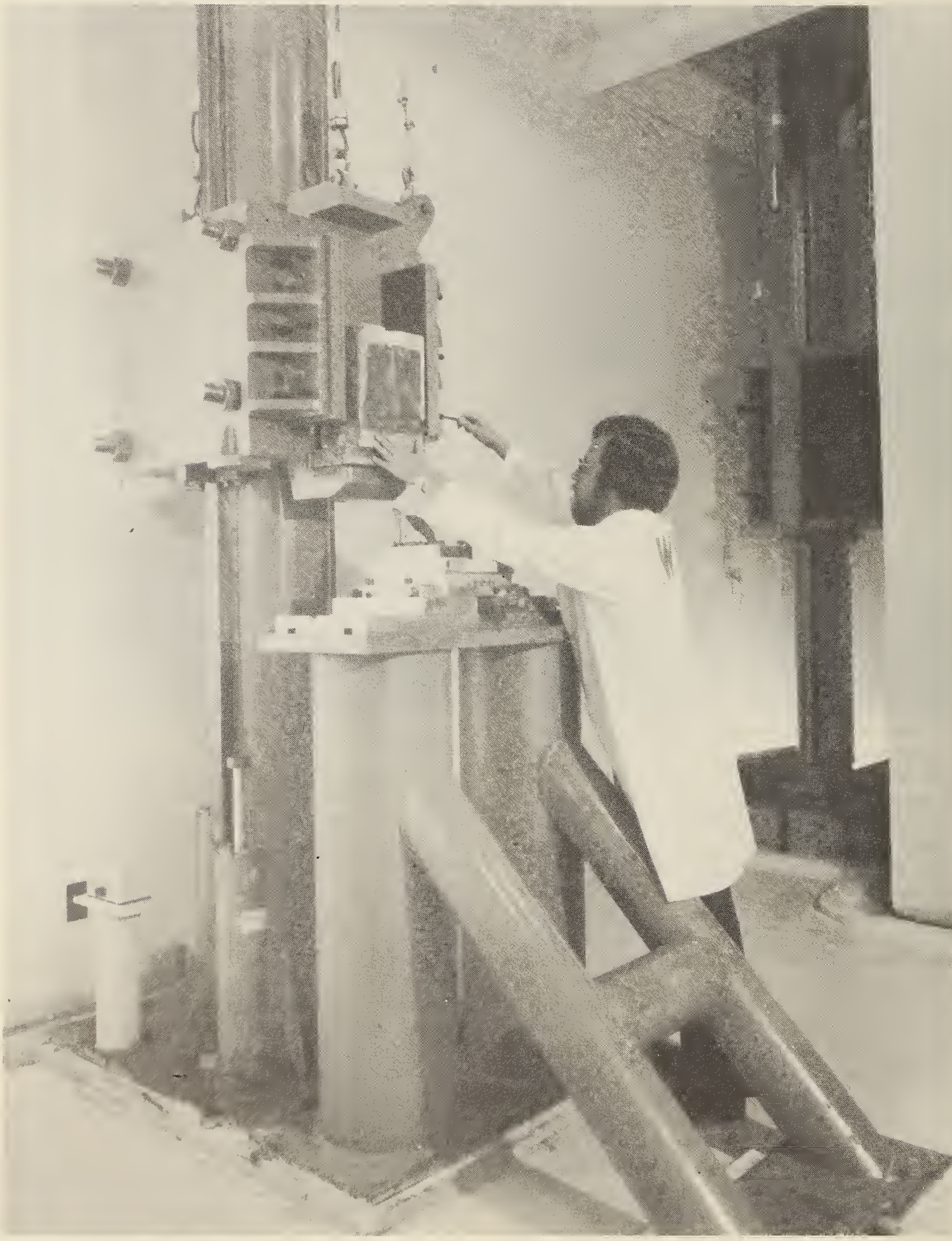


FIGURE 10. - Linear cutting apparatus.

struck the bit and continued downward, resulting in a single, linear cut on one face of the sample. The instrumented bit measured the coal-cutting forces, a counterbalance system regulated the acceleration of the coal-sample carriage (i.e., the "cutting speed"), and the bit-mounting pedestal could be adjusted to control the depth of cut.

The entire LCA was enclosed in an anechoic chamber--virtually no noise was reflected from the walls, floors, or ceiling. The anechoic chamber was enclosed in an underground building with thick concrete walls to prevent outside noises from entering the chamber. The hollow interiors of the carriage-guide mast and the bit-mounting pedestal were filled with sand to reduce the LCA's "self-noise" during cutting. Coal-cutting noise could be measured quite accurately with this test setup because it was the only significant noise within the enclosure.

LCA tests showed how coal fracture and face-radiation noise was affected by eight different cutting parameters: cutting speed, depth of cut, overburden pressure, cut spacing, bit type, cutting angle, bedding plane orientation, and coal type. Using these eight parameters as independent variables (i.e., they were controlled by the experimenters), five dependent variables were measured: cutting force, sound pressure level, coal-sample surface acceleration, production rate, and specific energy. The results of the LCA tests are described below in terms of these dependent variables.

Cutting Force

One of the most important findings of the LCA tests was that coal resists the advance of a cutting bit in a manner analagous to the action of a spring. The cutting force of the bit increases until the tensile stress in the coal initiates a localized brittle fracture. This fracture propagates out from the point of force application for a small distance. The bit continues to advance through fractured coal, meeting relatively little resistance until it again contacts unfractured coal, when the process is repeated.

Figure 11 is a graph of coal-cutting force versus time; it clearly shows the impulsive nature of the coal-cutting process. Note that the initial impact force is no higher nor longer lasting than the subsequent fracture events. The peak

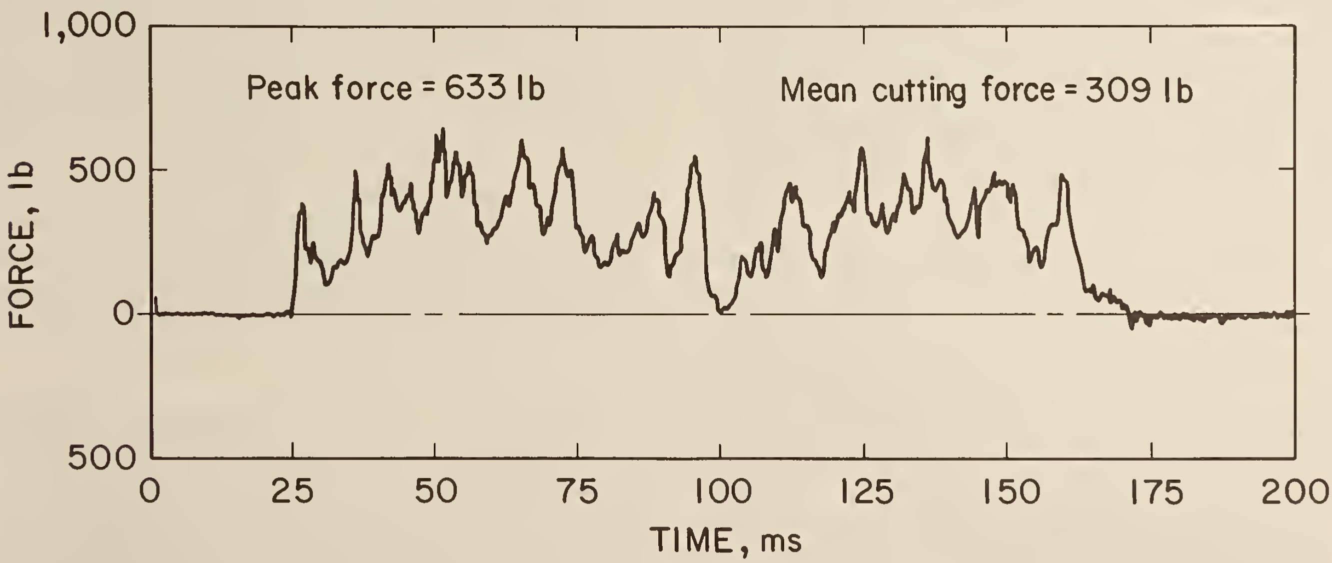


FIGURE 11. - Coal-cutting force versus time.

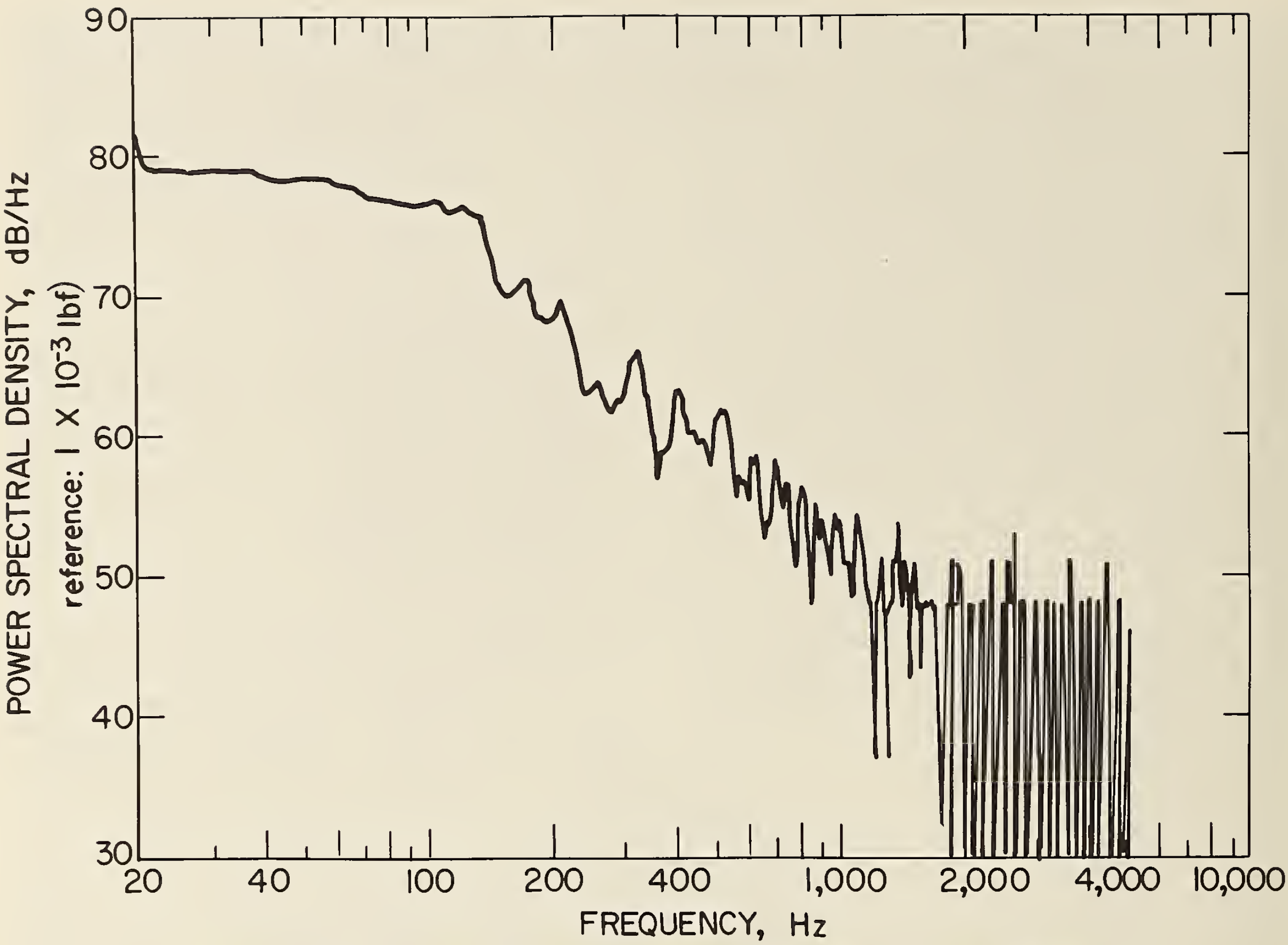


FIGURE 12. - Coal-cutting force (power spectral density) versus frequency.

force initiating coal fracture and the number of fracture events occurring within a given length of cut were found to be independent of cutting speed. However, the type of coal, depth of cut, and bit configuration significantly affected the cutting force.

Figure 12 is a graph of coal-cutting force (power spectral density[7]) versus frequency, taken from the force-time history of figure 11. The cutting force is relatively flat (fig. 12) until the "cutoff frequency," the point after which it declines at a rate that is inversely proportional to the square of the frequency. The cutoff frequency is primarily a function of the coal type and cutting speed--the faster the cut, the higher the cutoff frequency. Knowledge of this force-versus-frequency behavior played a very important role in the subsequent design of noise-control treatments for coal-cutting machinery.

In addition, the relationship between cutting speed and cutoff frequency could be exploited in terms of reducing the noise of existing cutting machinery. Since the A-weighting scale deemphasizes the importance of low-frequency noise, slower cuts would be "less noisy" than faster cuts with respect to human

[7]In figure 12, power spectral density is expressed as the force level (in decibels) divided by the frequency bandwidth (in hertz) in which the force is measured. To obtain the force level, the measured force is compared to a reference force of 1×10^{-3} lb. (The decibel is defined in footnote 6.)

hearing, because the forces initiating the noise would be predominantly low-frequency forces.

Sound Pressure Level

With a cutting speed of 96 in/s and a cut depth of 1.0 in, the sound pressure level (SPL) ranged from 89 to 102 dB, depending on coal type and bit type. The SPL increased with increasing cutting speed and depth of cut, and the noise spectra shifted to higher frequencies as cutting speed increased.

Coal Sample Surface Acceleration

The root-mean-square (RMS) values of face acceleration were proportional to the SPL's and were affected by the independent variables in the same manner as the SPL's. This proportionality suggested that sample face vibration rather than fracture noise was the dominant noise source during the LCA tests.

Production Rate

The average production rate was measured by dividing the total weight of coal produced from a linear cut by the time needed to make the cut. The production rate was found to be directly proportional to the cutting speed; it increased slightly with increasing overburden pressure but was unaffected by the angle of bit attack. The production rate varied with the depth of cut according to the relationship

$$\text{Production rate} = \text{Depth}^n,$$

where n = an experimentally determined exponent. The value of n ranged from 1.29 to 1.99, depending on the coal and bit type.

Specific Energy

The specific energy of a cut is the single best indicator of cutting efficiency; it is defined as the cutting energy per unit of coal extracted. In the LCA tests, the specific energy of a cut was measured as the ratio of power consumed (energy per unit time) to the production rate (mass per unit time). The most important variable affecting specific energy was the depth of cut; specific energy decreased as the depth of cut increased. In terms of noise control, this finding was important because it showed that for equal production rates, deep cuts would be quieter than shallow cuts.

Coal type, overburden pressure, bedding-plane orientation, and bit type also affected the specific energy of the cutting process. (But somewhat surprisingly, cutting speed did not.) Of these variables, only the bit type can be changed by the mine operator to achieve quieter, more efficient cutting. However, the "most efficient" cutting bit in terms of specific energy (as measured in the LCA tests) may not last as long as a "less efficient" bit when used on operating continuous miners or longwall shearers. More rigorous cutting tests are needed to confirm the mine-worthiness of the bits found to be "most efficient" when used on the LCA.

To summarize, the results of the LCA tests suggested that the noise produced by coal fracture and face radiation could be reduced by increasing the cut depth, decreasing the cutting speed, and choosing the most efficient cutting bit. The Bureau has also found that deeper, slower, more efficient coal cutting reduces the amount of respirable dust generated (31). Therefore, if these characteristics could be incorporated into future designs for coal-cutting machinery, multiple health and safety benefits would result.

Noise Caused by Cutting Drum Vibration

As previously stated, noise generated by coal cutting has three components: fracture noise, face-radiation noise, and vibration of the cutting head of the mining machine. The LCA tests only investigated the first two components; therefore, further laboratory tests were required to determine the contribution of cutting head vibration to coal-cutting noise. These tests consisted of operating a continuous mining machine in a large reverberation chamber--a building whose predictable internal sound-reflecting characteristics made it possible to accurately measure the sound power generated by noise sources within. A large block of synthetic coal was placed in the reverberation chamber to serve as a cutting medium. The synthetic coal material was a concrete-and-coal mixture that accurately simulated the acoustic efficiency (ability to radiate sound power from mechanical cutting power) of real coal. Figure 13 shows the continuous miner and synthetic coal test setup.

In order to determine the contribution of cutting head vibration to the overall noise level, the noise generated by the continuous miner while idling was first compared to the overall noise generated while cutting. The conveyor of the miner was not operated during these tests because the presence of conveyor noise would have made cutting noise more difficult to measure. Idling noise (pumps on, cutting drums spinning in air) was found to be 81.5 dBA at the operator's position. As shown in table 5, the overall noise level was measured in two cutting modes--sumping (advancing forward into the seam) and shearing (cutting downward at an 8-in sump depth). Noise levels in these two modes (94.8 and 97.0 dBA, respectively) were substantially higher than in the idling mode.

The surface of the miner's cutting drum was then wrapped with an acoustical material (vinyl-backed foam) that greatly reduced its ability to radiate noise. The differences between the noise levels measured while cutting with the treated and untreated drums (table 5) showed that cutting head vibration contributed an additional 3.6 to 4.4 dBA to the overall noise level. This suggested that cutting head vibration was indeed a significant contributor to overall cutting noise. Due to the logarithmic nature of the decibel scale, a 3-dB increase in noise level is approximately equal to a doubling of the sound power within the reverberant environment, and a 6-dB increase in noise level represents a fourfold increase in sound power. Since the noise levels of the untreated drum tests were 3.6 to 4.4 dBA greater than those of the treated drum tests, the contribution of cutting head vibration to the overall noise level was at least as great, and often greater, than the sum of coal-fracture noise, face-radiation noise, and the idling noise of the miner.

TABLE 5. - Results of continuous miner cutting-noise tests

(Overall sound levels, dBA)

	Cutting mode	
	Sumping	Shearing (8-in depth)
Untreated drum........	94.8	97.0
Treated drum..........	91.2	92.6
Noise reduction..	3.6	4.4

The acoustical treatment used on the cutting drum in these experiments may not have completely eliminated the noise generated by cutting head vibration. This suggests that cutting head vibration may be even more important than implied above. Unfortunately, a much sturdier acoustical treatment than the vinyl-backed foam wrapping would be required for underground use; but to date, no mineworthy acoustical treatments for cutting drums have been developed. A 3.6- to 4.4-dBA noise reduction through cutting drum treatments appears to be a reasonable goal; however, if the cutting drums themselves were redesigned, greater noise reductions would be possible.

The results of the cutting head vibration tests suggest that coal-cutting noise can be reduced substantially if coal-cutting forces are not allowed to excite the cutting drum. The concept presently being investigated by the Bureau is the "isolated cutting drum," a technique that involves the complete redesign of the drum and a significant change in the bit-mounting scheme. The LCA tests provided valuable information

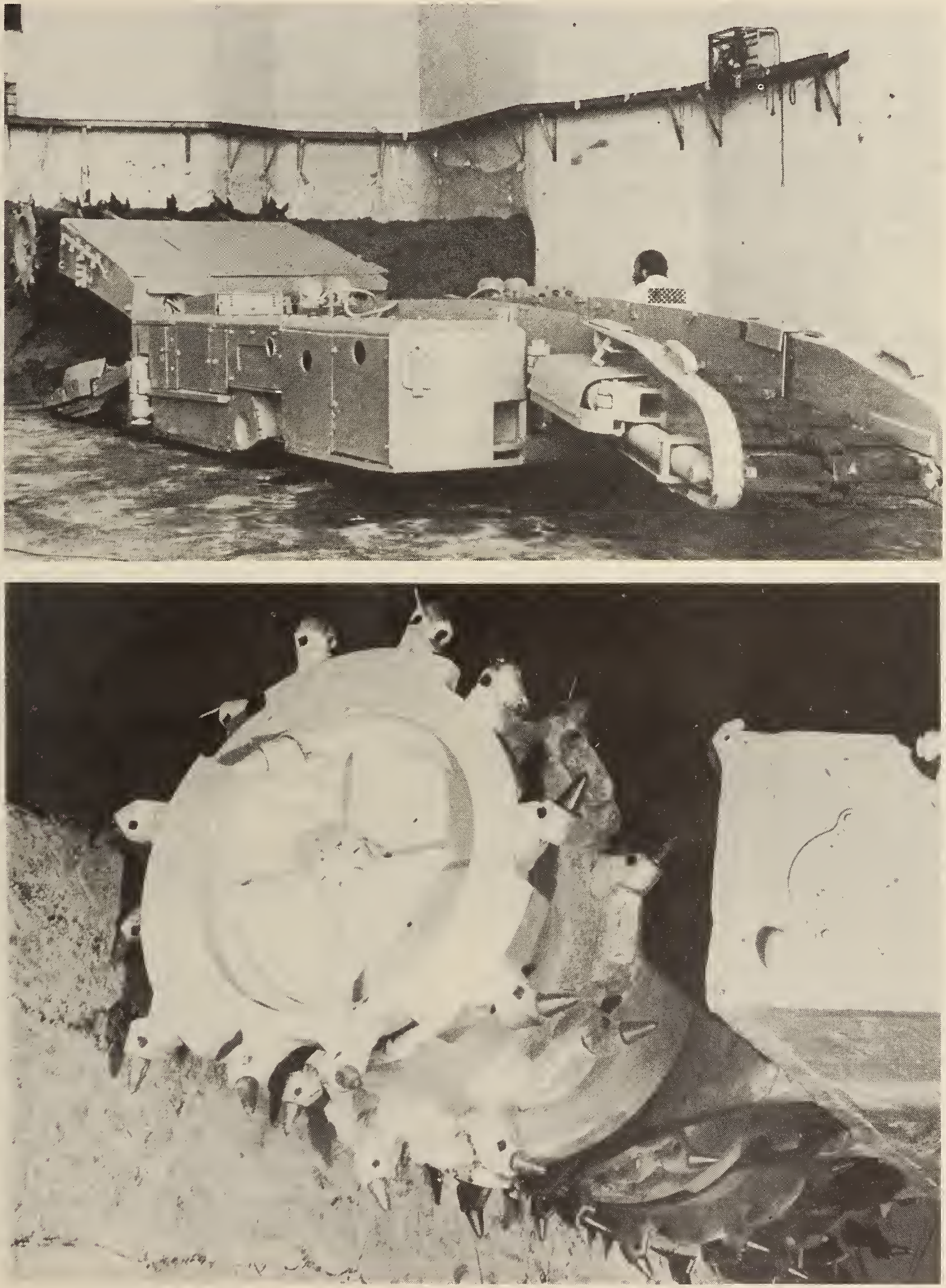


FIGURE 13. - Continuous miner in reverberation room (top) and closeup showing cutting head and synthetic coal (bottom).

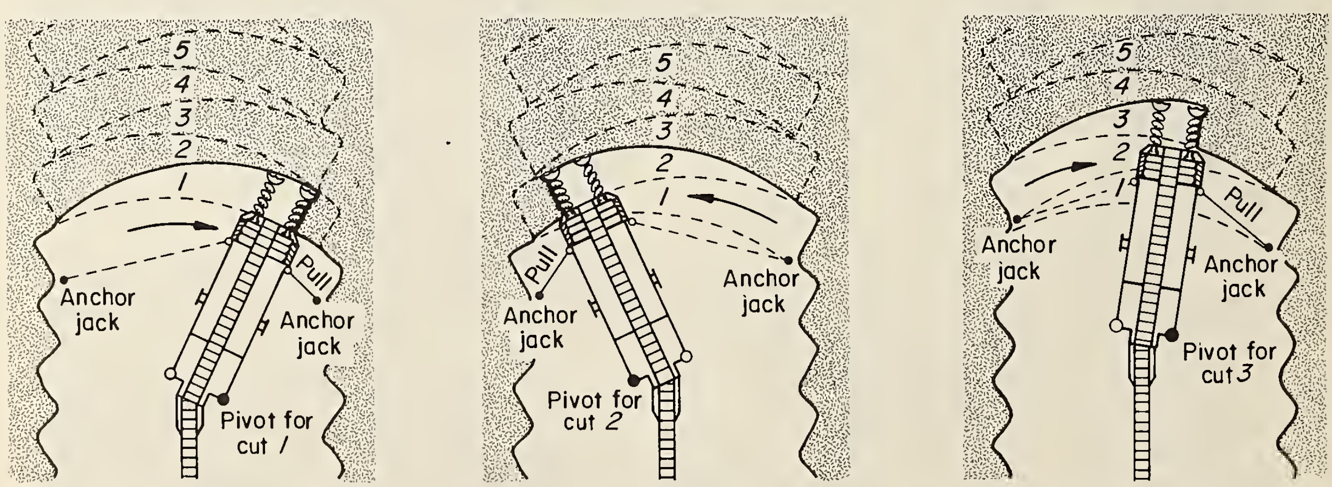
on how coal-cutting forces are generated, how large they are, and how they are transferred from the bit block to the standard cutting drum. This information was needed to select appropriate energy-absorbing materials for the new "isolated" drums now being designed for both continuous miners (42) and longwall shearing machines (43).

Reduced-Noise-Auger-Miner Cutting Head (26-27)

Auger-type continuous miners are designed to extract coal from thin seams, approximately 26 to 50 in in height. Figure 14 shows how auger miners advance into the coal face with a sweeping motion. The two rotating augers at the front of the miner cut the coal and move it to the chain conveyor at the center of the machine. The conveyor carries the coal to the rear of the machine and dumps it onto a bridge conveyor system. The bridge conveyor connects with a panel conveyor (panline), which removes the coal from the face area.

The anchor jacks (fig. 14) of most older auger miners are emplaced manually by "jacksetters." Newer auger miners do not require jacksetters, but other support workers (timbermen and/or cleanup workers) are still needed in the immediate face area, inby the operator. Because of their close proximity to the cutting heads, these workers are exposed to more noise than most other underground coal miners. Noise levels in a typical auger-mining section are 106 to 108 dBA at the jacksetter position and 102 dBA at the operator position. Table 2 shows that the allowable operating time at these levels is only 45 to 90 min per shift. The standard auger cutting heads are by far the dominant noise sources for the jacksetters, timbermen, and cleanup workers; whereas cutting noise and conveyor noise are approximately equal at the operator position.

The laboratory studies described in the previous section greatly aided in the design of a reduced-noise auger cutting head. Since coal-cutting forces are predominantly low-frequency forces (fig. 12), the auger design was based on reduction of its vibratory response to low-frequency excitation forces. The cutoff frequency for the standard auger cutting head was found to be approximately 100 to 200 Hz while cutting the synthetic coal seam shown in figure 13.



Miner pivots on extended right pivot jack as it swings to right, making cut 1. Retracted left pivot jack swings forward toward cut 2 pivot point.

Pivoting on extended left pivot jack, miner swings to left through cut 2. Retracted right pivot jack advances toward cut 3 pivot point.

Again pivoting on extended right pivot jack, miner swings right, making cut 3. Retracted left pivot jack moves ahead toward cut 4 pivot point.

FIGURE 14. - Cutting sequence of auger-type continuous miner.

The standard auger-miner cutting head (fig. 15) consists of a central cylindrical core surrounded by two helixes. The cutting helix contains all the cutting bits; the bitless, or conveying helix helps transport cut coal to the conveyor of the miner. These helixes vibrate violently, like high-powered speakers, when excited by coal-cutting forces. Since they are the primary noise sources on the cutting head, the design effort was directed at reducing helix vibration.

The mass, stiffness, and damping characteristics of the helix control its vibrational response to coal-cutting forces. The first natural vibration frequency of the standard helix was found to be about 200 Hz. Below this frequency, the helix's mass and stiffness control its vibrational response; above 200 Hz, the amount of damping at its resonant frequencies becomes more important. These structural response characteristics indicated that the reduced-noise auger design would have to (1) increase the first natural frequency of the helix and (2) increase the amount of damping at its resonant frequencies.

Several methods were used to stiffen and damp the auger helixes; however, the design most suitable for in-mine use was found to be the sand-filled auger shown in figure 16. First, the conveying helix shown in figure 15 was removed. Extensive in-mine tests of the reduced-noise augers showed that the single remaining helix was sufficient for both cutting and conveying. Although this change alone did not drastically reduce cutting noise, it simplified the auger substantially and made the subsequent stiffening and damping treatments easier to install.

Next, the helix was stiffened by enlarging the auger's core size and adding a "conical helix stiffener." The larger core helped reduce helix vibration by decreasing the helix's height. The conical helix stiffener was a second helix that was leaned against and welded solidly to the main helix to act as a continuous support. The addition of the stiffener resulted in the formation of three

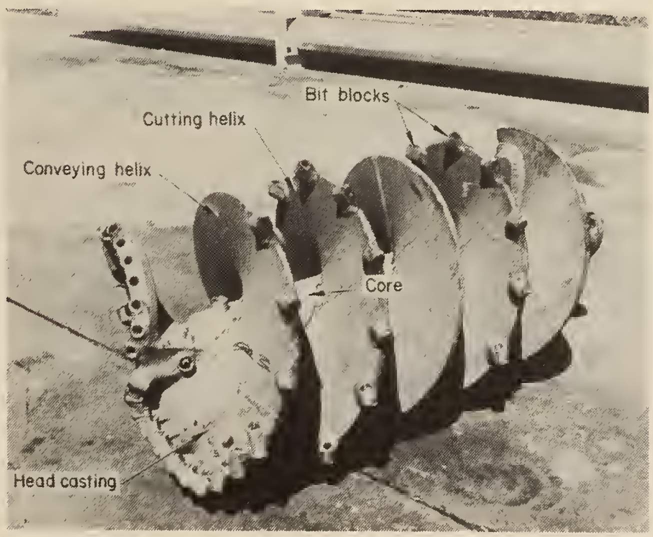


FIGURE 15. - Standard auger-miner cutting head.

FIGURE 16. - Reduced-noise auger-miner cutting head. (Top: view from front; bottom: view from rear.)

cavities with triangular cross-sections (figs. 16-17). The largest cavity was on the nonconveying (inby) side of the helix, but because of space constraints, the two smaller cavities were located on the conveying (outby) side. In-mine tests showed, however, that the addition of the stiffener to the conveying side did not reduce the auger's coal-carrying capability.

As shown in figure 17, the triangular-shaped cavities were filled with sand and sealed. The sand added mass, which further reduced the vibration of the helix and helped dissipate its bell-like ringing sound at its resonant frequencies. The added mass did not hamper the auger's performance because it merely replaced the mass lost when the conveying helix was removed.

A set of reduced-noise augers was tested for approximately 6 months in an underground coal mine. Although the miners were initially very skeptical about the new auger design, they were completely satisfied with its performance by the end of the test period. More importantly, the new augers resulted in substantial noise reductions--10 dBA at the jacksetter position (98 dBA overall noise) and 6 dBA at the operator position (96 dBA overall noise). This reduction was sufficient to eliminate the cutting head as a contributor to operator noise; no further reduction could be achieved without treating the chain conveyor or motors (17). The 10 dBA reduction at the jacksetter position resulted in a fourfold increase in allowable operating time--from 45 min to almost 3 h.

The conical helix stiffener and sand are relatively simple to install; they could be installed by most mine shops. However, the larger core is rather difficult to fabricate and does not produce

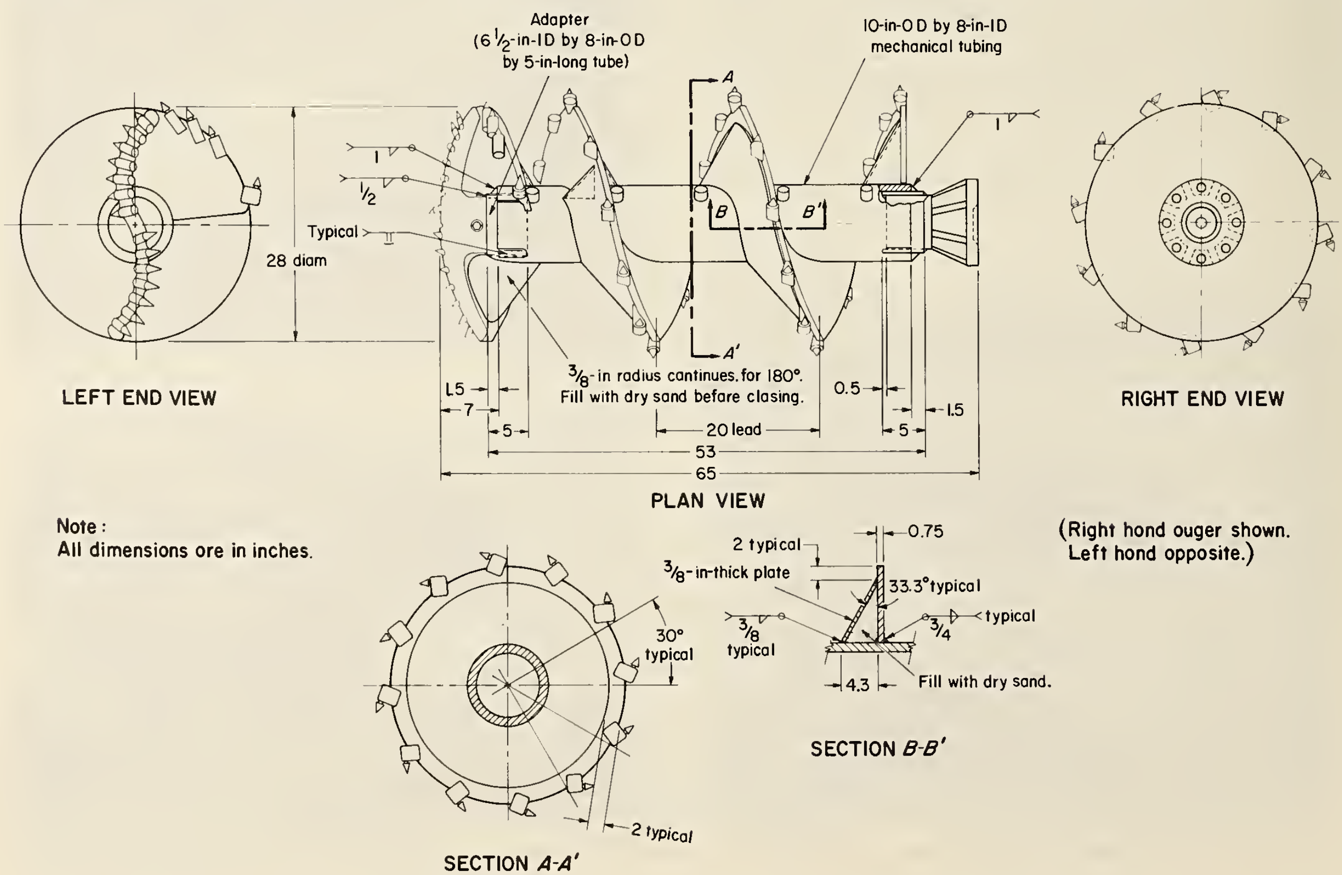


FIGURE 17. - Fabrication drawing of reduced-noise auger.

as much noise reduction as the stiffening and sand-filling treatments. Therefore, it is recommended that mine shops do not attempt to enlarge the auger core. Detailed instructions for converting a standard two-helix auger into a sand-filled single-helix reduced-noise auger are now available upon request from the Bureau. The reduced-noise augers are also available from the auger manufacturer.

Chain Conveyors

Part 2 briefly described the purpose of a chain conveyor, its major components, how it generates noise, and the Bureau's approach to conveyor noise control. Here, the results of Bureau research on conveyor noise (16) are discussed more thoroughly. Figure 4 (in part 2) shows the location of the conveyor on a continuous miner; figure 18 shows only the conveyor and points out the components that produce the most noise. The basic noise-generating mechanisms on the conveyor are (1) scraping of the chain and flights against the upper and lower decks and (2) impacts at discontinuities (gaps, misalignments, etc.), such as those at the idler roller, takeup plate, guide plate, and flex plate edge.

Aboveground Tests

Most of the Bureau research on conveyor noise control was done in an aboveground test facility. The key element of this facility was the conveyor portion of a continuous miner, including all the components pictured in figure 18. Prior to the installation of any noise-control treatments, the overall noise level at the operator's position (next to the bend of the conveyor) was 101.5 dBA. The following paragraphs describe the noise-control treatments developed for each noise source in figure 18 and discuss how each treatment contributed to the reduction of conveyor noise.

Figure 19 shows the basic components of the noise-control treatments applied to the conveyor decks and sidewalls. The top surface of the upper deck, the bottom surface of the lower deck, and the outer faces of the sidewalls received a constrained-layer damping treatment. In addition, the damped deck plates were isolated from the conveyor chain and flights by resilient wear strips. Both the damping treatment and the wear strips contained a layer of wear-resistant energy-absorbing polymer material sandwiched between layers of steel. The wear strips were also backed with rubber to further isolate the decks from the moving conveyor. The upper deck wear strips were originally welded to the deck in one piece, however, the relative motion between adjacent conveyor sections would have damaged these one-piece strips during normal underground operation.

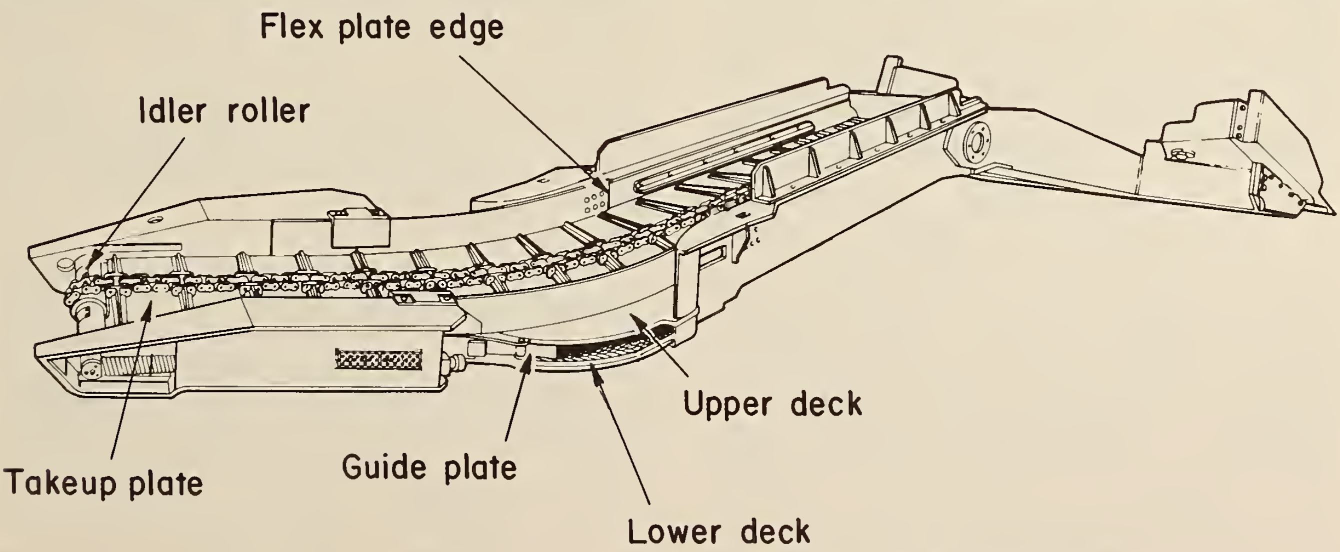


FIGURE 18. - Noise-producing components of a continuous miner chain conveyor.

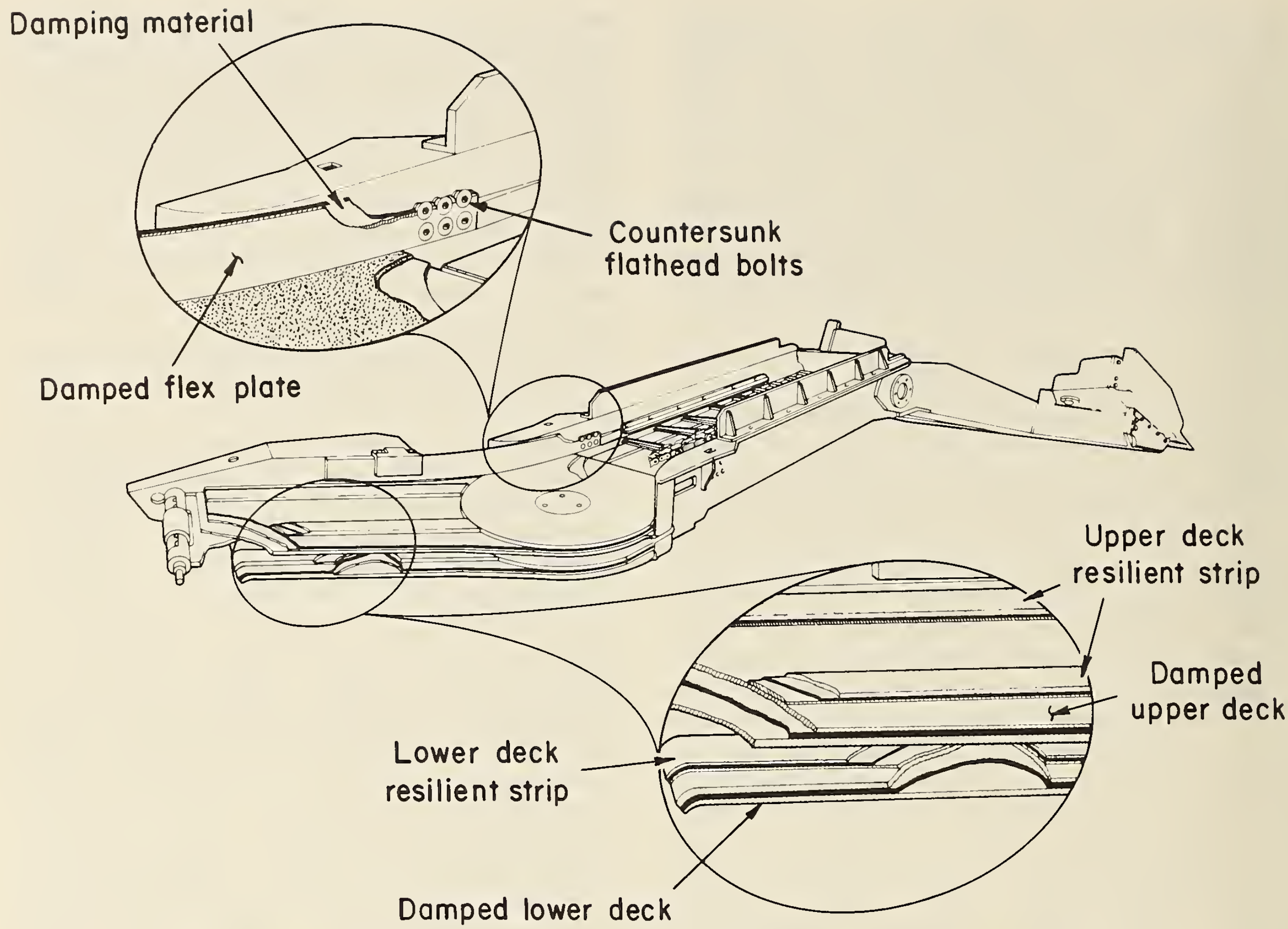


FIGURE 19. - Noise-control treatments on conveyor decks and sidewalls.

Therefore, the upper deck wear strips were cut, and their leading edges were tapered to reduce flight-strip impacts. Since this created discontinuities between adjacent conveyor sections, it reduced the quieting effect of the strips; however, cutting the strips in this manner increased their durability.

Figure 19 also shows several noise-control treatments designed to reduce noise due to impacts at the conveyor bend point. First, tapered metal strips were welded upstream of the flex plates to minimize impacts between the flight tips and the flex plate edges. Second, the original round-headed carriage bolts holding the flex plates to the sidewalls were replaced by countersunk flathead bolts, thereby reducing impacts between the flights and bolt heads. Third, the flex plates were damped in much the same way as the conveyor decks and sidewalls were damped. Fourth, a piece of leaded vinyl tape was placed over a hole in the sidewall near the operator's ear. However, the tape was only a temporary treatment; the conveyor manufacturer stated that the entire bend point area would have to be redesigned to eliminate the hole permanently.

Figure 20 shows the noise-control treatments applied to the tail section of the conveyor. The vertical mismatch between the idler roller and the rear edge of the upper deck was improved significantly by installing a larger diameter roller. This roller was mounted on resilient support slides to isolate the tail section from the remaining chain-roller impacts. Figure 20 also shows

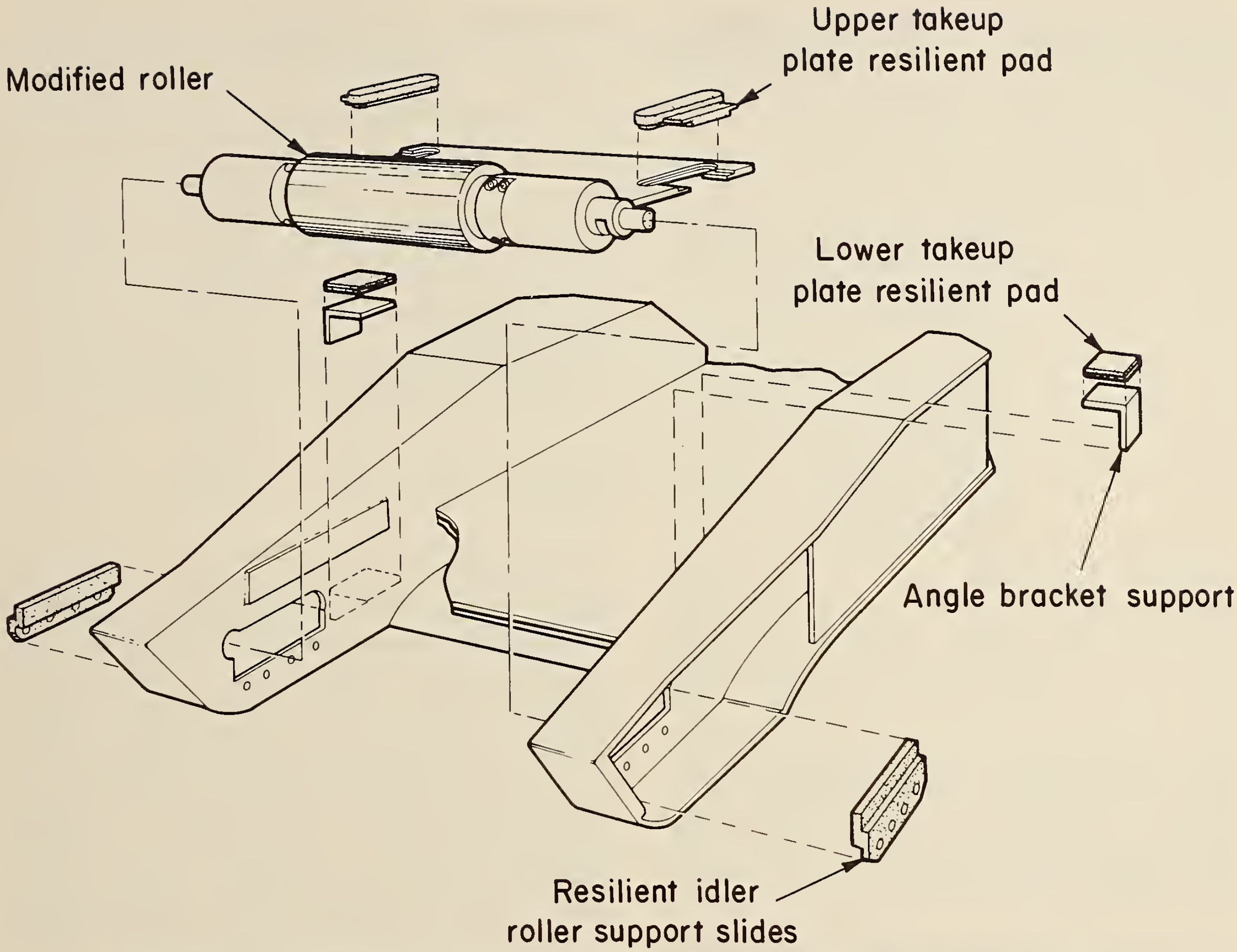


FIGURE 20. - Noise-control treatments on conveyor idler (tail) roller and takeup plate.

that the takeup plate between the tail roller and the rear portion of the upper deck was mounted on resilient support pads.

Table 6 summarizes the aboveground noise reductions resulting from the conveyor noise-control treatments. (However, as shown, a noise increase rather than a reduction resulted when the upper deck wear strips were cut to make them more durable.) Not including the blocking of the lower deck hole (a temporary treatment), the noise-control treatments produced an overall noise reduction of 10.5 dBA (from 101.5 to 91.0 dBA) at the operator's position. The most effective treatments were the constrained-layer damping of the decks and sidewalls, the resilient wear strips, and the larger diameter idler roller; they reduced noise by an estimated 5, 3, and 2 dBA, respectively. These results indicate that a fully treated conveyor without a lower deck hole would have a noise level 12.0 dBA lower than that of the untreated conveyor with the lower deck hole.

The installation of the wear strips on the lower deck was one of the last modifications made to the conveyor because it was a relatively difficult procedure. The entire lower deck had to be removed from the conveyor assembly, fitted with

TABLE 6. - Summary of aboveground chain conveyor noise-control tests

(Noise level at operator's position, dBA)

Treatment	Result[1]
None (untreated conveyor)	101.5
Lower deck damped	101.0
Upper deck damped	97.0
Installation of upper deck wear strips	96.5
Sidewalls damped	95.5
Large-diameter idler roller (substitution)	93.0
Isolation of takeup plate	91.5
Upper deck wear strips cut	93.0
Installation of lower deck wear strips	91.0
Lower deck hole blocked	89.5

[1]Cumulative.

the strips, and rewelded to the conveyor slightly below its original position to compensate for the thickness of the strips. The reason for the comparatively large noise reduction (2.0 dBA) after this modification was that all other major noise sources on the conveyor had already been treated. With the addition of the lower deck wear strips, the largest single remaining noise source (i.e., the lower deck) was quieted.

The aboveground tests showed that noise generated by a chain conveyor can be significantly reduced without drastically changing its original design; however, the noise-control treatments would be even easier to install on newly designed conveyors. Allowable operator exposure time would increase from 1.6 h (untreated conveyor, 101.5 dBA) to almost 7 h (treated conveyor, 91.0 dBA) if the conveyor were the only noise source. The potential effect of these treatments on operating continuous miners would be to make conveyor noise insignificant compared to coal-cutting noise.

Underground Tests

The original underground test plan called for noise measurements on the same continuous miner before and after conveyor noise-control treatments were installed. However, this plan proved to be unfeasible because too much equipment downtime would have been required to install the noise-control treatments and transport the miner to and from an aboveground shop. (The treatments were too complex to install underground.) Therefore, noise measurements were made on several different machines--both treated and untreated, but of the same model whenever possible. The main disadvantage of this approach was that a more extensive series of measurements was required for a statistically proper evaluation of the noise-control treatments.

The constrained-layer damping of the conveyor decks and sidewalls was the only noise-control treatment evaluated extensively in the underground tests. It was the first, simplest, and most effective treatment installed aboveground, so it was readily accepted for underground use by both the equipment manufacturer and the mine operators. The other noise-control treatments described in the "Aboveground Tests" section involved more substantial design changes, so a fully-treated miner conveyor was never manufactured for underground use. However, some useful information was obtained on the resilient wear strips and a previously neglected noise source, the guide plates near the bend point of the lower deck (fig. 18).

Table 7 shows the average underground noise levels produced by two groups of continuous miners. Six miners were in the treated group, and eleven were in the "untreated" group; all were in the Jeffrey[8] 120 series of models (120 L, 120 M, 120 H, 120 H2, or 122). All six of the treated miners had damped decks and sidewalls, and one of these also had wear strips on the upper deck (fig. 19). As shown in table 7, noise measurements were taken with the miners in five different operating modes and with their tail booms in three different positions.

Since the data in table 7 are average noise measurements rather than "before and after" measurements of the same machine, any conclusions from them about the effectiveness of the noise-control treatments must be made cautiously. Considerable variations in noise levels were found within the treated and untreated groups, some as large as the differences between the two groups (average noise reduction). The variations within groups were largely attributable to differences in mine conditions, equipment models, equipment age, and quality of maintenance. Nevertheless, the data collected during the underground tests revealed some general trends that led to these three conclusions: (1) The treated machines were usually quieter than the untreated machines; (2) Noise-level reductions were greater for operations that utilize the conveyor; and (3) Miners whose noise-control treatments were installed by the manufacturer were quieter than miners whose treatments were installed in mining company shops. In addition, table 7 shows that the average noise reduction in the "Conveyor only (no coal)" operating mode was much larger than those in the "load only" and "cut and load" modes. This is because the presence of coal on the conveyor had a greater muffling effect on the untreated machines than on the treated machines. In fact, the coal on the conveyor reduced the average noise level more than the damping treatment; that is, the average noise level of the untreated miners in the "load only" mode was 1.2 dBA lower than that of the treated miners in the "conveyor only" mode (97.7 versus 98.9 dBA).

The durability of the constrained-layer damping treatment was satisfactory on all six treated miners. No signs of failure were found in either the viscoelastic damping material or the bond between this material and the steel. In one case, this bond proved to be stronger than the original bond between the upper deck and sidewall; the conveyor continued to operate for 2 weeks after the deck-sidewall bond had failed.

[8]Reference to specific products does not imply endorsement by the Bureau of Mines.

TABLE 7. - Summary of underground chain conveyor noise-control tests

(Noise level at operator's position, dBA)

	Operating mode				
	Conveyor only (no coal)[1]	Load only[2]	Cut only	Cut and load[2]	Idle
Untreated miners[3]................	103.8	97.7	97.2	100.6	91.0
Treated miners[4]..................	98.9	95.6	96.3	97.8	91.3
Average noise reduction.....	4.9	2.1	.9	2.8	-.3

[1]Average from tests using 3 conveyor tail boom positions: straight, angled away from operator, angled toward operator.
[2]Tail boom position: straight.
[3]Average; 11 miners tested.
[4]Average; 6 miners tested.

Although the resilient wear strips were sufficiently durable during several months of aboveground tests, more problems were expected underground because coal could abrade the exposed rubber bases of the strips. However, after a 3-month underground trial period, damage had occurred only where the flights abruptly struck the upper deck after rounding the drive sprocket at the front of the conveyor. Upstream and downstream of this point, the strips showed negligible wear.

The underground noise levels were generally higher when the conveyor was angled than when it was straight. This was caused primarily by impacts between the conveyor flights and the guide plates (fig. 18) at the conveyor bend point. The guide plates used in the aboveground tests were welded to the sidewalls and were relatively quiet. However, some of the conveyors observed underground had pinned-on guide plates that rattled noisily due to flight-plate impacts. In fact, guide plate rattle was sometimes the dominant noise source at the operator's position. The obvious solution to this problem would be to use welded-on rather than pinned-on guideplates.

In summary, the underground tests showed that the constrained-layer damping treatments were both durable and effective in reducing noise. Continuous miner manufacturers could easily incorporate these treatments into the design of new conveyors. Although noise reductions were not as dramatic underground as they were in the aboveground test facility, this was partially due to (1) other noise sources (coal cutting, gathering arms, motors, drive train, etc.), (2) the reverberant nature of the underground environment, and (3) the muffling effect of the coal on the conveyor. One significant finding was the superiority of welded-on versus pinned-on guide plates as a means of noise control. Additional underground tests of chain conveyors containing all the Bureau-developed noise-control treatments (table 6) are needed to further verify their durability and acoustical effectiveness.

Mantrip Vehicles

Although the mantrip vehicle (a large rail-mounted personnel carrier) is not one of the loudest noise sources in underground coal mines (figure 3, part 2), almost all face workers are exposed to mantrip noise. Since face workers' regular jobs often expose them to high noise levels, the additional contribution of mantrip noise could easily result in noncompliance with Federal noise regulations. The Bureau investigated two slightly different approaches to mantrip noise control--retrofit treatments and the integration of quieting techniques into new mantrip vehicles. The goal of both approaches was to reduce noise to a maximum of 85 dBA for all passengers.

Retrofit Treatments (17)

The mantrip chosen for retrofit treatments (fig. 21) had four passenger compartments and a central battery and motor compartment. Operator controls were located in both of the end compartments to allow the driver to face the direction of travel. The four major elements of the retrofit noise-control program were (1) aboveground diagnostic tests, (2) installation of noise-control treatments, (3) aboveground testing of the retrofitted vehicle, and (4) underground tests.

The three major noise sources on the unmodified mantrip were wheel-rail interaction, motor noise, and drive train noise. As shown in figure 22, all three sources generated both airborne noise (direct path to passengers' ears) and structureborne noise (vibration of the frame, panels, etc.). Structureborne noise produced by wheel-rail interaction (fig. 22*A*) was the largest single noise source, followed by airborne motor noise (fig. 22*B*), structureborne motor noise, and the sum of airborne and structureborne drive train noise (fig. 22*C*).

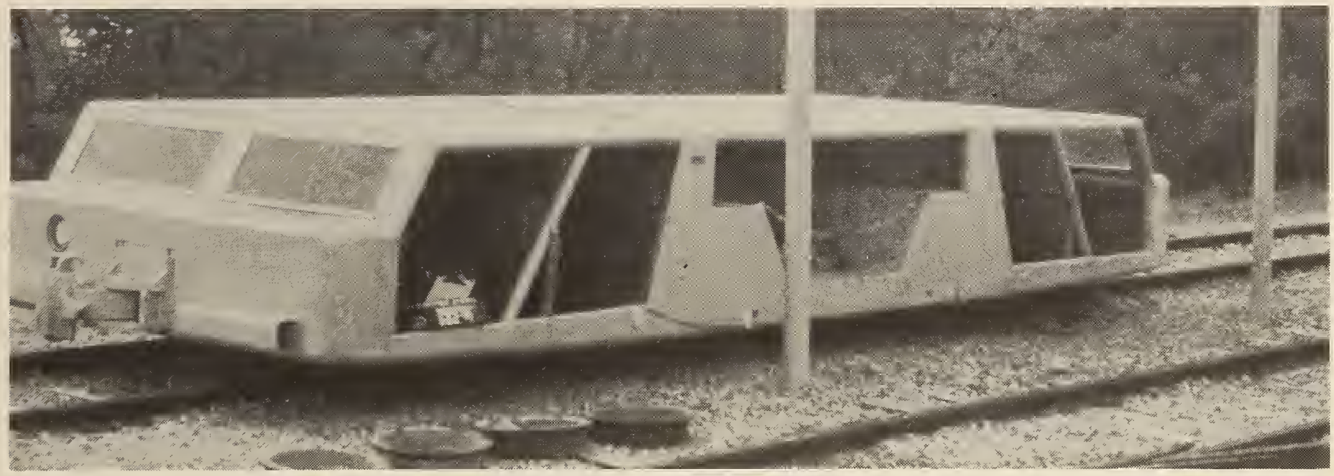


FIGURE 21. - Mantrip vehicle used in retrofit noise-control program.

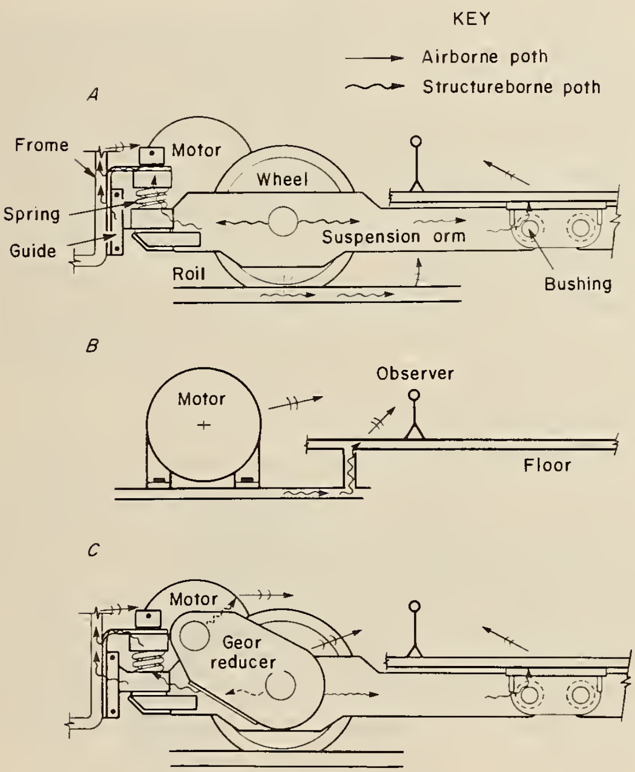


FIGURE 22. - Mantrip noise sources and transmission paths. *A*, Wheel-rail noise; *B*, motor noise; *C*, drive-train noise.

The overall noise levels within the unmodified mantrip ranged from 83.5 to 93.5 dBA, depending on travel speed, track curvature, and compartment location. More noise was produced at higher travel speeds, mostly because of increased wheel-rail interactive forces. Noise on curves was higher than noise on straight track because of the nature of wheel-rail interaction during curving. That is, a "chattering" noise was produced when the wheels repeatedly climbed the rail and fell back downward while negotiating a turn. Finally, noise in the "passenger compartments" was greater than in the (end) "driver compartments" because the latter were farther away from both the wheels and the central battery-motor compartment. (See figure 21.)

Three retrofit noise-control treatments were installed: resilient wheels, a sound-absorbing motor enclosure, and damping of the mantrip roof and sidewall panels. The resilient wheels (fig. 23) contained rubber inserts that isolated the wheel-rail interface from the rest of the vehicle, thus decreasing structureborne wheel-rail noise. A layer of sound-absorbing fiberglass was attached to the inner surfaces of the motor enclosure to reduce airborne motor noise, and a thin sheet of perforated metal covered the fiberglass to protect it from damage. The roof and sidewall damping treatment consisted of a layer of polymer material constrained by a steel sheet.

Extensive tests of the modified mantrip were conducted on an aboveground track. Noise levels in the passenger and driver compartments ranged from 80 to 92 dBA, again depending on travel speed, track curvature, and compartment location.

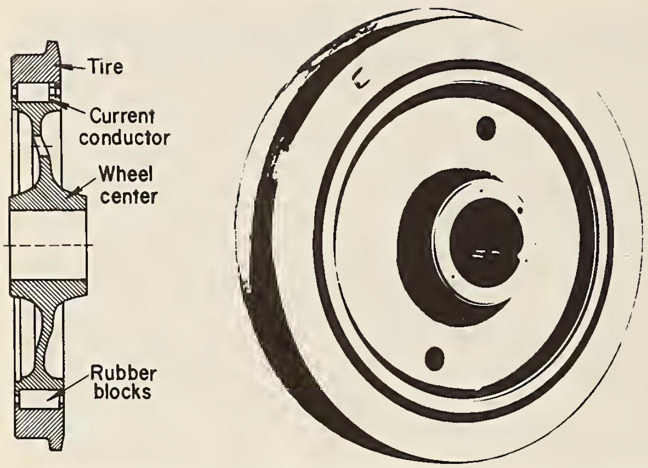


FIGURE 23. - Resilient wheels to isolate mantrip from wheel-rail noise.

Although these noise levels were generally lower than in the unmodified mantrip, the noise reductions were not as great as expected. The major reason was that the new, resilient wheels had not yet been "broken in" to conform to the track. That is, the sharp edges of the new resilient wheels caused them to climb farther up the rail during curving than the worn-down, all-steel wheels of the unmodified mantrip.

The retrofitted mantrip was then tested underground. At the end of 3 months of testing in two different coal mines, all three treatments remained basically intact and undamaged. Evidence of wear was beginning to show on the resilient wheels. Noise levels within the mantrip ranged from 83 to 86.5 dBA, measured over a wide variety of tram speeds and track curvatures. These noise levels corresponded to an average speed of 10 mi/h, as recorded by a machine-mounted radar unit.

Factory Integration of Noise Controls (15)

The major problems of the retrofit noise-control approach were the high costs of labor and materials associated with one-of-a-kind installation. However, factory-integration of the treatments was considered feasible because the materials could be prefabricated and their dimensions could be designed to be compatible with the mantrip. The factory-designed "quiet" mantrip was similar to the retrofitted vehicle but differed in four basic ways: (1) It was a trolley-powered model (same manufacturer); (2) the roof and sidewall panels were prefabricated damped plates; (3) a redesigned suspension system (fig. 24) replaced the resilient wheels as the means for isolating the mantrip structure from wheel-rail interactive forces; and (4) the electric motor was mounted on vibration-isolation pads and enclosed in a sound-absorbing structure (fig. 25).

These treatments were evaluated by comparing the noise levels of the factory-quieted mantrip with those of an untreated vehicle of the same model, in the same underground mine, and under the same operating conditions. Noise levels within the quieted mantrip were about 84.5 dBA, compared to 90 to 92 dBA in the untreated vehicle, recorded at an average speed of 10 mi/h. The same trends as were previously mentioned with regard to travel speed, track curvature, and compartment location were observed.

The noise reduction met the goal of the mantrip program--a vehicle with an 85-dBA maximum interior noise level. Importantly, the factory-quieted mantrip cost less than 5 pct more to build than an unquieted machine of the same model. Equipment manufacturers could easily incorporate the same basic noise-control treatments on almost any similar mantrip vehicle.

Stoper Drills

As shown in part 2 (fig. 3), stoper operators consistently experience noise levels greater than 115 dBA, which is far out of compliance with Federal noise regulations. Control of stoper noise was therefore a high-priority area of Bureau research. Both retrofit and redesign techniques were used, and stoper drills for both coal and hardrock use were addressed.

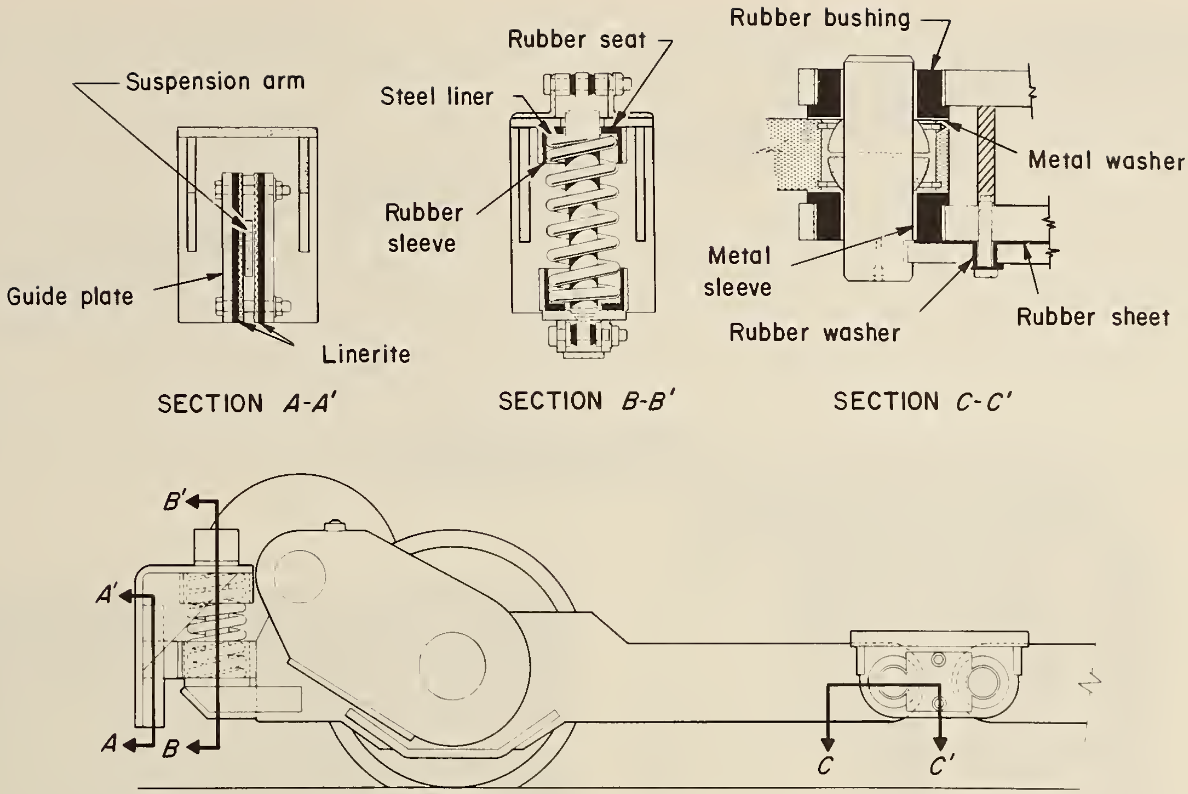


FIGURE 24. - Redesigned suspension system of factory-quieted mantrip.

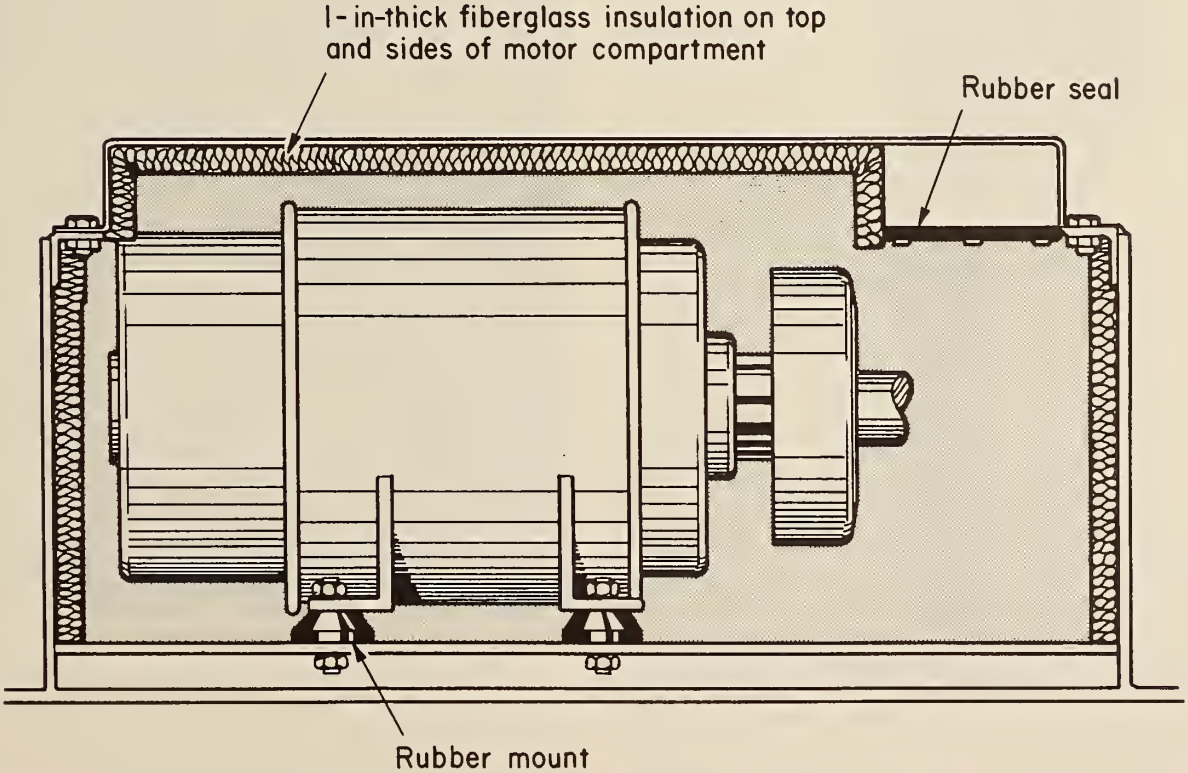


FIGURE 25. - Motor enclosure of factory-quieted mantrip.

Retrofit Treatments (38)

The most effective retrofit noise-control treatment for a standard stoper (figure 5, part 2) included a jacket-type muffler surrounding the drill body and the air-exhaust port (fig. 26). Urethane end caps held the jacket material (a polymer sheet) in place. Drill-steel noise was partially abated by placing a 6-in-long collar near its bottom end (fig. 27). The collar was made of a poured-in urethane layer constrained by a steel sheath.

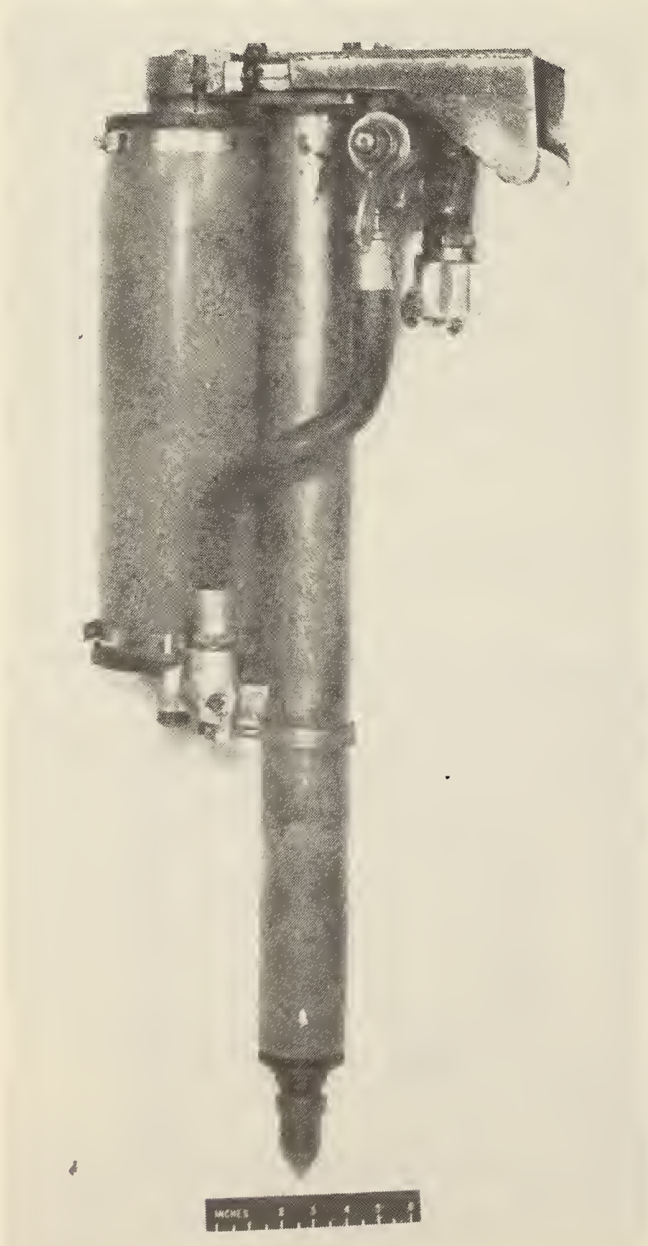


FIGURE 26. - Wraparound jacket-type muffler for stoper drill.

In tests conducted in the Bureau's (Pittsburgh, PA) experimental coal mine (fig. 28), the jacket muffler caused about a 13-dBA noise reduction, and the drill-steel collar resulted in an additional reduction of about 2 dBA. The quieted noise level, 100 dBA, would permit about 2 h of operating time per shift, versus no permissible time for an untreated stoper. The entire retrofit package increased the total drill weight (including feedleg) by about 10 pct. The materials used were fairly inexpensive (about $150 in 1980). Retrofit kits similar to those tested are now commercially available for several models of stopers.

Retrofitted stopers (jacket muffler only) were tested in 15 operating underground coal mines, and muffled-versus-unmuffled noise reductions of 7 to 8 dBA were consistently obtained. The 13-dBA experimental noise reduction was not achieved because the underground mines did not control the drill feed rate or maintain the noise-control treatments as diligently as the Bureau did in its experimental mine. Nevertheless, the typical muffled noise levels (105 to 106 dBA) were low enough to permit a doubling of the allowable operating time per shift. Unfortunately, drilling rates with the modified stoper were about 15 to 50 pct slower than those of unmuffled stopers, and freezing was a common problem with the wraparound mufflers.

Redesign for Noise Control (8, 13)

Although the stoper retrofit noise-control treatments were fairly successful, Bureau studies showed that greater noise reductions and improved drilling performance could be obtained by redesigning the drill to incorporate noise-reducing features. The redesign effort included three major steps: (1) redesign of the drill-steel rotation mechanism and other drill parts, (2) development of a more effective muffler-enclosure device, and (3) development of a "shroud tube" to attenuate drill-steel noise.

FIGURE 27. - Damping collar for stoper drill steel.

FIGURE 28. - Stoper with retrofit noise-control treatments in operation.

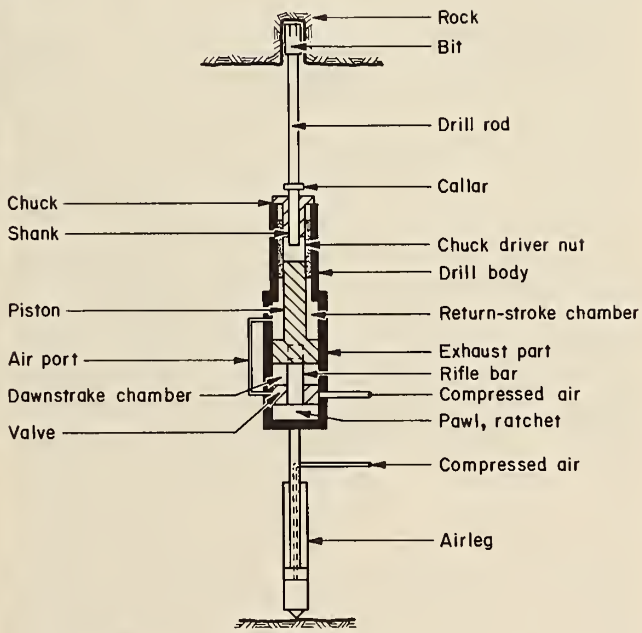


FIGURE 29. - Internal components of standard stoper drill with rifle-bar rotation.

A standard stoper drill (fig. 29) produces drill-steel rotation through a "rifle-bar" arrangement. The oscillating piston supplies percussive energy to the steel and imparts rotation on its backstroke through a pawl-and-ratchet mechanism. The steel rotates through a 15° to 20° arc with each stroke, resulting in a rotation speed of about 150 to 200 rev/min.

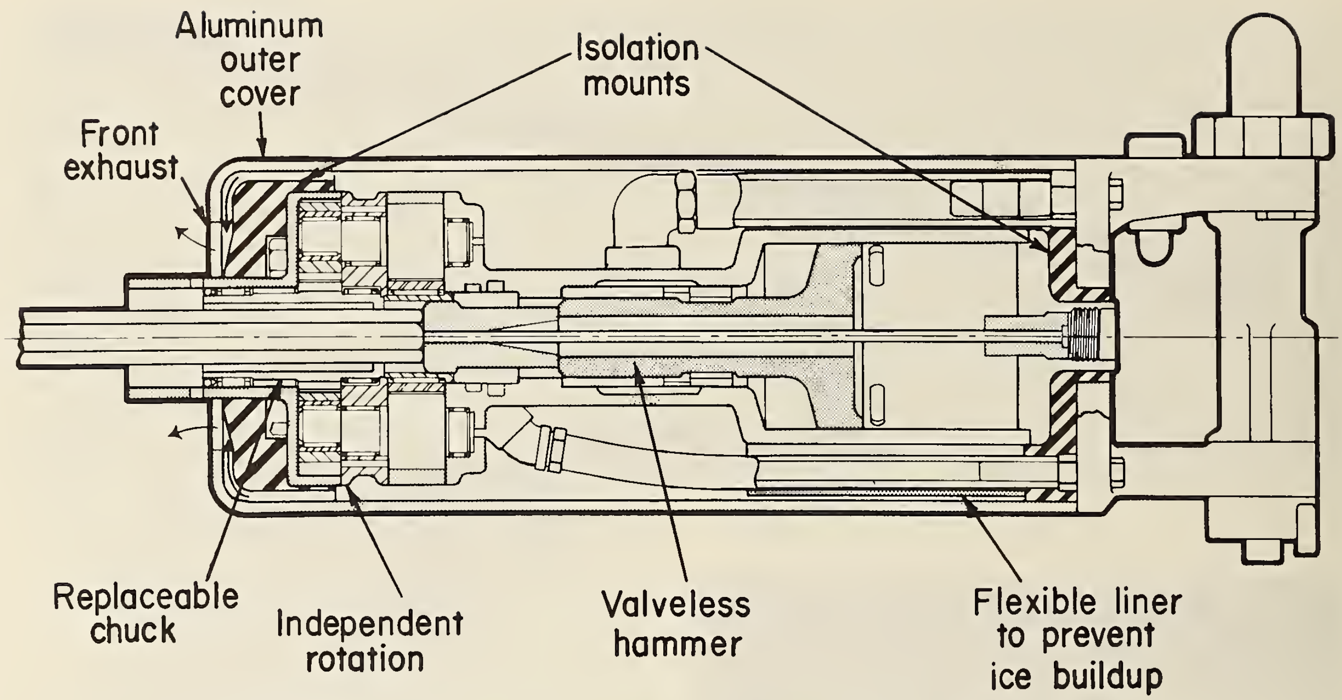


FIGURE 30. - Internal components of redesigned "quiet" stoper drill.

The rifle-bar rotation mechanism generated a great deal of high-frequency "rattling" noise that was beyond the effective noise-attenuating range of the retrofit jacket-type muffler. Therefore, muffler effectiveness was increased by using a quieter motor-and-gear arrangement to achieve the same drill-steel rotation speed. The piston no longer initiated rotation, so it was redesigned to serve as the valve controlling the flow of compressed air within the drill. The annular clearance between the chuck and shank was reduced, and the collar on the drill steel was eliminated to reduce misalignment and rattling impacts at the top of the drill body. These design changes improved the efficiency of the drill and also reduced its high-frequency noise. Figure 30 shows the major internal components of the redesigned stoper drill.

The new drill-body design necessitated the development of a special muffler-enclosure device consisting of an aluminum outer cover and rubber isolation mounts at each end of the drill that prevented the transfer of vibration from the drill cylinder to the outer aluminum shell (fig. 30). During drilling, the exhaust air from the piston chamber and rotation motor left the acoustical enclosure through an exhaust hole near the top of the drill. The muffler enclosure attenuated both drill-body and air-exhaust noise, and a flexible deflector plate near the exhaust port of the piston chamber helped reduce icing.

Another important component of the redesigned stoper drill was the steel "shroud tube" that surrounded the drill steel like a sheath and acted as a barrier against the noise produced by drill-steel vibration. The outer diameter of the shroud tube was small enough to allow it to follow the drill bit into the hole, and its inner diameter was large enough to keep it from touching the drill steel. The tube was connected to the top of the drill body through a "shroud tube damper" to provide isolation from drill-body vibration.

Figure 31 shows the "feedleg version" of the redesigned handheld drill. Six of these "quiet" drills were manufactured and tested in operating mines. All six

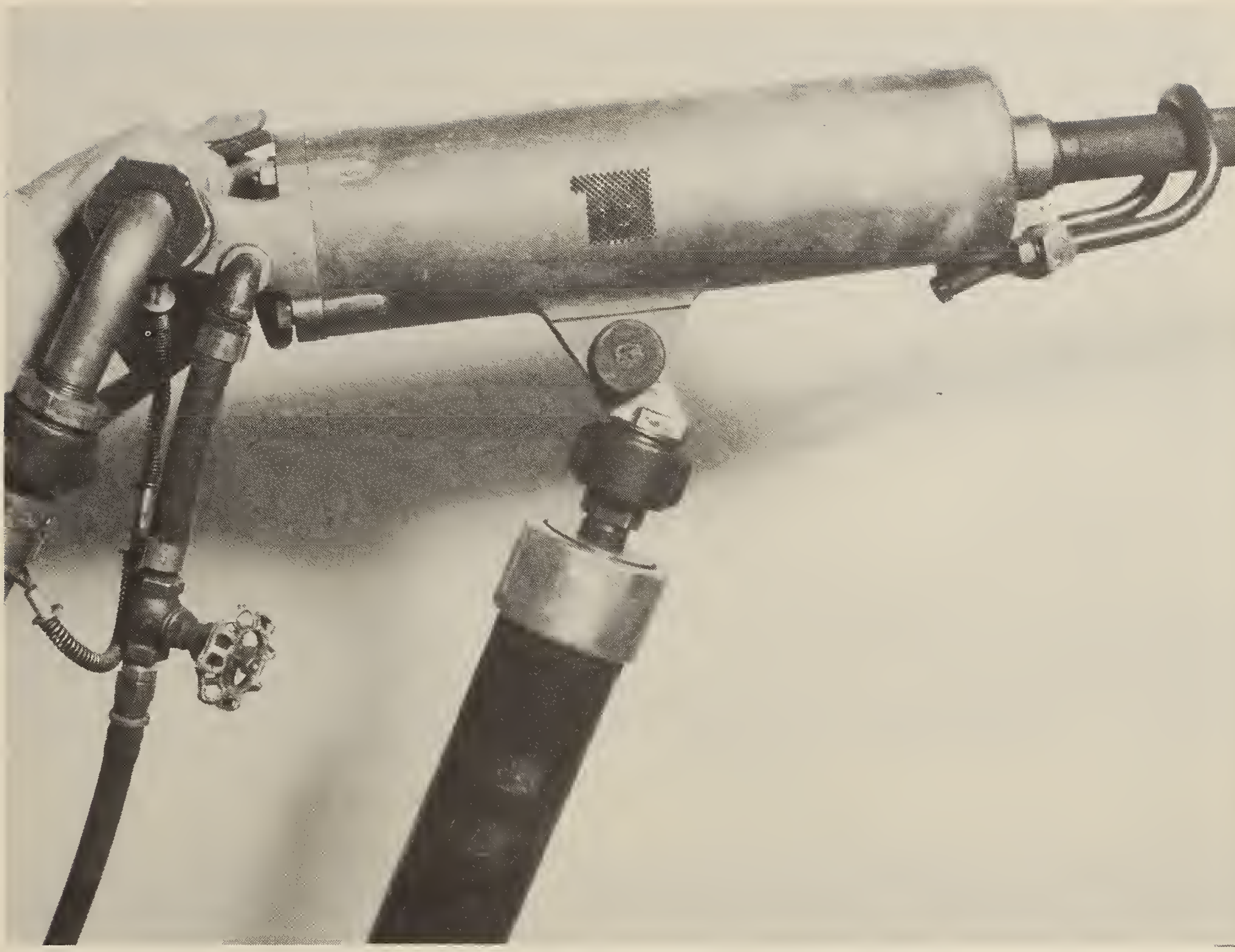


FIGURE 31. - Redesigned "quiet" stoper on feedleg.

produced noise levels of 98 to 105 dBA at the operator's position, reflecting a 10- to 17-dBA reduction versus the noise of standard stopers. Importantly, the weight and penetration rates of the redesigned drills were approximately equal to those of standard stopers. In addition, the three machine control levers--thrust, hammer, and rotation--were located together on the drill backhead (fig. 32), allowing simultaneous operator control of all three functions. These design and performance features greatly aided operator acceptance of the redesigned drill and illustrated the advantages of the redesign approach versus the retrofit approach to stoper noise control.

The only disadvantage of the redesigned stoper (other than its initial cost) was that the shroud tube required removal and replacement during the drill-steel changing process. Since this proved to be time-consuming, operators often drilled without the shroud tube, partially negating the effectiveness of the redesigned drill. However, noise levels without the shroud tube were still about 108 dBA, which was substantially lower than those of standard stopers or retrofitted stopers with untreated drill steels.

UNDERGROUND HARDROCK MINING

Part 2 briefly reviewed the noise problems associated with underground hardrock mines. The two major underground hardrock mining noise sources the Bureau has investigated (other than handheld drills)

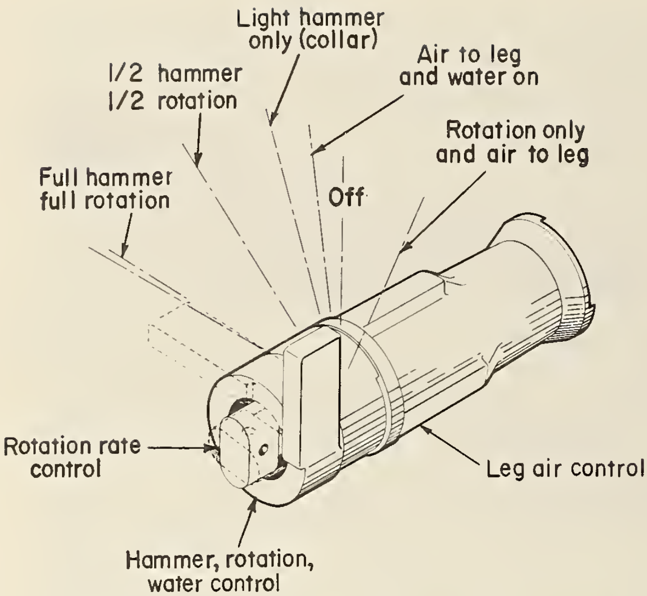


FIGURE 32. - Drilling controls of redesigned "quiet" stoper drill.

are jumbo-mounted pneumatic percussion drills and diesel-powered LHD machines. These machines have been identified by the Bureau as the two most serious noise offenders in terms of both the noise levels produced and the number of workers overexposed.

Jumbo-Mounted Percussion Drills

As with mantrip vehicles and stoper drills, the Bureau has investigated both retrofit and redesign measures for reducing jumbo drill noise. A potentially workable retrofit package was developed under Bureau contract and is now being tested in-house to determine its long-term durability. The redesigned jumbo drill is now being field-tested by another contractor. As with stoper drills, the two major components of the noise-controlled jumbo drills were (1) a muffler enclosure to attenuate air-exhaust and drill-body noise and (2) a shroud tube to attenuate drill-steel noise.

Retrofit Treatments (11)

Figures 33 and 34 show the retrofit muffler enclosure designed by the Bureau contractor for a drifter with rifle-bar rotation. This muffler enclosure had to surround the drifter completely because there were three air-exhaust ports--a main port on the top and two auxiliary ports on the underside of the drill body. The halves of this two-piece, boxlike enclosure fit together snugly around a horizontal centerline. Its octagon-shaped profile was a compromise reached after considering the requirements of exterior slimness and light weight and requirements regarding interior volume and noise-attenuating properties. The top portion of the enclosure was hinged to the bottom portion to allow easy access to the drill (fig. 33). Figure 34 shows the retrofitted drill in its normal drilling position (cover closed).

Figure 35 shows the exit path of the main exhaust airflow (arrows). The exhaust air exited the drill radially, struck a silicone rubber deflector (not shown) at the top of the enclosure, and moved forward to escape through an opening at the front of the enclosure. Because the deflector was very flexible, it shook off any ice that began to form on it. The fiberglass in the muffler section at the front of the enclosure was held in place by a perforated metal plate, and a thin layer of Mylar polyester film prevented it from absorbing oil and water. This muffler section can also be seen in figure 33. The three major advantages of this muffler-enclosure design were that (1) exhaust noise was directed away from the operator and absorbed; (2) the cold exhaust air cooled the coupling and shank at the front of the drifter; and (3) the warm drill components heated the exhaust air, thus inhibiting ice formation.

Figure 36 shows the components of the shroud tube surrounding the drill steel. The outer diameter of the shroud tube was slightly smaller than the bit diameter, allowing the tube to enter the hole behind the bit. The inner polymer layer rode loosely on the drill steel, causing the tube to rotate slightly during operation. The foam interlayer absorbed some of the vibration imparted to the polymer,

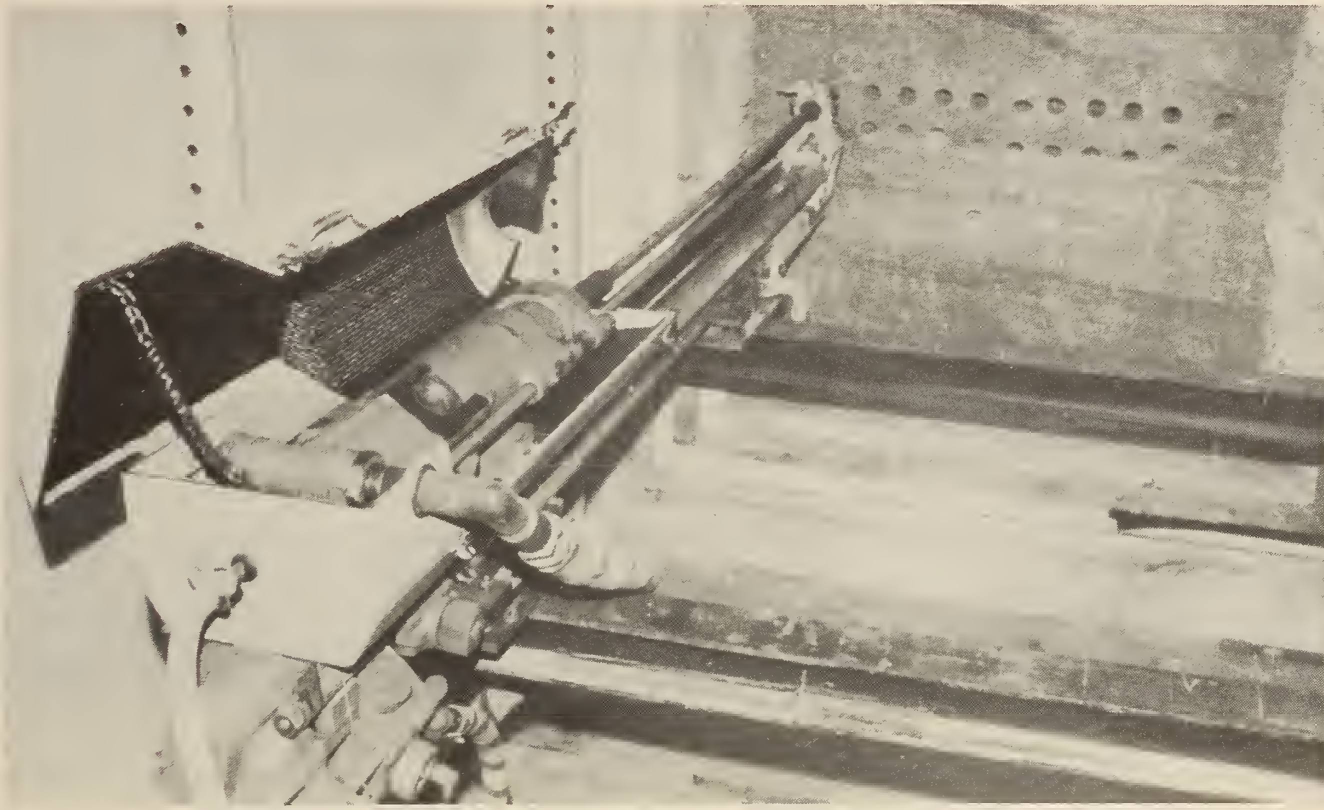


FIGURE 33. - Jumbo drill within retrofit muffler enclosure (cover open).

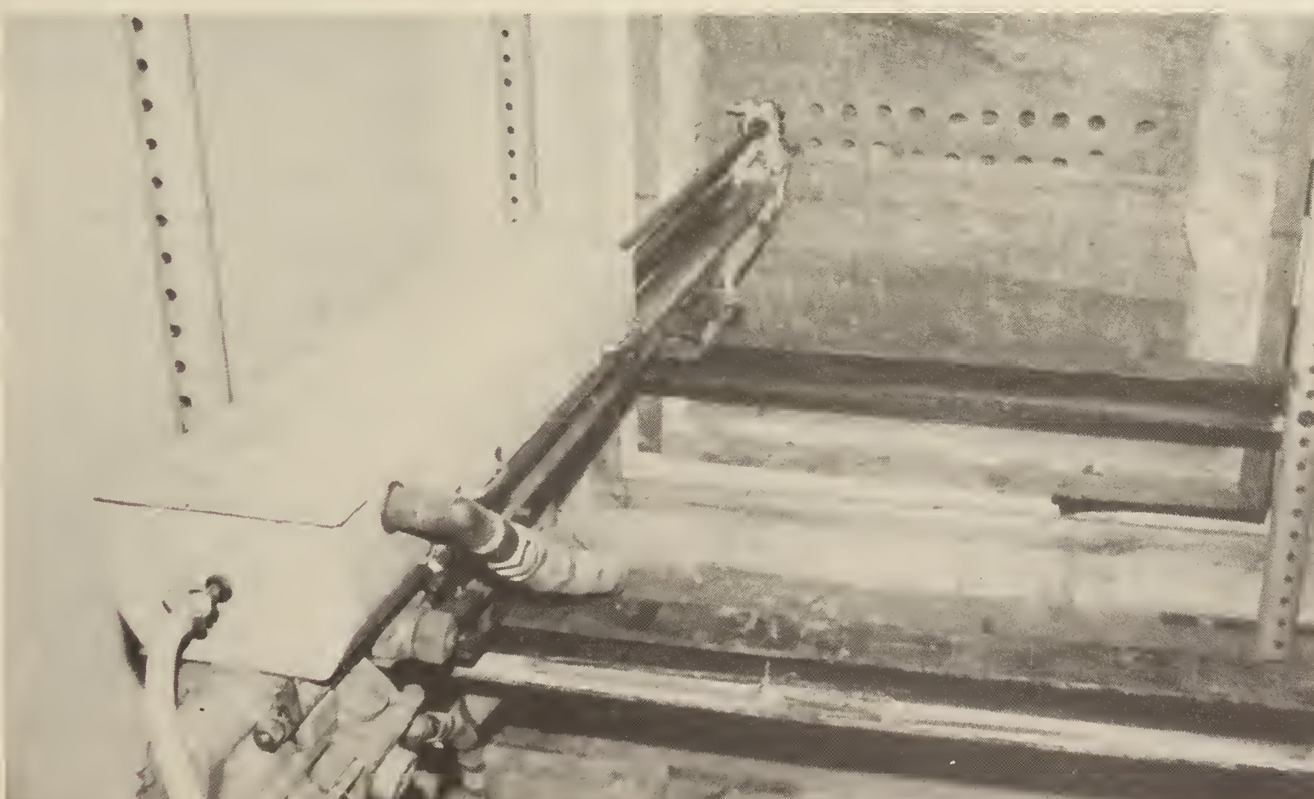


FIGURE 34. - Jumbo drill within retrofit muffler enclosure (cover closed).

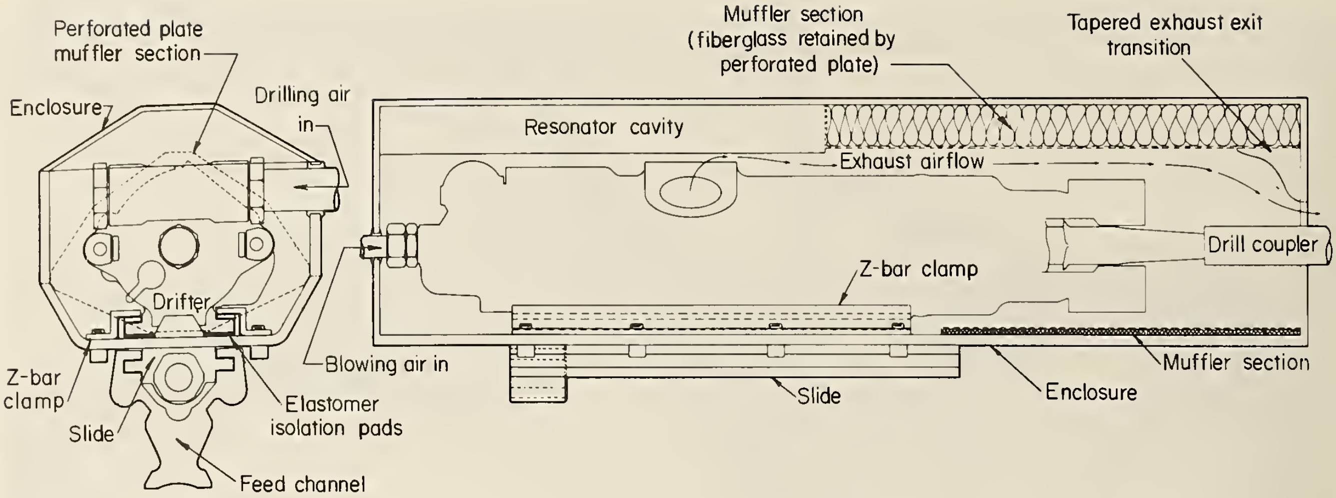


FIGURE 35. - Schematic views of retrofit muffler enclosure for jumbo drill.

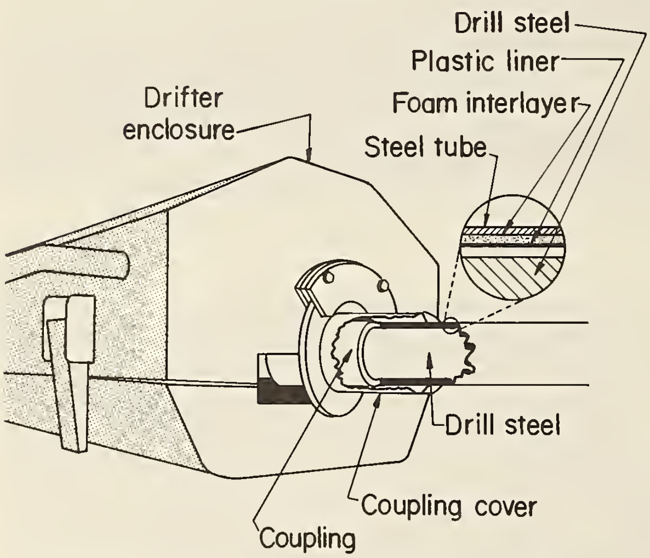


FIGURE 36. - Retrofit shroud tube for controlling jumbo drill-steel noise.

and the steel outer layer protected the two inner layers from damage. Exhaust air from the muffler enclosure traveled forward through the annulus between the steel and the shroud tube, escaping just behind the bit.

Performance of the jumbo drill with and without the retrofit noise-control treatments was evaluated first in the laboratory, then at an aboveground test site. Laboratory tests in a reverberation room (figures 33 and 34) showed that the sound power level of the treated drill was 19.3 dBA lower than that of the untreated drill. At the aboveground test site, noise reductions of 16.5 to 18.5 dBA were recorded at the operator's position (table 8). Diagnostic tests showed that the muffler enclosure accounted for about 11 dBA of this reduction; the shroud tube and/or the rock mass surrounding the drill hole accounted for the remainder. Ice formation and damage to the noise-control treatments were almost negligible during these tests.

The retrofitted drill was then tested in an operating underground zinc mine (fig. 37). As shown in table 8, noise levels at the operator's position were 12.5 to 15 dBA lower than those of the untreated drill. One of the reasons for the more modest noise reductions in the underground tests was that the confined, reverberant underground environment resulted in reflections that partially negated the advantage of directing the exhaust air away from the operator. Also, the overall noise levels were much higher underground than aboveground. The noise levels of the treated drill indicate that it could have been operated for about 8 h per shift aboveground (88 to 92 dBA) or about 1-1/2 h underground (101 to 105 dBA).

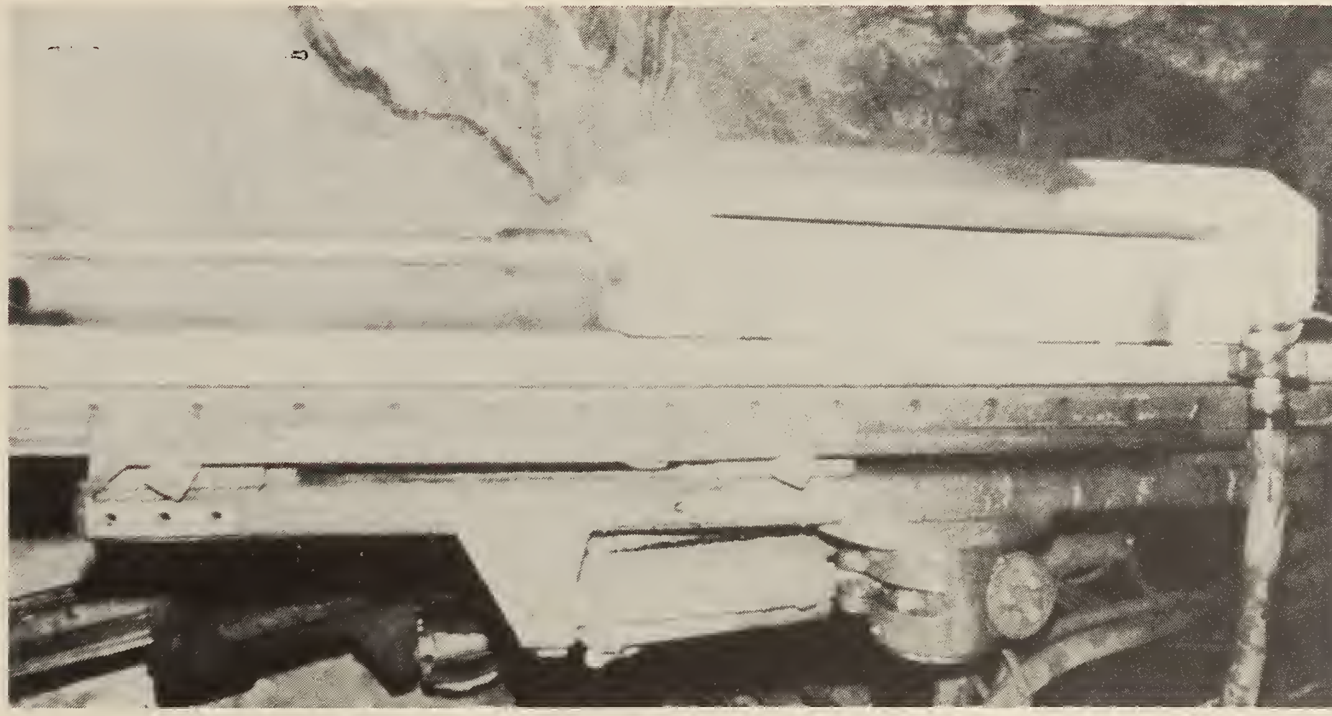


FIGURE 37. - Jumbo drill with retrofit noise-control treatments in underground zinc mine.

TABLE 8. - Results of retrofit jumbo drill noise-control tests

(Noise level at operator's position, dBA)

	Position of drill[1]		
	Collaring hole (10 ft steel)	Middle of hole (5-6 ft steel)	End of hole (1-2 ft steel)
ABOVEGROUND TESTS			
Untreated drill.........	108.5	107	105.5
Treated drill...........	92	88.5	88
Noise reduction....	16.5	18.5	17.5
UNDERGROUND TESTS			
Untreated drill.........	117.5	116	115.5
Treated drill...........	105	101	101.5
Noise reduction....	12.5	15	14

[1]Holes were drilled to 10 ft.

The durability of the noise-control treatments was evaluated by drilling approximately 10,000 ft of hole in the underground zinc mine. Although only about 500 ft was drilled with the shroud tube,[9] the muffler enclosure was used during the entire test period. Overall, the components of the muffler enclosure were quite durable; the outside was not damaged, the fiberglass baffles were in good condition, the protective film had only two small holes, and the rubber exhaust deflector showed no signs of wear. The only damaged acoustical component was a rubber seal at the drilling-air inlet (fig. 35) that came off when the bolts supporting the drill mounting bracket failed. This failure, however, was not the fault of the acoustical treatments.

[9]The mine did not have the 10-ft-long drill steels for which the shroud tube was designed; by the time they were obtained, the test was almost completed.

Mine personnel reported very good operator acceptance of the partially quieted drill (muffler enclosure only) during underground tests, despite the need to fix damaged drill parts and support brackets on several occasions. The presence of the muffler enclosure did not interfere significantly with either the replacement of broken parts or routine drill maintenance. Operators generally agreed that the treated machine drilled just as fast or faster than the unmodified drills used at the mine.

The Bureau is presently testing the fully quieted drill to evaluate the durability of the shroud tube depicted in figure 36 and other similar shroud-tube designs. It is also evaluating the effect of the shroud tube on operator acceptance (e.g., with respect to ability to observe a stoppage of drill-steel rotation).

Redesign for Noise Control (14)

Although the retrofit muffler-enclosure described above would be quite effective for most jumbo drills with rifle-bar rotation, it would not be appropriate for drifters containing independent drill-steel rotation motors. This is because independent rotation drills are usually somewhat larger than rifle-bar drills and would require larger, heavier muffler enclosures. The problem of air exhaust from the rotation motor would also have to be addressed. Therefore, the Bureau sponsored a program to redesign an independent-rotation drill for the purpose of reducing noise.

Figure 38 is a photograph of the prototype redesigned jumbo drill immediately prior to drilling. In order to make a simple, compact muffler enclosure for the drifter, the rotation motor was removed from the drifter body and relocated at the front end of the feed channel. This design change required the use of a very long drill shank called a kelly bar. The drifter percussed the rear end of the kelly bar while the new rotation mechanism (an air motor, belt drive, and gears) imparted rotation to its front end. The kelly-bar drive mechanism was then fitted with a muffler enclosure (not shown in figure 38) to attenuate its noise.

The muffler enclosure for the drifter was a two-piece boxlike structure made entirely of molded polymer material. The top half fit snugly atop the bottom half and could be removed for easy access to the drill. The drifter was mounted within the bottom half of the enclosure through rubber bushings that isolated the feed channel from drifter vibration.

The shroud tube, which is also shown in figure 38, was a collapsible steel coil approximately 8 in in diameter. Unlike the shroud tube on the retrofitted jumbo drill, it did not touch the drill steel or enter the hole during drilling. Instead, it was suspended firmly between the front portion of the drifter enclosure and the rear face of the kelly-bar rotation mechanism. The springlike shroud tube was completely extended at the start of the drilling (fig. 38) and collapsed as the drifter moved toward the face (fig. 39). Exhaust air from the drifter moved forward through the shroud tube and a plunger-shaped rubber "stinger" that was pressed against the rock face to attenuate noise produced by bit-rock interaction. Both the drifter exhaust air and the hole-flushing air exited through the small gap between the "stinger" and the rock face (fig. 39).

Initial testing of the redesigned drill was conducted in a surface rock quarry (figures 38 and 39) and in a nonproduction setting at the Colorado School of Mines' underground experimental mine to determine the acoustical performance and durability of the redesigned drill components. Noise levels at the operator's position were about 96.5 dBA on the surface and 100 dBA underground, reflecting a substantial improvement over those of standard jumbo drills. The redesigned drill has not yet been tested in an underground producing mine. At present, it is being modified to accommodate a semiautomatic drill-steel changing device that should facilitate long-hole drilling

FIGURE 38. - Redesigned, noise-controlled jumbo drill at start of hole.

FIGURE 39. - Redesigned, noise-controlled jumbo drill at completion of hole.

and increase the likelihood of operator acceptance.

Load-Haul-Dump Machines

As stated in part 2, the Bureau designated the diesel-powered LHD vehicle as a high-priority machine in terms of noise control because (1) almost all LHD operators are overexposed to noise; (2) the LHD is one of the most common machines in underground hardrock mines; and (3) the LHD is one of the most difficult diesel-powered machines to noise-control. As with other equipment types, the Bureau investigated both retrofit and redesign approaches to the LHD noise problem.

Retrofit Treatments (22)

Figure 40 shows the location of the major noise sources of a typical LHD vehicle with respect to its operator. Diagnostic tests conducted at the LHD manufacturer's shop produced operator noise levels of 99 to 101 dBA, depending on the vehicle operating mode. Table 9 shows that the three major noise sources on the LHD, in decreasing order of importance, were the transmission, the diesel engine, and the engine cooling fan. The engine intake and exhaust were also significant noise sources; however, they were not treated in the retrofit program so that efforts could be concentrated on the three main sources. In table 9, the estimated underground noise levels of the untreated LHD are 1 dBA *lower* than the noise levels recorded during diagnostic tests in the aboveground shop because the underground environmrnt was expected to be slightly less reverberant than the shop. The "Required reduction" column in table 9 shows the noise reductions needed to result in a combined noise level of 90 dBA at the operator's position during underground operation (85 dBA from each source).

Transmission noise was dominant because the transmission compartment was immediately adjacent to the operator's compartment (fig. 40). Airborne transmission noise was treated by sealing several holes between the two compartments and installing compôsite foam-and-plate linings on the top and forward sides of the transmission compartment (fig. 41). Structureborne transmission noise was treated by mounting the transmission on specially designed rubber vibration-isolation pads and installing similar materials around the underside of the top cover.

Engine airborne noise, the second largest source on the LHD, was treated primarily by building an acoustical enclosure around the engine (fig. 42). The top, left, and right sides of the

TABLE 9. - Breakdown of noise sources on unmodified LHD vehicle

(Noise level at operator's position, dBA)

Noise source	Recorded aboveground	Underground (estimated)	Required reduction[1]
Transmission:			
Airborne...........	99	98	ND
Structureborne.....	96	95	ND
Combined...........	101	100	15
Engine:			
Airborne...........	96	95	ND
Structureborne.....	88	87	ND
Combined...........	97	96	11
Cooling fan.........	94	93	8

ND Not determined.

[1]Reduction needed to achieve 90-dBA overall level underground (85 dBA from each source).

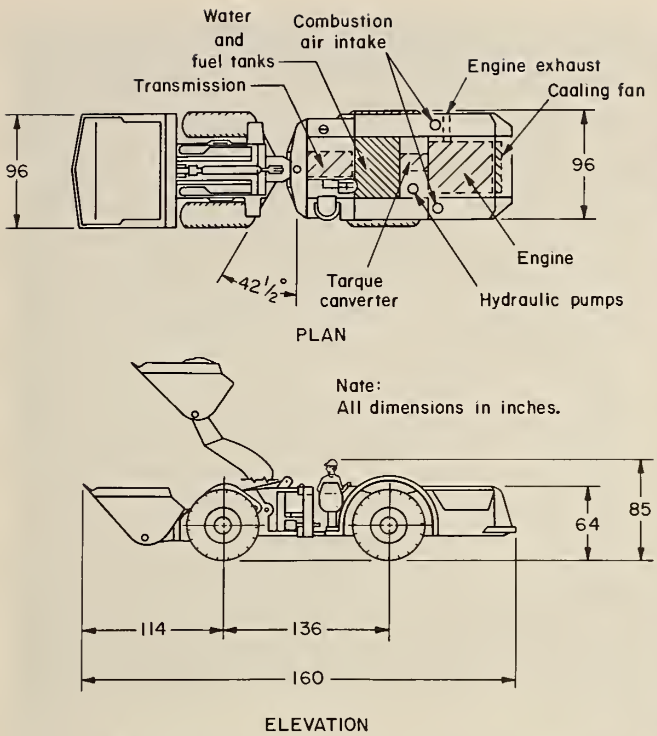


FIGURE 40. - Noise sources on typical diesel-powered LHD vehicle.

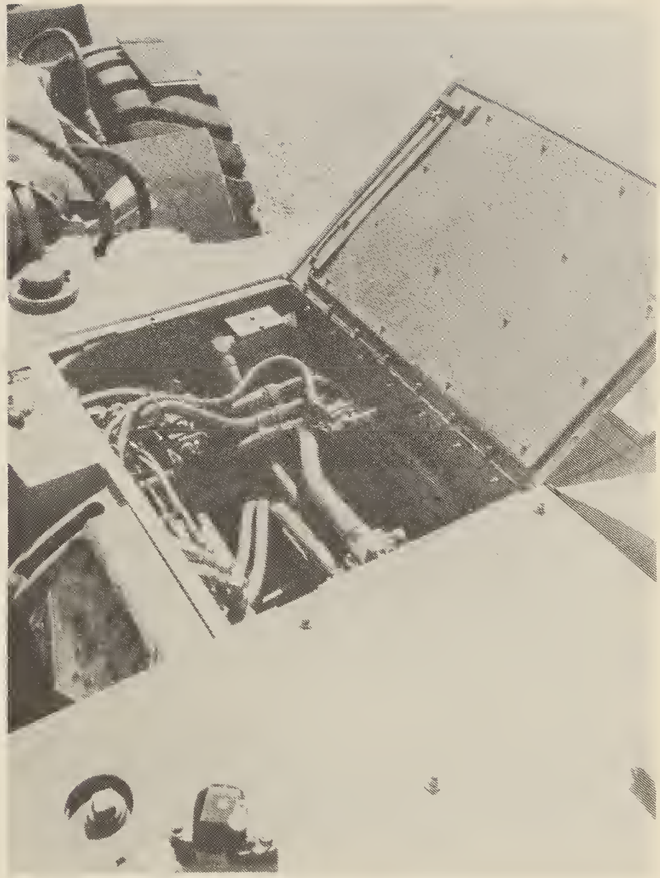


FIGURE 41. - Sound-absorbing foam lining within LHD transmission compartment.

enclosure were lined with noise-absorbing polyurethane foam. Two foam-lined cutouts for air exhaust were added to the "belly pan" beneath the engine. Extensive analysis of this enclosure configuration showed that it would not result in engine overheating. Structureborne engine noise was treated by welding triangular stiffening gussets to the frame rails on which the engine was mounted.

The cooling fan was located at the rear of the engine compartment. A fold-down baffle that covered the cooling fan outlet received the same foam-and-plate treatment as the transmission cover, and the walls surrounding the fan outlet were treated with polyurethane foam (fig. 43).

Similar acoustical foam treatments were installed on the interior walls of the torque converter compartment and the compartment containing the water and fuel tanks. (See figure 40 for the locations of these components.) In addition, numerous existing LHD components had to be relocated or modified slightly to facilitate the installation of the noise-control treatments. The total cost of the acoustical materials was approximately 5 to 7 pct of the selling price of a new LHD vehicle.

The noise-controlled LHD was then tested in an underground gypsum mine; unfortunately, noise levels within the operator's compartment could not always be measured directly.[10] However, operator noise levels for the two loudest stationary LHD modes (high idle and torque converter stall) ranged from 92.5 to 93 dBA, which was approximately 7 to 9 dBA quieter than in the untreated vehicle. In addition, the operator NEI was approximately 103 pct when measured shortly after the retrofitted LHD was placed into

[10] At the time of this study (1977), sound level recording equipment was too bulky to place in the operator's compartment during tramming without interfering with operator movement.

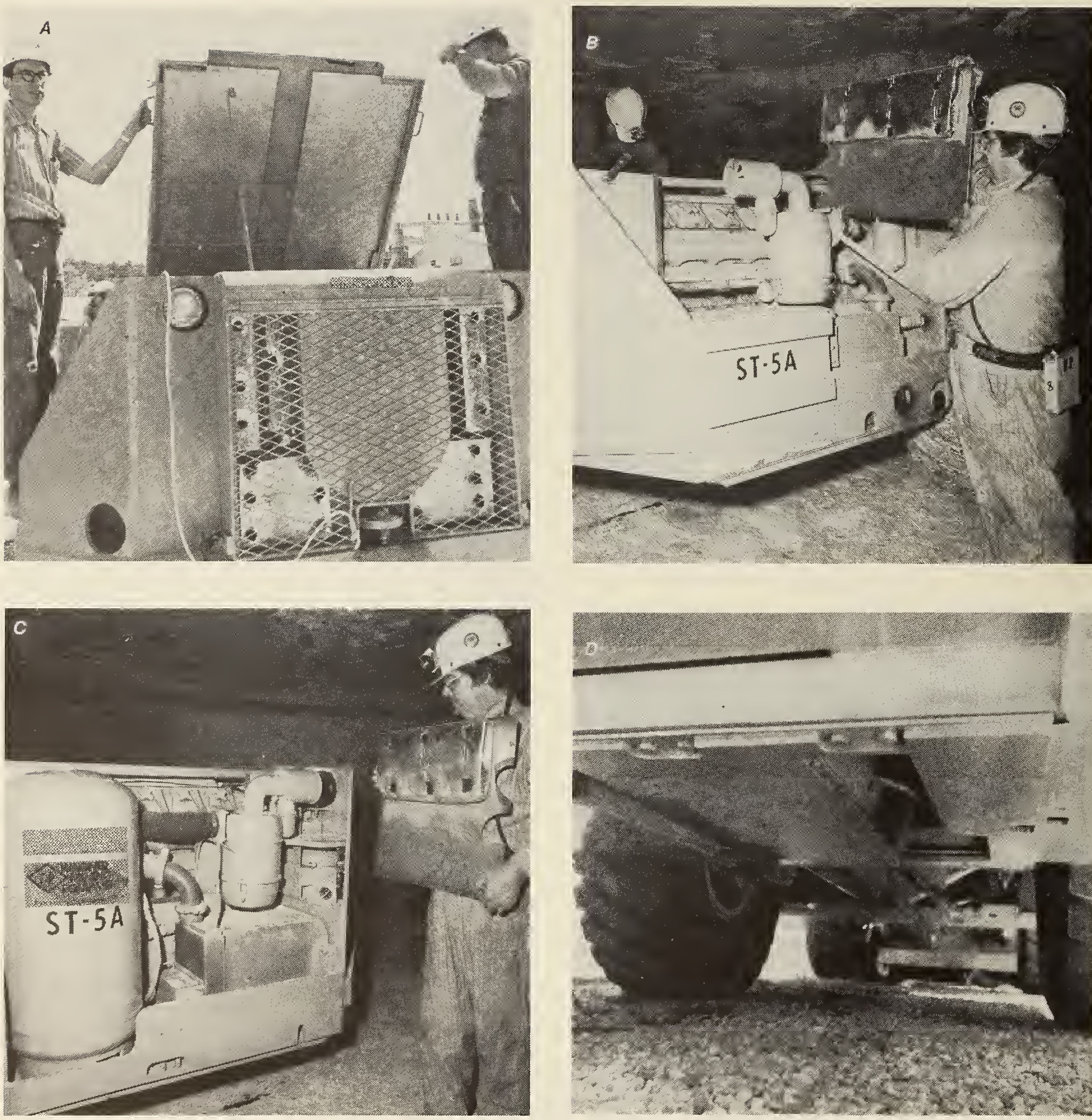


FIGURE 42. - Retrofit acoustical enclosure for LHD engine. *A*, Top cover; *B*, right side cover; *C*, left side cover; *D*, belly pan treatment.

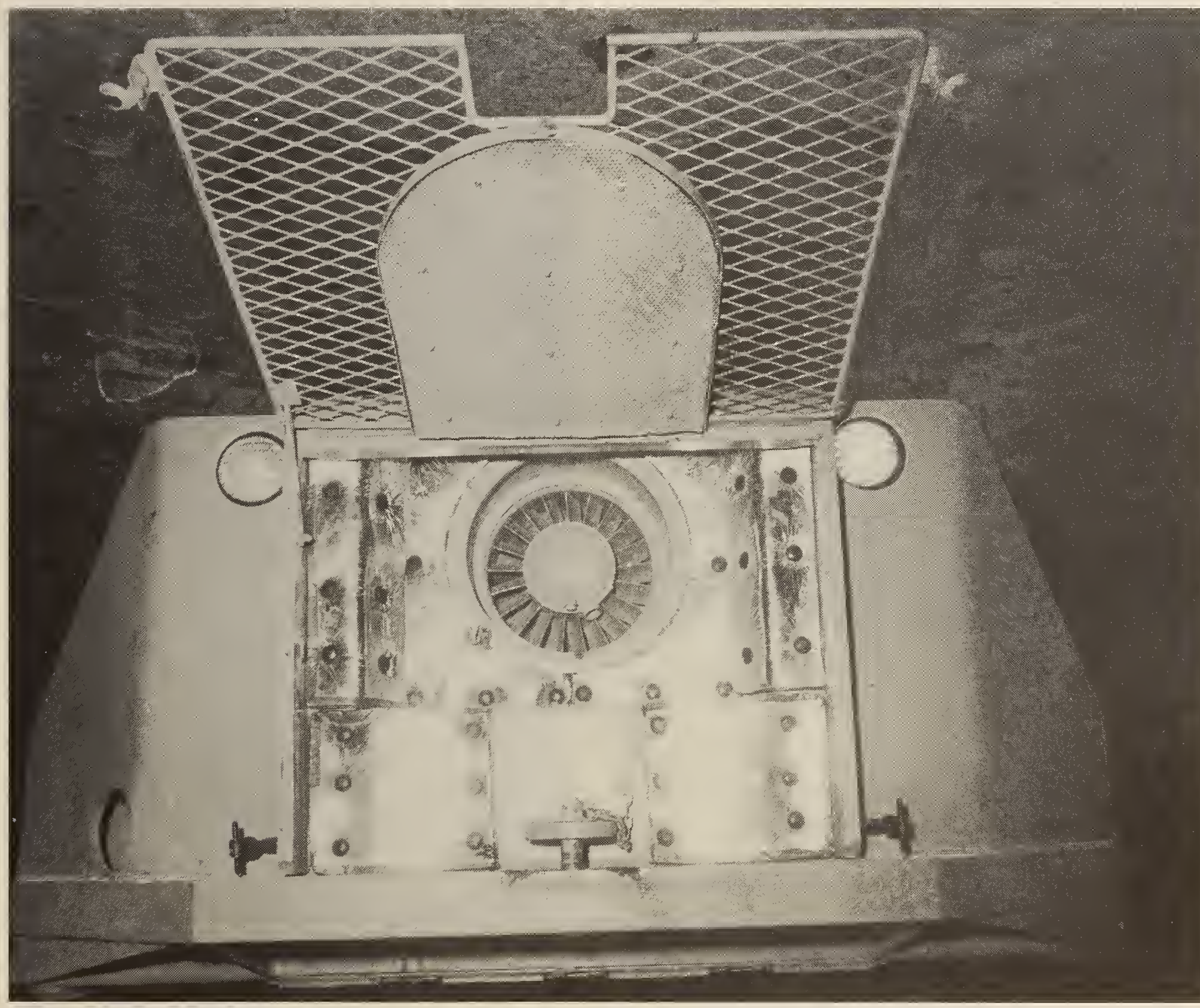


FIGURE 43. - Retrofit noise-control treatments on LHD engine cooling fan (cover and fan compartment lining).

underground service; 1 yr later, the NEI was only 89 pct. Although reduced operating time per shift may have been partially responsible for this decrease, it showed that the noise-control treatments had not deteriorated over time. Mine officials reported that the noise-control treatments did not pose serious maintenance problems or hinder machine performance.

The LHD retrofit noise-control treatments were successful only because the individual noise sources were properly diagnosed and the treatments were carefully designed, installed, and maintained. Each LHD vehicle is slightly different, so preliminary diagnostic work would have to be performed before similar noise-control treatments could be installed on a different LHD model. Engine enclosures must be designed with special care to prevent overheating.

The Bureau is presently sponsoring a program to equip four different LHD vehicles with retrofit noise controls. Preliminary results have been only moderately successful (noise reductions of 4 to 5 dBA), but the program has been significantly affected by problems unrelated to the noise-control treatments (machine breakdowns, mine closings, poor maintenance of noise-control treatments, difficulty in locating mines that will cooperate, etc.). The Bureau, in cooperation with MSHA, has also initiated an in-house program dealing with LHD retrofit noise controls.

Redesign for Noise Control (40)

Although retrofit LHD noise-control treatments can be successful, incorporating these treatments in a newly designed vehicle would proably be a more cost-effective approach. Under Bureau contract, a major LHD manufacturer incorporated noise-control treatments into two of its new machines--one with an 8-yd^3 bucket capacity and one with a 2-yd^3 bucket capacity. The redesign approach was somewhat similar to the retrofit approach; preliminary diagnostic tests were performed on the manufacturer's standard-design LHD vehicles before treatments were designed. Since the manufacturer was not constrained by existing machine dimensions, better fitting acoustical treatments and mechanical components were designed and installed.

Diagnostic tests revealed that the three major noise sources on the standard-design LHD's were again the transmission, engine (including intake and exhaust) and engine cooling fan. Therefore, the manufacturer installed noise-control treatments similar to the retrofit treatments described earlier. In addition, the manufacturer placed exhaust mufflers on both sides of the engine (fig. 44), lined the interior surfaces of the operator's compartment with acoustical foam (fig. 45), and mounted the transmission on rubber vibration-isolation mounts (fig. 46). These treatments were much easier to incorporate in the redesigned machines than in the retrofitted machine.

Aboveground tests of the redesigned LHD's revealed a 9.3-dBA noise reduction for the 8-yd^3 LHD (from 99.0 to 89.7 dBA) and a 10.3-dBA reduction for the 2-yd^3 LHD (from 101.1 to 90.8 dBA). The 8-yd^3 LHD was then sent to an underground mine for extended testing. The results are shown in table 10. Although the initial underground tests were encouraging (94-dBA operator noise level), the noise-control treatments were not maintained properly and were gradually removed during the 8-month evaluation period. The final noise level of 102 dBA corresponded to that of an untreated machine, implying that an 8-dBA noise reduction was achieved by the manufacturer during the redesign process. The 8-dBA noise increase over the evaluation period resulted in more than a threefold decrease in allowable operating time (1.5 to 4.7 h per shift); for this reason, the lack of proper maintenance of the noise-control treatments was particularly harmful.

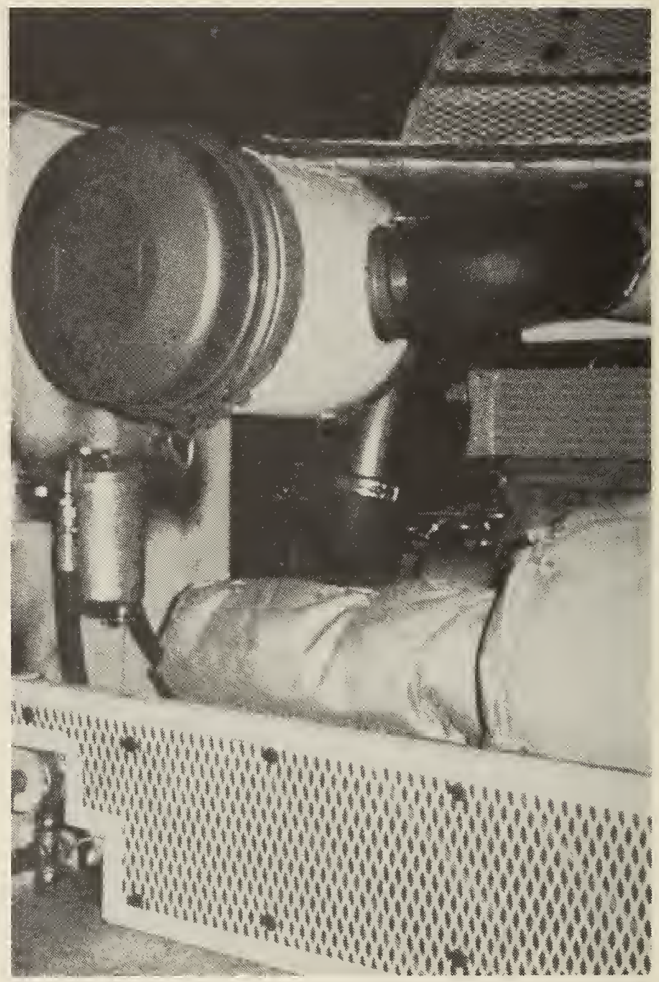


FIGURE 44. - Exhaust muffler on redesigned, noise-controlled LHD vehicle.

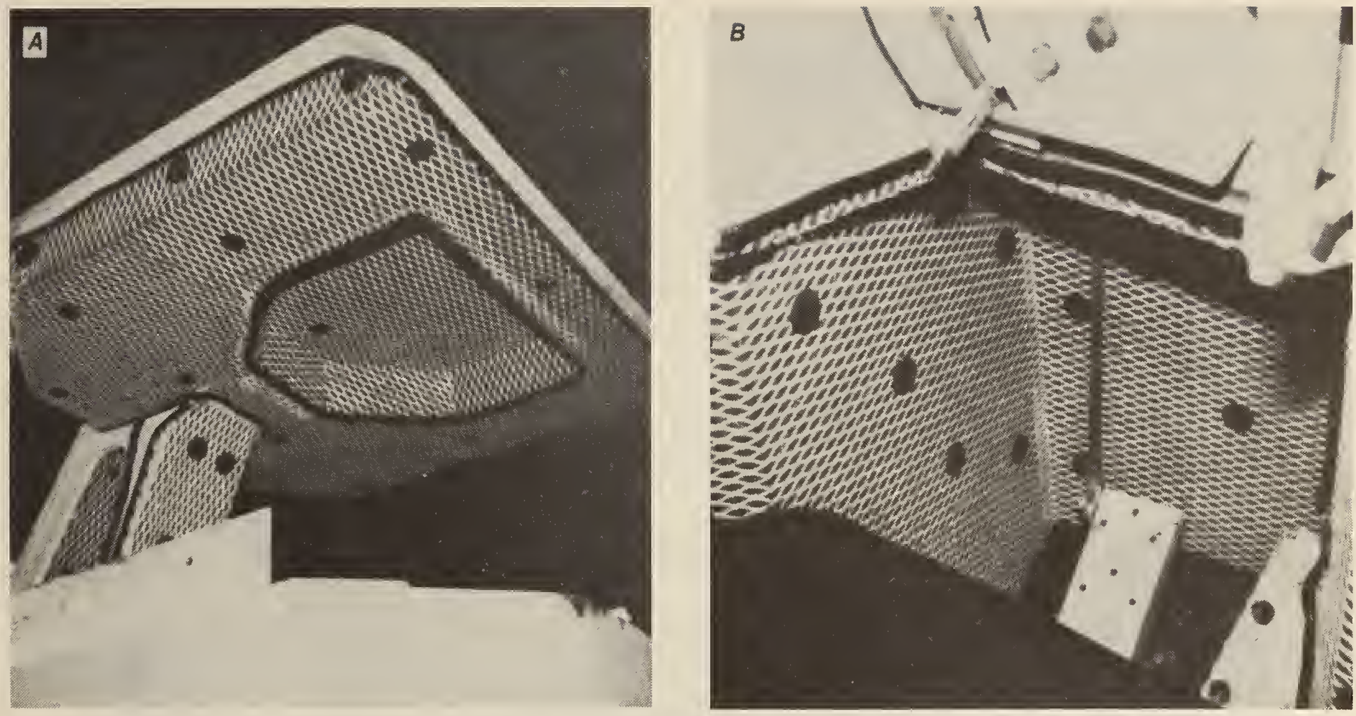


FIGURE 45. - LHD operator-compartment noise-control treatments. *A*, Canopy; *B*, foot-pedal area.

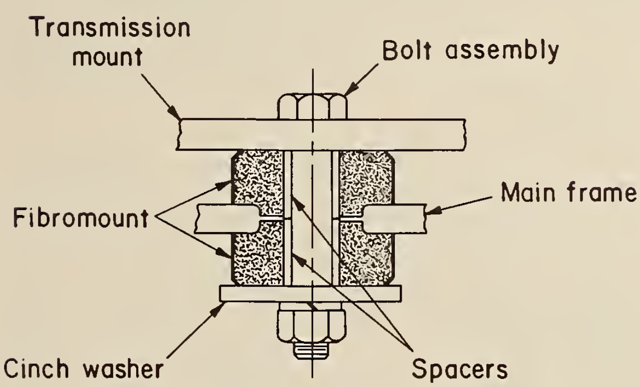


FIGURE 46. - Vibration-isolation mount for LHD transmission.

SURFACE MINING

As explained in part 2, the Bureau's surface mining noise-control research program has concentrated on retrofit acoustical cab treatments for bulldozers and front-end loaders. Two models of both machine types were selected for these treatments, based on their overall popularity in the surface mining industry. The retrofitted dozers and front-end loaders were field tested in surface coal mines for a period of about 1-1/2

TABLE 10. - Results of underground tests of redesigned, noise-controlled LHD

Status of treatments	Months in use	Operator noise level, dBA
All treatments in place	1	94
Some treatments removed	4	97
All treatments removed.	8	102

yr. In general, mine operators were satisfied with the durability and effectiveness of the noise-control treatments.

Detailed fabrication manuals, containing photographs and illustrations that show how the noise-control treatments were installed, have been prepared for both bulldozers and front-end loaders. Numerous Bureau-sponsored workshops were held throughout the country to provide equipment users with a closer look at the retrofit process. Most of the workshop attendees found them beneficial, and many equipment users have since applied the noise-control treatments to their own bulldozers and front-end loaders.

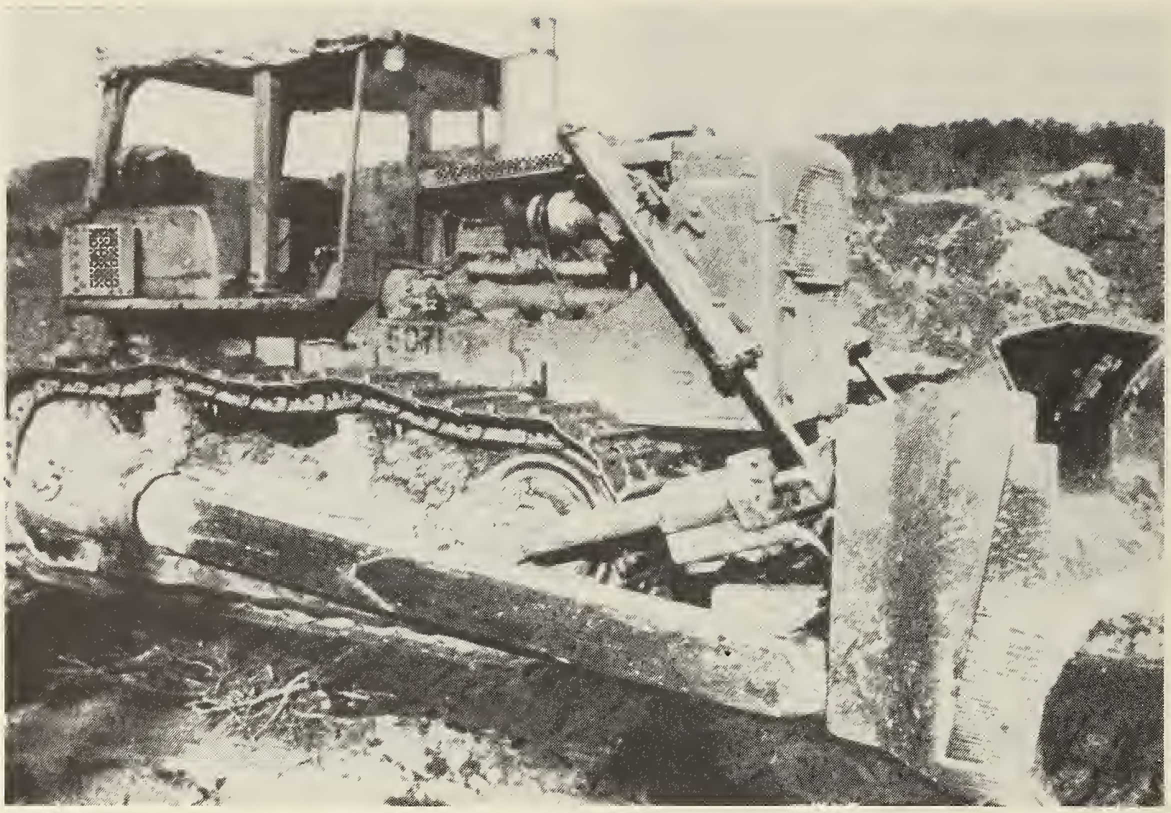


FIGURE 47. - Caterpillar D-9G bulldozer (ROPS-FOPS only) with retrofit noise-control treatments.

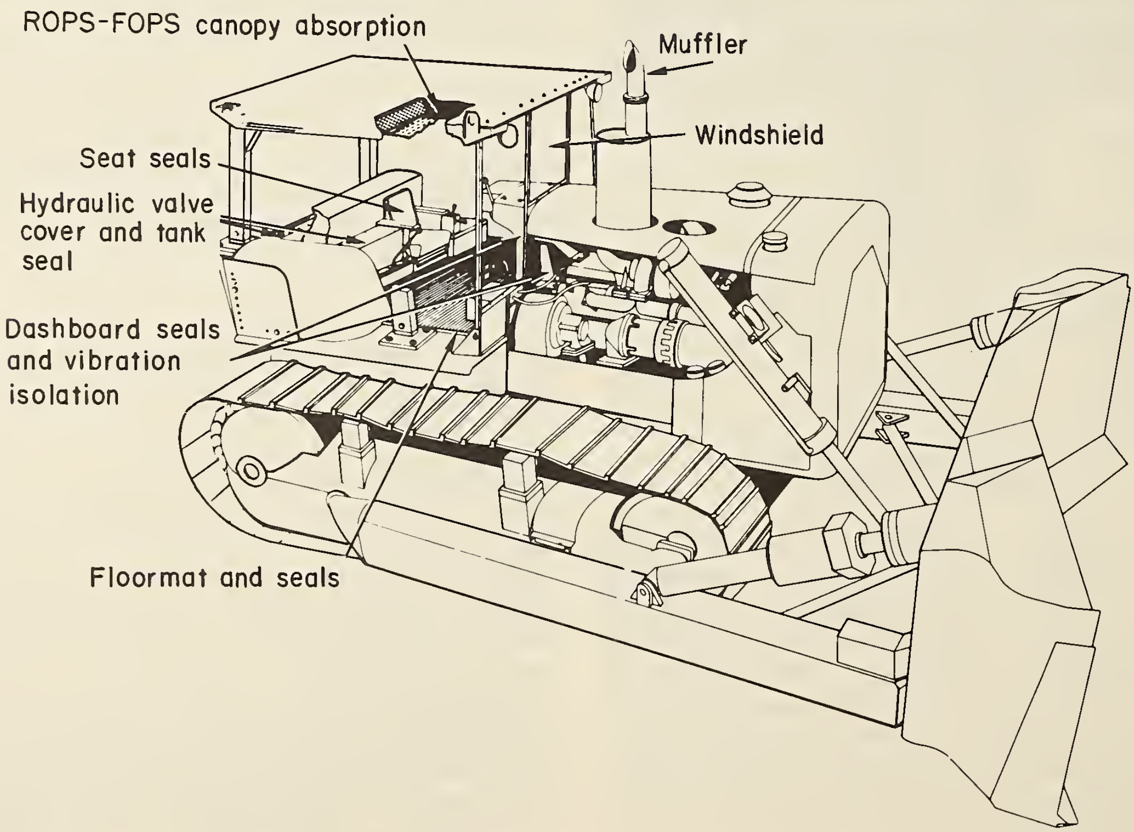


FIGURE 48. - Noise-control treatments installed on Caterpillar D-9G bulldozer (ROPS-FOPS only).

Bulldozers (6)

A breakdown of the 1977 bulldozer population in U.S. surface mines (table 11) shows that the Caterpillar model D-9 was by far the most popular model, comprising 47 pct of the population (40). For this reason, the Bureau treated two different varieties of D-9 dozers, one with only a roll-over-protective and falling-object-protective structure (ROPS-FOPS) and one with a complete (but not acoustical) cab. To show that retrofit noise-control treatments could also be applied successfully to another manufacturer's bulldozer, an International Harvester model TD-25C (ROPS-FOPS only) was also treated.

TABLE 11. - Breakdown of bulldozers used in U.S. surface mines, 1977, by model

Model	Pct of total
Caterpillar D-9..................	47
Caterpillar D-8..................	17
International Harvester TD-25....	11
All others.......................	25

Although the design details of the three machines were somewhat different, the same four basic treatments were used: (1) installing a muffler on the diesel engine exhaust, (2) sealing numerous holes in the floor and dashboard of the operator's station, (3) adding sound-absorbing materials under the ROPS-FOPS and under the cover of the hydraulic tank, and (4) installing vibration-isolation materials between the engine and dashboard. In addition, windshields were installed on the two dozers that originally contained only ROPS-FOPS. The windshields were extremely important because they blocked the direct path between the diesel engine (the largest single noise source on the machines) and the dozer operators. Seals were also installed around the doors of the cab-equipped D-9 dozer.

Tables 12 and 13 summarize the noise reductions achieved through the bulldozer retrofit treatments, the cost of the acoustical materials and hardware, and the labor time it took to install them. Table 12 shows that the operator noise levels after treatment were 89 to 94 dBA, low enough to permit 6 to 8 h of daily operating time without violating Federal noise regulations; before treatment, only 1 to 2 h of operating time was allowed. The effects of the individual treatments on the three machines are described below.

Caterpillar D-9G With ROPS-FOPS Only

Figure 47 is a photograph of the treated dozer, and figure 48 shows the seven major components of the retrofit noise-control package. Diagnostic tests of the untreated dozer indicated that the windshield would be the single most effective noise-control treatment, followed by the ROPS-FOPS canopy absorption and the engine exhaust muffler; therefore, these three treatments were installed first.

Figure 49 shows how the operator noise level decreased as each of the seven treatments was added. The overall noise reduction was 11 dBA, but the reduction obtained through one treatment depended on the presence of the previous treatments. It can be seen from figure 49 that the windshield alone would have

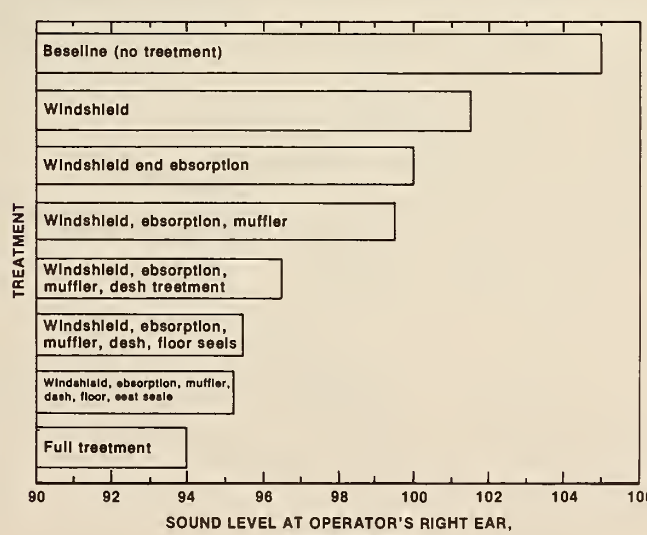


FIGURE 49. - Step-by-step noise reduction of Caterpillar D-9G bulldozer (ROPS-FOPS only).

reduced the noise by about 4 dBA, the canopy absorption alone would have reduced the noise by about 3 dBA, and the exhaust muffler alone would have reduced the noise by about 1.5 dBA. The remaining treatments would have had a negligible effect on operator noise if the windshield, canopy absorption, and muffler had not been installed; therefore, these three treatments were by far the most important components of the retrofit package.

TABLE 12. - Summary of bulldozer retrofit noise-control treatment results

Model	Operator noise level, dBA		Noise reduction, dBA	Cost	
	Before treatment	After treatment		Materials, 1978 dollars	Labor, h
Caterpillar D-9G:					
ROPS-FOPS only............	105	94	11	825	106
Cab (nonacoustical).......	99[1]-100[2]	89[2]-91[1]	9-11	725	88
International Harvester TD-25C; ROPS-FOPS only........	102	91	11	912	80

[1]Cab doors open. [2]Cab doors closed.

TABLE 13. - Summary of treatments and costs for bulldozer noise-control treatments

Treatment component	Materials (approx), 1978 dollars	Labor (estimated), h	
		Welder	Mechanic
CATERPILLAR D-9G WITH ROPS-FOPS ONLY			
Windshield................................	275	29	16
Sound absorption materials for FOPS canopy..................................	115	4	10
Exhaust muffler...........................	190	0	2
Dashboard seals (and vibration isolation).	25	1	4
Floormat and seals........................	80	0	8
Seat seals................................	55	0	8
Hydraulic valve cover and tank seal.......	80	4	16
Miscellaneous.............................	5	2	2
Total................................	825	40	66
CATERPILLAR D-9G WITH CAB			
FOPS canopy absorption....................	150	4	8
Cab wall seals............................	75	2	22
Floormat and seals........................	80	2	8
Seat and hydraulic valve seals............	105	4	12
Sound absorption materials for cab surfaces................................	95	0	16
Dashboard seals (and vibration isolation).	25	2	4
Miscellaneous.............................	5	2	2
Subtotal..............................	535	16	72
Muffler[1]................................	190	0	2
Total................................	725	16	74
INTERNATIONAL HARVESTER TD-25C WITH ROPS-FOPS ONLY			
Windshield................................	537	8	53
FOPS canopy-absorption materials..........	182	1	8
Floormat..................................	43	0	2
Seat seals and hydraulic box seal.........	150	.5	7.5
Total................................	912	9.5	70.5
Optional: Dashboard barrier seal.........	400	0	7

[1]Needed only if existing muffler is ineffective.

Caterpillar D-9G With Cab

Figure 50 shows the six major components of the retrofit noise-control package applied to the cab-equipped D-9G dozer. This machine already had a relatively new muffler, so none was installed; however, this would ordinarily have been included in the package. Since a windshield was already a part of the cab, the simpler "cab wall seal" treatment replaced the windshield treatment required for the D-9G dozer with ROPS-FOPS only. The interior walls of the cab were treated with the same sound-absorbing materials as the underside of the canopy. As shown in table 12, the operator noise level in the untreated cab was higher when the doors were closed than when they were open; this was because the untreated doors tended to rattle in their sockets when they were closed. After door seals were added, however, the operator noise level was lower when the doors were closed.

Figure 51 shows how the operator noise level decreased as the treatments were added (11-dBA total reduction, cab doors closed). As with the D-9G dozer with ROPS-FOPS only, the noise reduction at each stage of treatment depended on the presence of the previously installed treatments.

International Harvester TD-25C With ROPS-FOPS Only

Figure 52 shows the major components of the retrofit noise-control package for the TD-25C dozer. Since the manufacturer had already installed an exhaust muffler

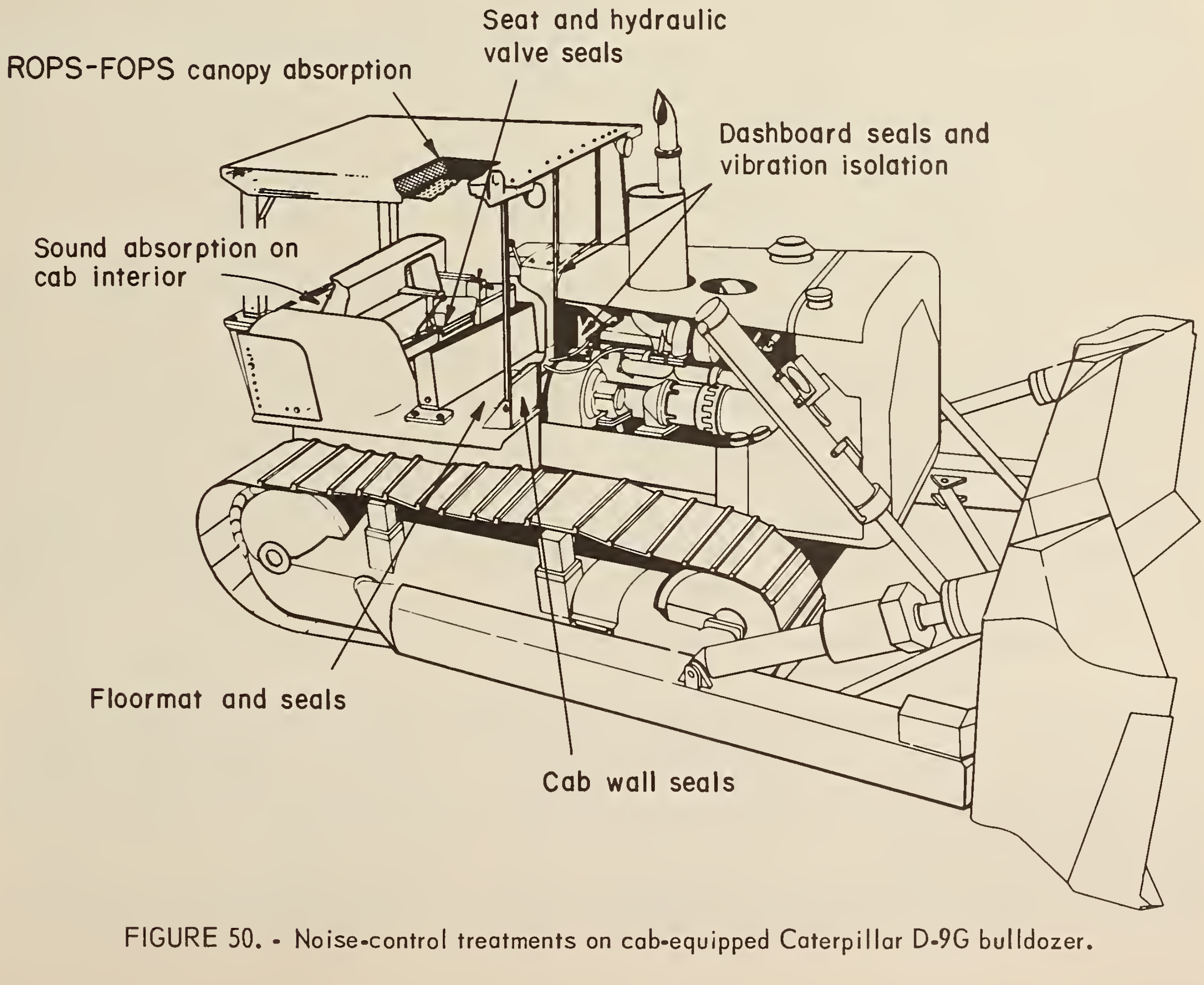


FIGURE 50. - Noise-control treatments on cab-equipped Caterpillar D-9G bulldozer.

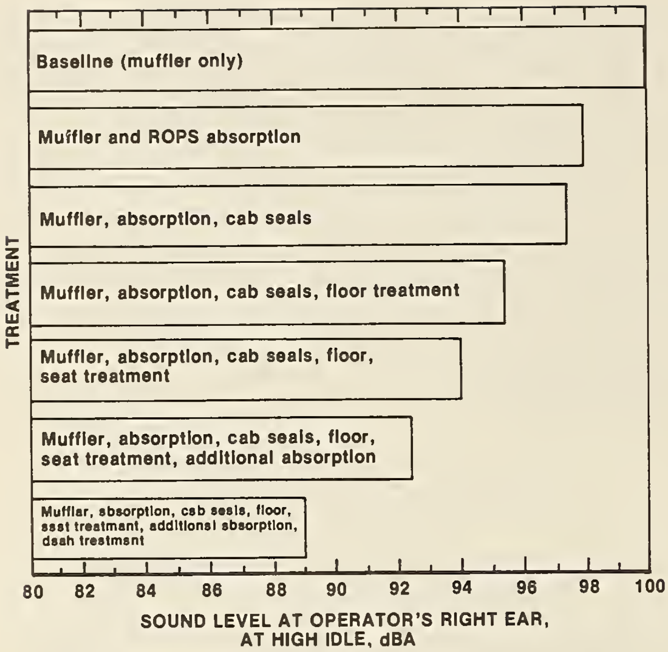


FIGURE 51. - Step-by-step noise reduction of cab-equipped Caterpillar D-9G bulldozer.

on this machine, none was needed; however, a muffler would have to be installed if none were present. Figure 53 shows how the operator noise level decreased as the treatments were added (11-dBA total reduction), and table 13 summarizes the material costs and labor hours associated with each component of the package.

Table 13 shows that the cost of the windshield was the biggest difference between the retrofit packages for the International TD-25C and the Caterpillar D-9G with ROPS-FOPS. More materials and labor were needed for the TD-25C windshield because it was larger and more difficult to fabricate, but it provided more noise reduction (5 dBA) than the D-9G windshield (4 dBA). As with the other two bulldozers, the noise reductions achieved with individual treatments on the TD-25C depended on the presence of the other treatments. The windshield and the ROPS-FOPS canopy absorption were the two most important treatments; the others would have been ineffective without them. The dashboard barrier was considered to be an optional treatment because its cost was high compared to the noise reduction resulting from its installation.

Front-End Loaders (7)

The front-end loader ranked second after the bulldozer, as a noise offender in the surface mining industry (40) (table 4). Although about 40 pct of the loaders identified during a 1977 census (40) were equipped with factory-designed acoustical cabs, the remaining 60 pct required some type of retrofit noise-control treatment. The Bureau chose two of the most popular loader models for the retrofit program--a Caterpillar 988 and an International Harvester H-400 B. Both machines had nonacoustical operator cabs, and this made the retrofit treatments easier to install than if they had been equipped only with ROPS-FOPS.

The treatments themselves were similar to those installed on the cab-equipped bulldozer: (1) exhaust mufflers; (2) seals around openings in the cab walls, doors, seats, and floors; and (3) sound-absorbing materials on all interior cab surfaces, including the canopies. Tables 14 and 15 summarize the noise reductions, material costs, and labor hours associated with the retrofit treatments. As with the cab-equipped bulldozer, the noise levels in the

TABLE 14. - Summary of front-end loader retrofit noise-control treatment results

Model	Operator noise level, dBA		Noise reduction, dBA[1]	Cost	
	Before treatment	After treatment		Materials, 1978 dollars[2]	Labor, h
Caterpillar 988.........	99[3]-101[1]	90[1]-91[3]	11	410	29
International Harvester H-400 B................	95[1,3]	83[1]-87[3]	12	580	19

[1]Cab doors closed. [2]Not including exhaust muffler. [3]Cab doors open.

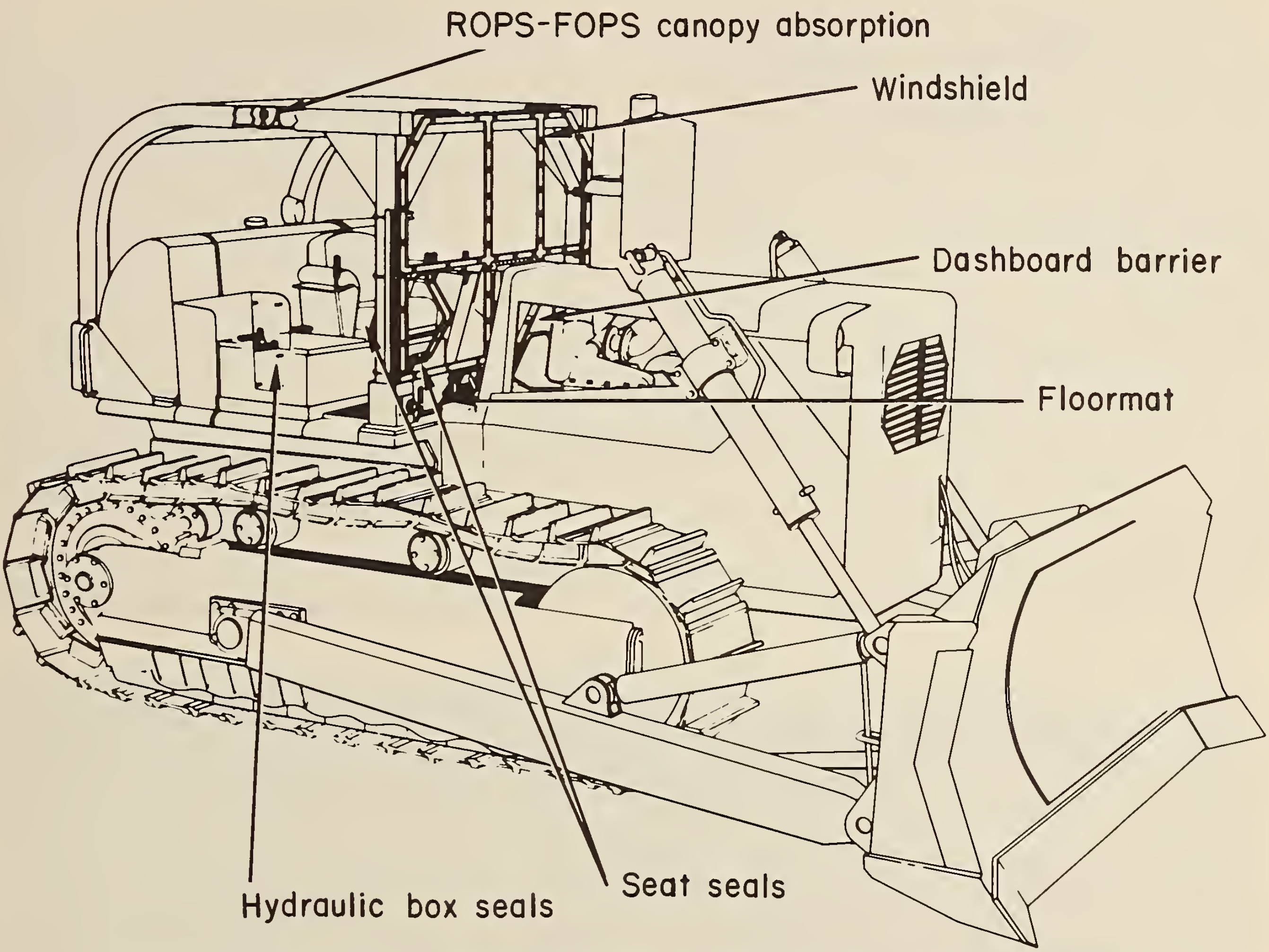


FIGURE 52. - Noise-control treatments installed on International Harvester TD-25C bulldozer.

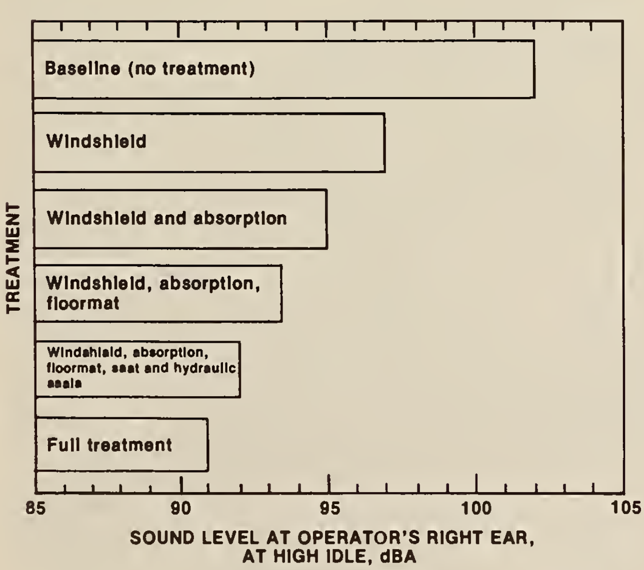


FIGURE 53. - Step-by-step noise reduction of International Harvester TD-25C bulldozer.

untreated loader cabs were the same or greater when the doors were closed than when they were open, due to the doors rattling in their sockets. After treatment, however, the loader cabs were quieter with the doors closed. The costs of installing exhaust mufflers are not included in tables 14 and 15 because the loaders already had mufflers. If mufflers had not been present, they would have been essential components of the noise-control packages.

Figures 54 and 55 show the retrofit package on the Caterpillar 988 loader and its results, and figures 56 and 57 do the same for the International H-400 B. As with the bulldozer retrofit packages, the effectiveness of each successive noise-control treatment depended on the presence of previous treatments.

TABLE 15. - Summary of treatments and costs for front-end loader noise-control packages

Treatment component	Materials (approx)[1]	Labor (mechanic, estimated), h
CATERPILLAR 988		
Cab wall seals	$58	7
Sound absorption materials for canopy and rear cab wall	200	8
Floormat	39	3
Pedestal seals	50	6
Additional sound absorption materials for cab interior	63	5
Total	410	29
INTERNATIONAL HARVESTER H-400 B		
Cab wall seals	$138	8
Sound absorption materials for cab	393	8
Floormat	49	3
Total	580	19

[1]In 1978 dollars for Caterpillar 988; in 1979 dollars for International Harvester H-400 B.

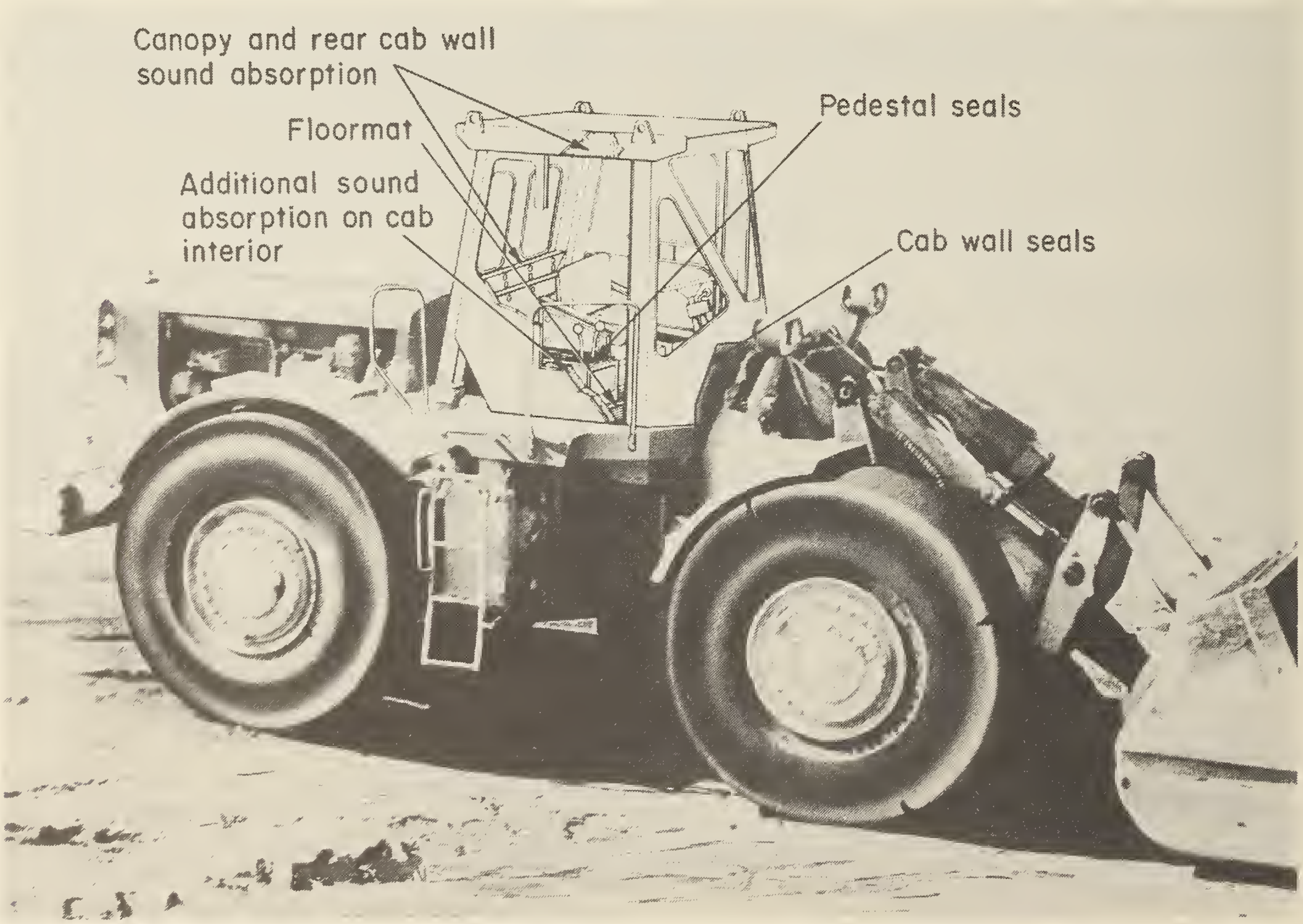


FIGURE 54. - Noise-control treatments installed on Caterpillar 988 front-end loader.

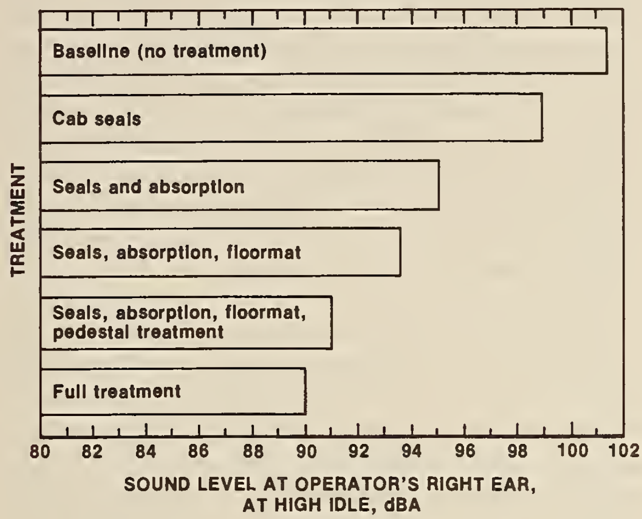


FIGURE 55. - Step-by-step noise reduction of Caterpillar 988 front-end loader.

PREPARATION AND PROCESSING PLANTS

Bureau studies in the 1970's identified the most serious noise problems in coal and mineral processing plants. Noise in the coal industry has been regulated since 1969, so most of the early Bureau work dealt with coal preparation plants. Federal noise regulations were extended to the metallic and nonmetallic mining industries in 1977, so several recent Bureau programs have addressed noise problems in these types of processing plants. Since the use of nonmetallic screen decks is one way to reduce noise in all types of processing plants, the Bureau sponsored an in-depth study to determine the screening efficiencies attainable with nonmetallic screen decks. The following sections summarize the results of Bureau research efforts in these areas.

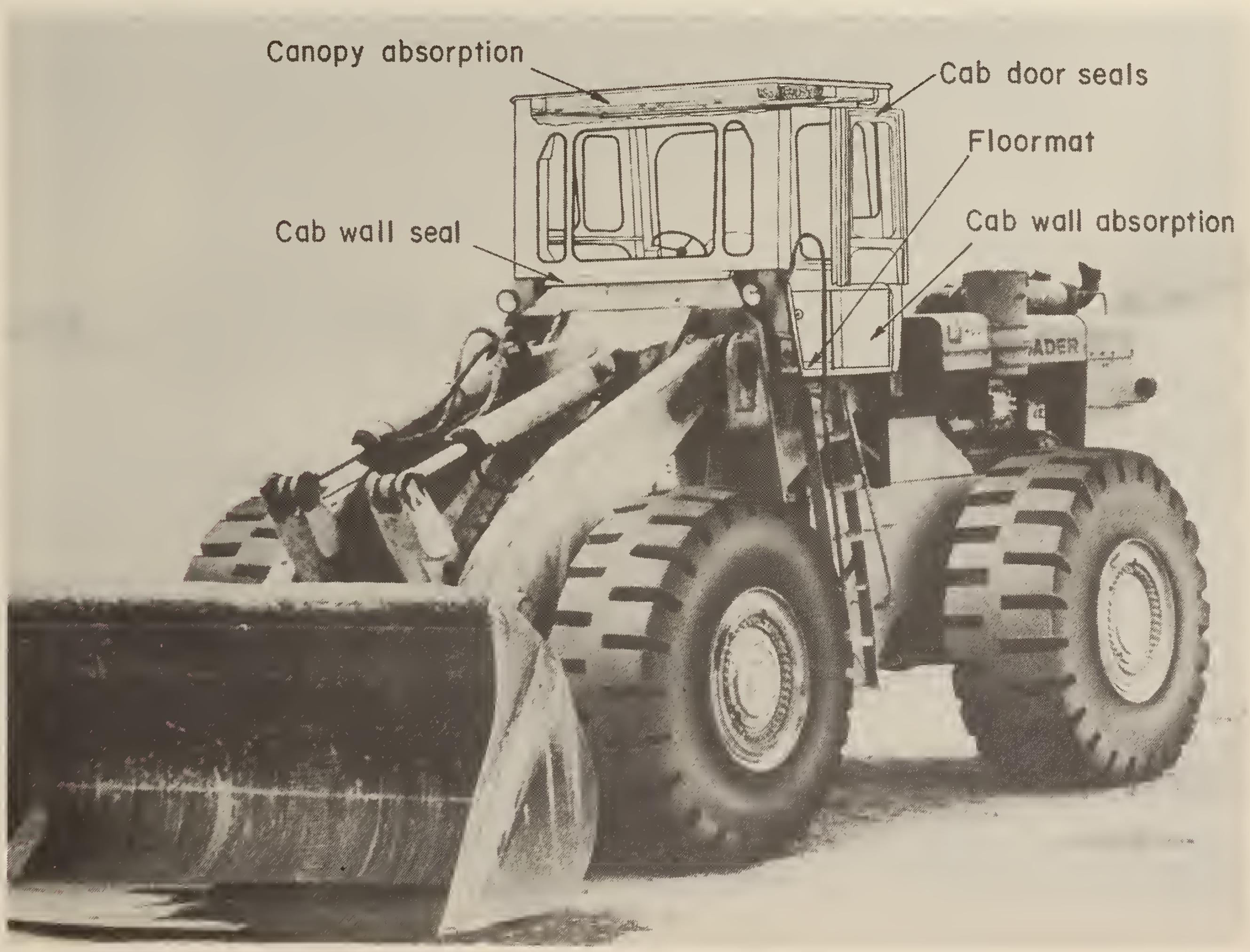


FIGURE 56. - Noise-control treatments installed on International Harvester H-400 B front-end loader.

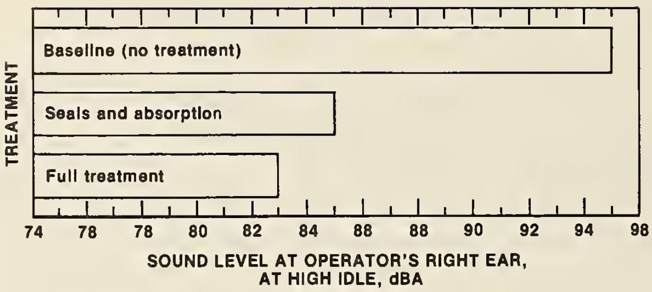


FIGURE 57. - Step-by-step noise reduction of International Harvester H-400 B front-end loader.

Coal Preparation Plants

Retrofit Treatments (32-33)

The Bureau's most successful program in coal preparation plant noise control was a retrofit project conducted at the Georgetown Preparation Plant, Consolidation Coal Co., Cadiz, OH. The work consisted of three major elements: (1) identification of the most serious noise sources, (2) selection and installation of retrofit noise-control treatments, and (3) both short- and long-term evaluations of the durability and acoustical effectiveness of the retrofit treatments.

Figure 58 shows the flow chart of the Georgetown preparation plant and depicts most of its noise-generating equipment. Since workers moved throughout the plant during the normal working shift, the noise sources could not be ranked in terms of noise level alone; the amount of time spent in the noisiest areas also had to be considered. The plant was

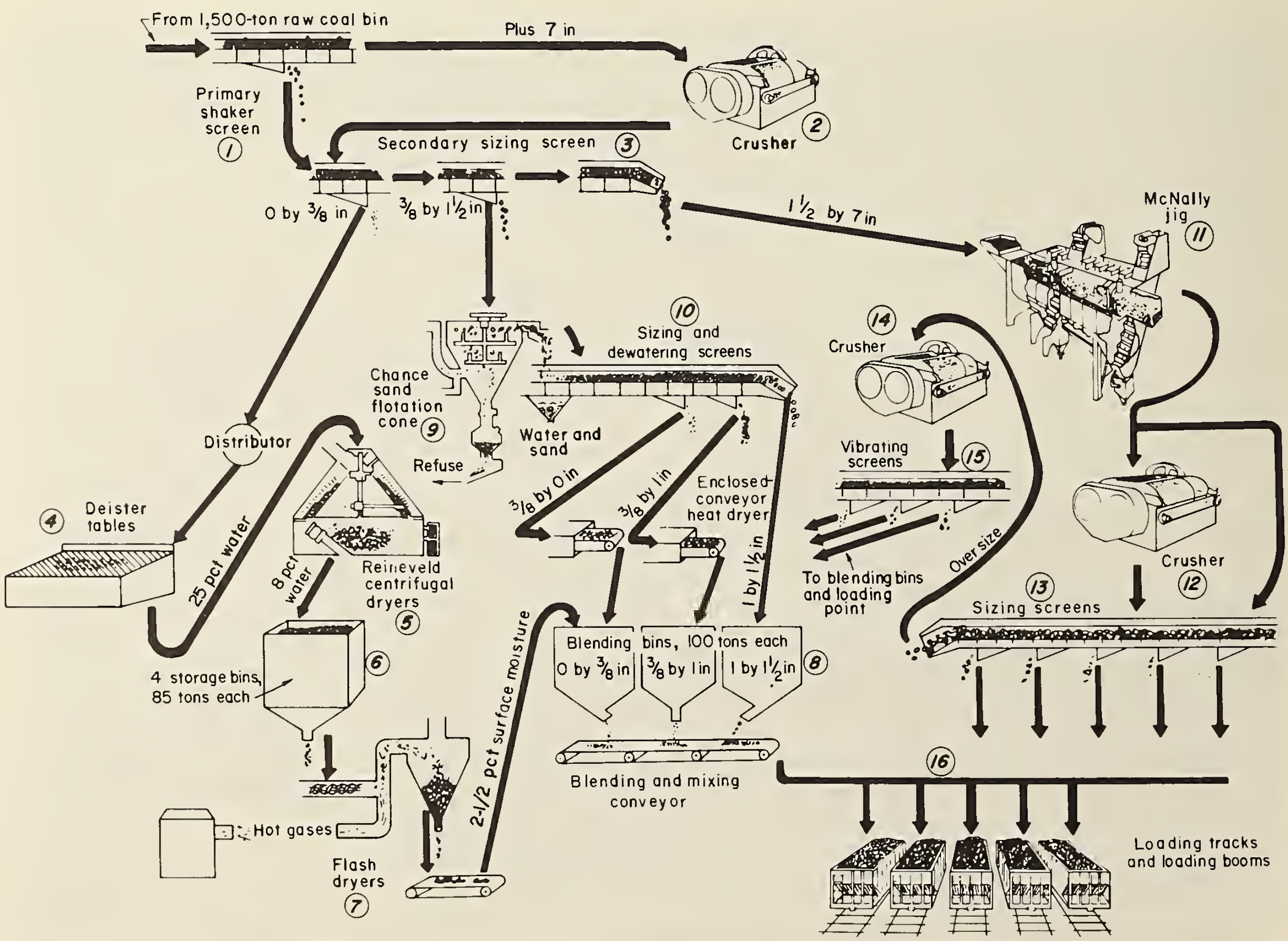


FIGURE 58. - Flow chart of Georgetown coal preparation plant.

therefore divided into 25 different "noise areas," of which 13 were identified as either "continuous-exposure areas" (i.e., at least one worker was present during the entire shift) or "frequent-exposure areas" (workers were present for about 50 pct of the shift). Table 16 shows the noise levels in these 13 areas and the equipment primarily responsible for the noise in each area. Material falling on the chutes and bins in these areas also contributed heavily to the recorded noise levels.

Most of the noise sources in table 16 received one or more of the following noise-control treatments: (1) resilient screen decks, (2) resilient impact pads, (3) chute liners, and (4) loaded-vinyl curtains. The resilient screen decks consisted of elastomeric top surfaces (rubber or urethane) bonded to metal bottom layers, and the impact pads and chute liners were also made of elastomeric materials. These three treatments reduced the noise generated by material (coal or rock) falling or sliding on bare steel. The loaded-vinyl curtains were used to enclose several particularly noisy pieces of equipment. In most cases, these curtains consisted of a series of vertical strips of the loaded-vinyl material, held together along the edges with Velcro fasteners (fig. 59). This construction allowed workers to inspect the enclosed equipment without removing the entire curtain. Table 17 describes the treatments applied to each piece of equipment listed in table 16.

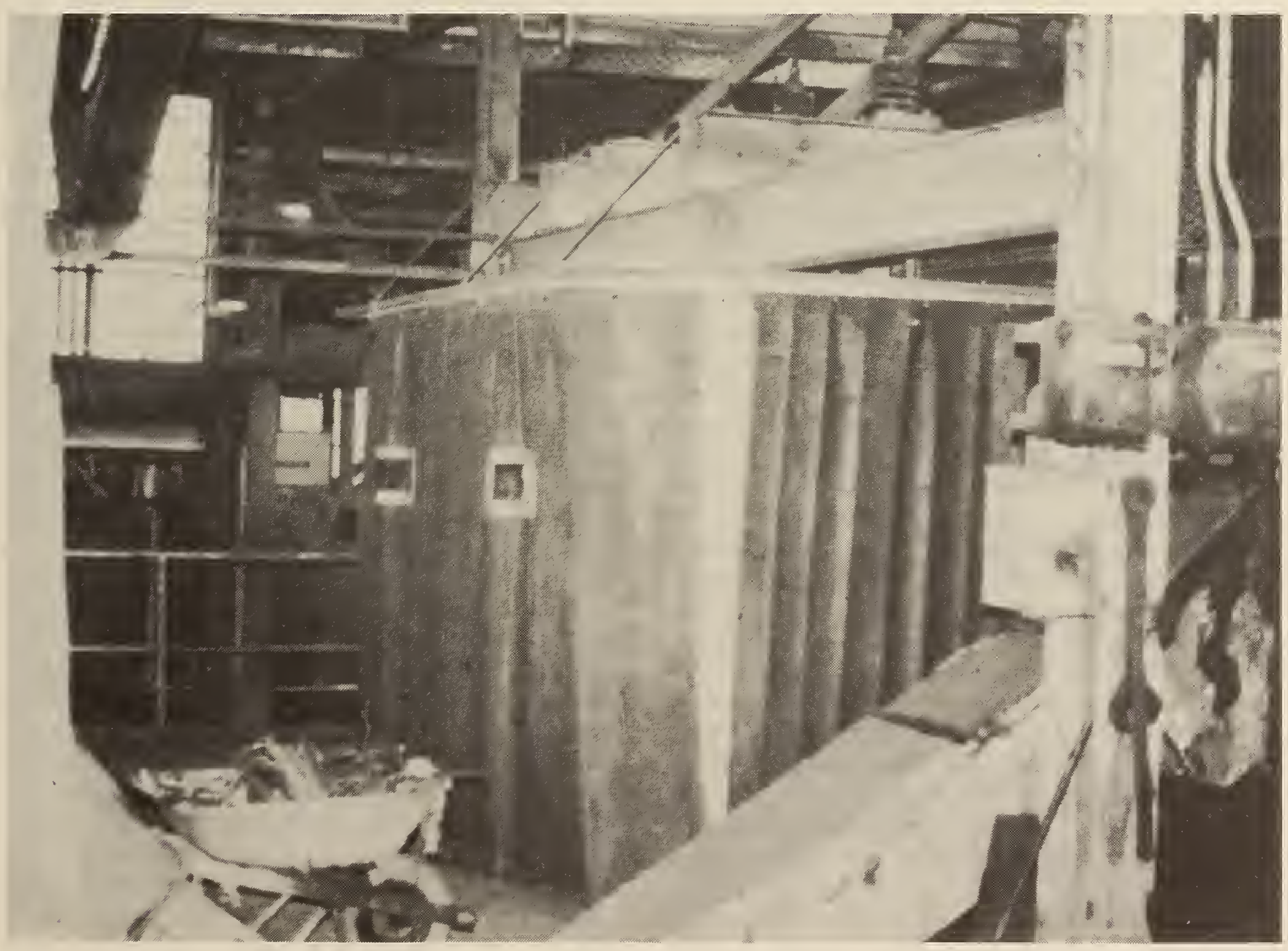


FIGURE 59. - Curtain around screening area in Georgetown coal preparation plant.

TABLE 16. - Short term and long term effectiveness of noise-control treatments at Georgetown coal preparation plant, A-weighted decibels

Equipment	Before treatment	Shortly after treatment	3-4 yr after treatment
Railcar shaker	111-113	([1])	([1])
Classifying screens	102-104	96-97	([2])
Centrifugal dryers	95-103	89-92	91-92
Vibrating screens	101	96	([2])
Rock crusher	93-100	91-92	93-95
Clean coal desanding screens	96- 97	93	94
Secondary sizing screens	95- 97	93	96
Baum jigs	94- 97	91-93	93-94
Middling shaker screens	94- 97	92	93-94
Coal crushers	96	90	95-99
Flight conveyor	94- 95	92-93	93
Picking table	94	90-92	93-94
Primary screens	94	91	92-94

[1]Not treated; shaker operation discontinued.
[2]Not measured; equipment not operating at full capacity.

The noise-control treatments listed in table 17 had to be evaluated in terms of both short-term noise reduction and long-term durability. Short-term noise reductions were relatively easy to assess through before-and-after noise measurements in the same areas. However, the long-term acoustical performance of the treatments was difficult to measure quantitatively because of (1) normal wear of the acoustical materials and (2) changes in the plant's operating procedures during the course of the project. Table 17 describes the relative durability of many of the treatments; but of course, the listed equipment "lifetimes" would have to be compared to those of standard (usually steel) components to assess their true value. In addition, the size composition of the material handled by the plant became much coarser as surface-mined coal replaced underground coal[11] as the primary plant feed. This increased the wear rates of the acoustical materials and increased the "inherent noisiness" of the plant (because large particles produce larger impacts than small particles). Finally, the addition of a coal froth-flotation circuit and thermal dryers decreased the amount of material handled by some of the original equipment.

[11]Coal produced by continuous miners is more finely sized than that produced by surface coal mining equipment.

Table 16 shows the noise levels measured in the critical areas of the plant before treatment, shortly after treatment (when all treatments were relatively undamaged), and about 3 to 4 yr after treatment. The noise increases after 3 to 4 yr were due to treatment wear, increased throughput size, and/or other factors (including material failures) described in table 17. Changes in plant operating procedures accounted for the lack of long-term noise reduction data (table 16) for some equipment types.

The long-term physical performance of the noise-control treatments varied greatly. The loaded-vinyl curtains generally lasted longer than the other treatments simply because they were not exposed to physical impacts; however, some of the elastomeric impact pads and chute liners were both quieter and longer lasting than their steel counterparts. The following sections summarize the physical performance of the four major types of treatments used at the Georgetown plant:

TABLE 17. - Noise-control treatments used at Georgetown coal preparation plant

Equipment and treatment	Comments
Railcar shaker: No treatment................	Shaker no longer in use; plant switched from rail-carried to trucked-in feed coal. Acoustic booth for operator may be best treatment.
Classifying screens: Resilient impact pad beneath infeed chute; rubber-clad steel decks.	Impact pad successful for 2 yr. Rubber-clad screens caused blinding.
Centrifugal dryers: Loaded vinyl curtain enclosures; Velcro fastener strips sewn on curtain material.	Enclosures still in place 4-5 yr after initial installation.
Vibrating screens: Rubber liners in discharge chutes; urethane-clad steel decks.	Rubber liners successful. Urethane-steel bond separated after 7 months.
Rock crusher: 2 rubber impact pads in infeed chute (2-3/16 in thick); pads had ribbed profile to achieve 90° impact angle.	Pads completely successful, still intact 3 yr after initial installation.
Clean coal desanding screens: Plastic liners in receiving hoppers and discharge chutes; loaded-vinyl curtains separated screens from main aisle.	Hopper liner wore out due to impacts, but discharge chute liner remained intact. Curtains still intact 4 yr after installation.
Secondary sizing screens: All-elastomer and rubber-clad decks; partial covers over open discharge chutes; loaded-vinyl curtain enclosures.	All-elastomer decks caused blinding. Rubber-clad decks marginally successful. Curtains very successful.
Baum jigs: Ribbed rubber impact pads at infeed chutes; flat urethane impact pads in refuse chutes; plastic and ceramic liners in refuse chutes; partial covers on open chute tops; mufflers for air blowers.	Both types of impact pads lasted longer than steel. Plastic chute liners wore out after 2-1/2 months, but ceramic liners lasted 4 yr. No problems with mufflers.
Middling shaker screens: Loaded-vinyl curtains around screening area (both clear and opaque).	Clear curtains became obscured with dirt, but reduced noise successfully.
Coal crushers: Loaded-vinyl curtains between crushers and main aisle; Velcro fastener strips glued to curtain material.	Moderately successful; glued-on fasteners peeled off after 6 months. Sewn-on fasteners recommended.
Flight conveyor: Loaded-vinyl curtains separated conveyor from main aisle; sewn-on Velcro fasteners.	Curtains still intact 4 yr after initial installation.
Picking table: Urethane impact pad placed where material dropped from upper to lower portion of table; plastic layer downstream of impact pad.	Impact pad lasted 2 yr before replacement. Plastic layer wore out after 6 months.
Primary screens: Elastomer-clad steel decks; all resilient decks (polymer topped by rubber); impact pads between screen sections.	Elastomer-steel bond separated easily. All-resilient decks remained intact but caused blinding. Impact pads lasted over 3 yr before wearing out.

Resilient Screen Decks

The tests demonstrated that elastomer-clad and all-elastomer screen decks could reduce the noise produced by impacts of material on the decks. However, their acoustical advantage over all-steel decks could not be measured directly because of the noise generated by impacts at the screen feed and discharge chutes, scraping of the screen bottom decks, and vibration of the screen drive mechanisms.

Two operational problems also occurred with the resilient screen decks--"blinding" and delamination. Although "blinding" (plugging of screen holes by near-sized pieces of material) can occur on any screen, depending on screen loading and the amount of open area initially present, the resilient decks seemed to be more susceptible to this problem than all-steel decks. Older, crank-arm-type screens (e.g., primary screens) were particularly vulnerable. Delamination (separation of the elastomer and steel layers of the elastomer-clad screens) sometimes occurred before the elastomer top surfaces began to show significant wear due to material impacts. However, several types of elastomer-clad screens tested at other preparation plants (under the same overall program as the Georgetown tests) did not cause blinding, showed no signs of delamination, and lasted longer than all-steel decks. Reasons for these conflicting results could not be identified conclusively.

Resilent Impact Pads

In many cases, an elastomeric impact pad at the inlet or discharge point of a belt, screen, or chute was a very cost-effective means of noise control. When designed and installed properly, the long service life of an elastomeric pad more than compensated for its high initial cost. However, the material impact angle and the elastomer thickness had to be chosen carefully to achieve maximum performance. Since a 90° impact angle causes the minimum elastomer wear, impact pads placed on inclined surfaces (not perpendicular to material flow) were ribbed to create a 90° impact angle. A smooth impact pad was used where the material flow was perpendicular or nearly perpendicular to the pad surface. Thicker impact pads were successful in some areas where thinner pads had failed.

Chute Liners

Resilient chute liners (rubber and urethane) were more durable and more effective in reducing noise than rigid (plastic and ceramic) liners due to the resilient liners' ability to absorb material impact forces. Furthermore, plastic liners wore out quickly when exposed to tumbling or impacting material flows; although ceramic tiles were more durable, they showed evidence of cracking over time. Both the resilient and plastic chute liners lasted longer when exposed to smooth, sliding material flows.

In general, the chute liners were only marginally effective in open chutes due to the noise inherent in the material flow. In these cases, partial chute covers were just as effective and somewhat cheaper than chute liners. However, chute covers could only be installed where frequent visual monitoring was not essential and where surges of material flow did not occur.

Loaded-Vinyl Curtains

The flexible curtains proved to be the longest lasting and most effective noise-control treatments in the plant. They were effective in reducing noise produced by large, complicated machines and could be easily opened or removed when equipment inspection and maintenance were needed. The only conditions that would preclude the use of these curtains in other plants would be (1) extremely limited clearance around the noisy equipment and/or (2) the need for constant, unobstructed visual monitoring of the equipment from a distance. The clear loaded-vinyl curtains used at the Georgetown plant were just as effective as opaque curtains in reducing noise, but they soon became obscured with dirt.

Designing New Plants for Noise Control (34)

The Bureau's Georgetown study showed that noise levels in coal preparation plants can be reduced through retrofit treatments; however, it was obvious that the noise exposures of many workers in these types of plants could be lowered if new plants were designed in accordance with standard engineering noise-control principles. For this reason, the Bureau prepared a manual containing noise-control guidelines for designers of new coal preparation plants. The two major subjects addressed in this manual were (1) new plant layout and design and (2) noise control of new plant equipment.

In the area of new plant layout and design, three basic approaches were suggested: (1) isolation of high-noise areas, (2) isolation of operator locations and walkways, and (3) choosing inherently quieter preparation processes. The most obvious example of the first approach is to design the plant such that the noisiest equipment is located far away from the highest concentration of plant workers. Limiting the number of openings (walkways, chutes, drains, etc.) between relatively noisy floors and quiet floors of the plant and sealing all nonessential openings between these floors are two other techniques that can be used to isolate high-noise areas. The second approach, isolation of operator locations and walkways, is similar to the first except that the worker rather than the equipment is the primary focus. A good example of worker isolation would be a completely enclosed gallery-type walkway to allow visual observation of process equipment (fig. 60). Remote control and computer monitoring of all plant processes is probably the most logical combined application of the first two approaches. The third approach, choosing inherently quieter processes, is limited to situations where two types of process machinery perform the same basic function (e.g., "louder" vacuum disc filters versus "quieter" bowl-type centrifuges for fines dewatering). Choosing one large, easy-to-isolate process machine over several smaller machines of the same type is a combination of the first and third approaches.

Noise control of new preparation plant equipment can often involve the use of the retrofit treatments installed in the Georgetown plant--resilient screen decks, impact pads, chute liners, and loaded-vinyl curtains. In many cases, however, these and other treatments are more cost-effective when incorporated into the equipment before it is installed in the plant. The manual described above contains detailed descriptions of 13 different types of coal preparation equipment, discusses the noise sources on each type, and suggests potential noise-control alternatives. Table 18 summarizes this information.

Taconite Processing Plants

The Bureau's noise-control efforts in metal processing plants were directed at taconite (iron ore) operations. Since taconite is harder than most other metallic ores, it generates more noise when crushed and requires more powerful and more durable processing and handling equipment. Noise-control treatments for taconite processing plants could be applied to other processing plants with similar equipment.

The approach for controlling noise in taconite processing plants was about the same as for coal processing plants--the most serious noise sources within a typical plant were identified, the noise-generating mechanisms of each source were analyzed, and potential noise-control treatments for each source were suggested. The most important noise sources identified by the Bureau were (1) secondary crushers, (2) grinding mills, and (3) fines-dewatering screens. Several treatments were subsequently installed and evaluated, and other practical noise-control treatments were identified.

TABLE 18. - Noise-control alternatives for new coal preparation equipment

Equipment type and typical noise sources	Alternatives
Electric motors: Cooling fan, electromagnetic forces, mechanical noise (bearing, bushings).	Use low-horsepower, low-speed motors whenever possible. "Motor mute" fan mufflers, unidirectional cooling fans. Sound-absorbing motor enclosures.
Air compressors: Compressed air exhaust, internal piston or screw impacts.	Sound absorbing enclosures (standard on newer models).
Enclosed gear drives: Gear meshing, cooling fan.	"Quieter" gear designs (helical type, tighter tolerances, low ratios). Cooling-fan noise controls; see "electric motors." Complete gearbox acoustical enclosures.
Vacuum pumps: Pulsating air expansion, external gear reducers.	Use liquid-ring pumps (instead of lobe-type displacement pumps). Wrap mufflers and silencers with pipe lagging. Low-speed impellers and gearbox noise controls.
Fans and blowers: Air pulsations, drive motors.	Use centrifugal (rather than positive-displacement) blowers. Intake and exhaust mufflers. Motor noise controls.
Centrifugal pumps: Water pulsations, particle impacts within pump, drive motors.	Use V-belt (rather than gear-drive) motors. Avoid concentrating pumps in one location. Motor and gear noise controls.
Vibrating screens: Product-to-screen impacts, material flow above screen, drive motors.	Resilient screen decks. Barrier-type enclosures around screen area (loaded-vinyl curtains). Motor and gear noise controls.
Chutes: Product-to-chute impacts, material flow within chute.	Reduce product impact velocity (by reducing drop height). Resilient chute liners (internal. External chute-damping treatments or barrier-type enclosures.
Centrifugal dryers: Material flow within centrifuge, motor and gear noise.	Acoustic seals for centrifuge shell. Exterior lagging or damping treatments. Motor and gear noise controls.
Crushers: Product-to-crusher impacts, material flow within crusher, motor and gear noise.	Locate crushers away from personnel. Barrier-type enclosures (loaded-vinyl curtains). Vibration-isolated crusher mounts.
Jigs and heavy-media vessels: Jig blowers and exhaust, jig elevator discharge, material and water flow within vessel.	Mufflers for jig blowers and exhaust. Chute noise control (e.g., impact pads).
Cyclones: Material and water flow within cyclone.	Cover (with inspection doors) over cyclone sump.
Feeders and conveyors: Material flow and discharge, motor and gear noise.	Cover open-topped feeders and conveyors. Chute noise controls (impact pads). Motor and gear noise controls.

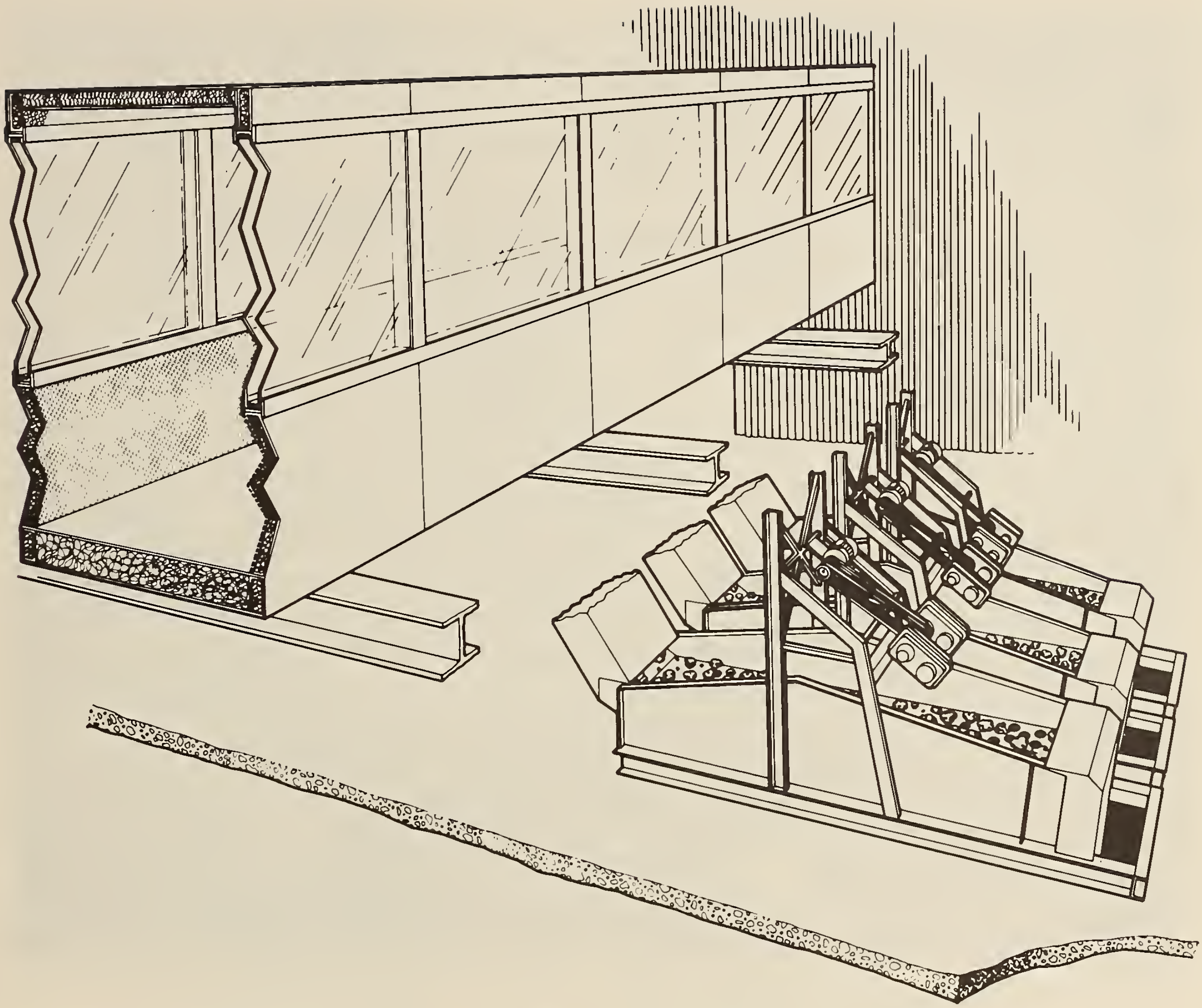


FIGURE 60. - Schematic of enclosed gallery-type walkway in preparation plant.

Secondary Crusher Enclosure (23)

Figure 61 shows that the secondary crusher occupied several vertical levels in the processing plant. For this reason, two separate enclosures were constructed--one for the lower (drive) level, and one for the upper (adjustment) level. The walls of both enclosures were made of sheet-metal panels lined with sound-absorbing material; the metal kept noise from radiating outward, and the sound-absorbing material prevented reverberant sound buildup within the enclosure. The drive-level enclosure had several doors and access panels to facilitate crusher maintenance. The panels of the adjustment-level enclosure were mounted on an overhead sliding track system because workers frequently needed access to the crusher at the adjustment level. Ceiling panels were also used on the adjustment-level enclosure.

Because of the close proximity of other noise sources in the crusher area (tertiary crushers, screens, crusher feed system, etc.), the total noise reduction provided by the secondary crusher enclosures was difficult to assess. However,

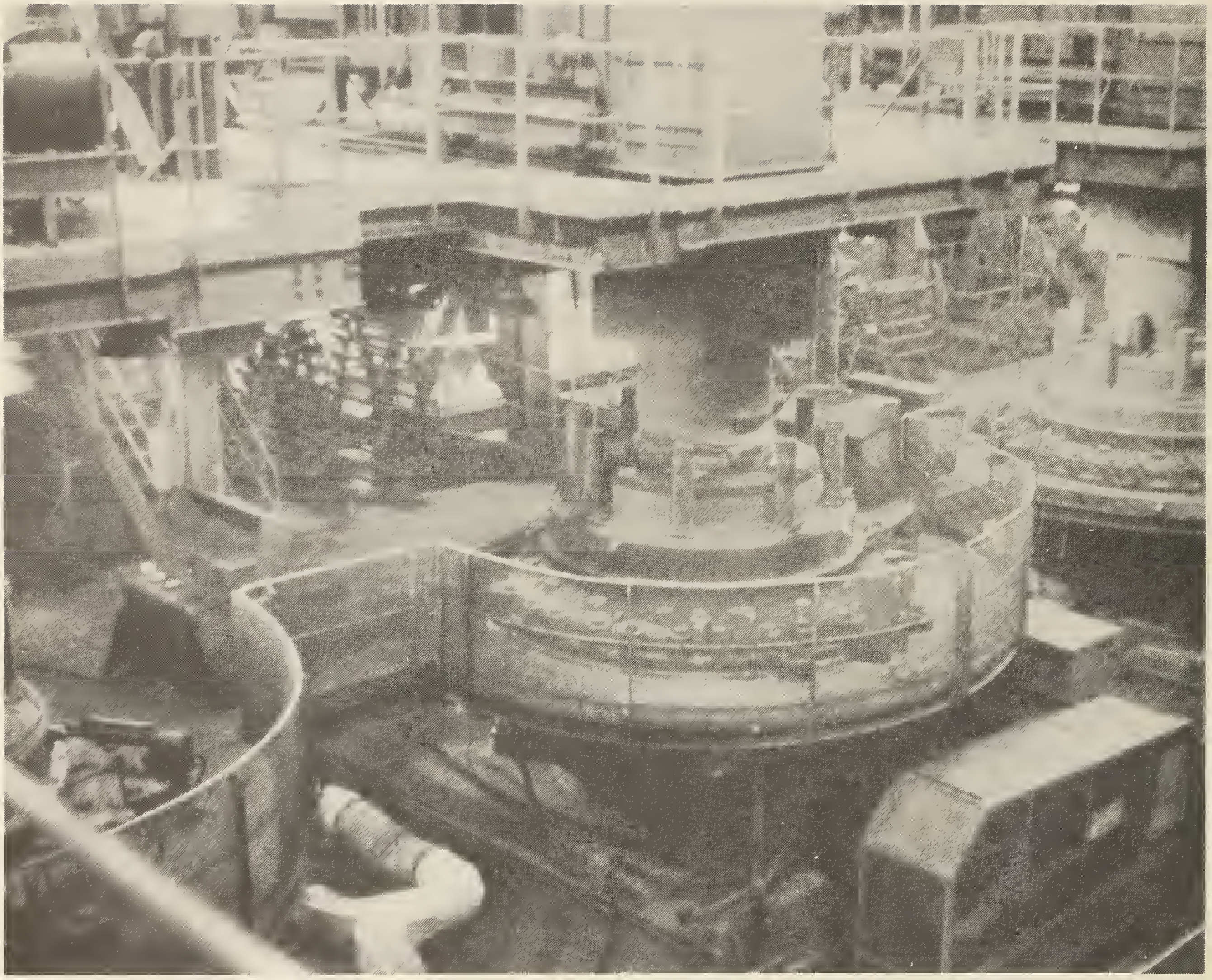


FIGURE 61. - Secondary crusher area in taconite processing plant.

noise levels measured at 1 ft outside the enclosures during normal operation were as much as 6 to 8.5 dBA lower than when the enclosures were absent. These reductions were recorded on the side of the enclosure opposite the side facing the "open," noisy area of the plant (i.e., the enclosures also served as a barrier against other noise sources). Noise reductions on the "open" sides of the enclosures were 1 to 3 dBA, despite the reflection of tertiary crusher and screen noise from the exterior enclosure walls. Even though the overall noise level at 1 ft outside the enclosure was still 97 to 101.5 dBA, the enclosures were very effective in reducing the noise contribution of the secondary crusher. Other noise sources would have to be treated to achieve further noise reduction in the secondary crusher area.

Noise levels within the adjustment-level enclosure were about the same as those measured before it was installed (85 dBA while the crusher was idling, 100 to 101 dBA while it was crushing ore). However, these levels would have been much higher if the interior enclosure walls had not contained sound-absorbing materials. The noise level within the enclosure would have been about 95 dBA if the secondary crusher were shut off completely (with other noise sources still operating), or about 5 dBA lower than the noise level with the enclosure absent.

The adjustment-level enclosure could thus protect workers from external noise during crusher maintenance operations.

Grinding Mill Treatments (10, 29)

Rod mills, ball mills, and autogenous mills are large rotating cylindrical structures (figure 9, part 2) used to grind taconite ore. As the mill rotates (fig. 62), the ore particles and/or the metal grinding media (balls or rods) rise along one side of the cylinder and fall back to the bottom of the other side. Impacts between the ore, grinding media, and cylinder linings cause the lower portion of the falling side of the mill to radiate about three times as much noise as the top and rising sides. For this reason, an 8-ft-high acoustical barrier (fig. 62) covering only the lower, falling side of a semiautogenous mill was designed, installed, and evaluated.

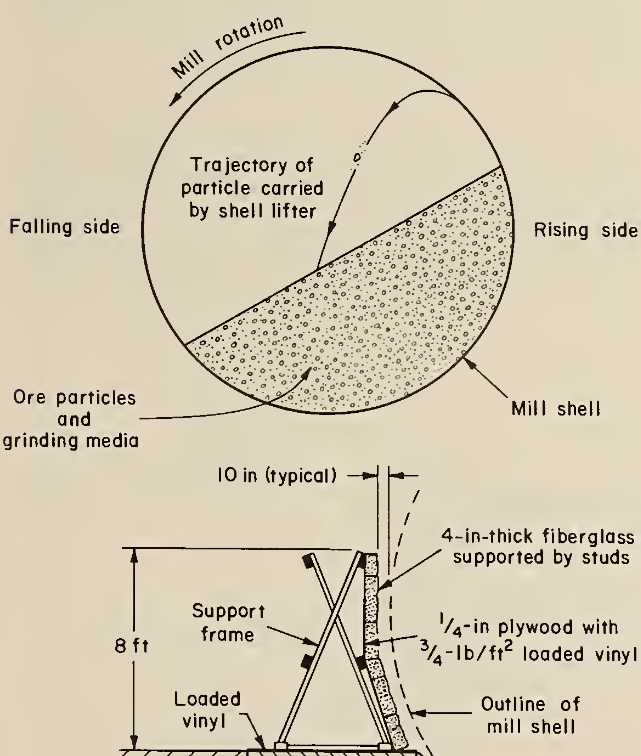


FIGURE 62. - Taconite grinding mill (top) and noise barrier (bottom) on falling side of mill.

At 15 ft away from the falling side of the mill, noise levels were about 6 dBA lower than before the barrier was installed; in the "shadow zone" close to the barrier, noise was reduced by about 10 dBA. Noise reductions behind the barrier at the feed end of the mill were only 2 to 6 dBA because of noise produced by the feed chute. After installation of the barrier, overall noise levels at most locations on the falling side of the mill were less than 95 dBA and were lower than noise levels on the rising side. However, since most of the noise on the rising side was actually "falling-side noise" reflected upward from the mill floor through the grating shown in figure 62, a loaded-vinyl mat covering the rising-side grating would have reduced this noise significantly.

Another practical grinding mill noise-control treatment, rubber shell liners, has been used successfully by several European and North American companies. Although the main reason for their use is for longer wear, reduced noise is an added benefit. Scandanavian processing plants have reported noise reductions of about 6 dBA due to rubber mill liners, and indirect measurements in North American plants indicated a 3- to 4-dBA reduction. Direct noise-reduction measurements could not be obtained in North American plants because (1) noise levels of standard metal-lined mills were not available for comparison and (2) other noise sources in the vicinity of rubber-lined mills were often dominant.

Rubber shell liners have been used only in autogenous and semiautogenous mills because metal grinding media would abrade the rubber too quickly. In addition, they have been effective only in "wet" mills, where harmful temperature increases (due to warming of the liners) can be avoided. However, a rubber layer constrained between the standard metal liner plates and the outer shell could significantly reduce the noise produced by ball and rod mills without the adverse effects of abrasion and temperature increases. Rubber washers for the liner mounting bolts on the exterior shell surface would provide additional vibration isolation. Although these two noise-control treatments have not yet been tested, they would be relatively easy to design and install and would not interfere greatly with mill maintenance.

Fines-Dewatering Screens

A typical fines-dewatering screen circuit consists of a parallel arrangement of boxes in which the concave screen surfaces are contained. To prevent blinding of the narrow (0.004-in) screen openings, a pneumatic rapping device strikes the screenbox at 2- to 10-s intervals. Most of the screening noise is generated by the rapping action and the flow of material across the screen. Substantial noise reductions of 11 to 13.5 dBA were achieved simply by installing sliding covers over the screen box, shrouding the rapper arm, and isolating the rapper head from its mounting bar at the back of the screenbox (fig. 63). Resilient screen decks such as those used in coal preparation plants would also help reduce noise produced by fines-dewatering screens.

Nonmetallic Processing Plants (30)

The nonmetallic mining industry is unique in that both stationary and portable processing plants are used. The stationary plants contain the same types of noise-producing equipment as coal and metal processing plants--crushers, screens, chutes, etc. Small portable processing plants are common in the sand, gravel, and crushed stone industries. These plants consist of a single component or unit operation, such as a crusher and screen, mounted on a chassis that can be moved around the mining site or towed on public highways. Typical operator noise levels in nonmetallic processing plants are 95 to 110 dBA, with exposure times as high as 6 to 7 h.

As with the other types of processing plants, a three-step approach to noise control was taken; it included (1) noise source survey and characterization, (2) design of retrofit treatments, and (3) field installation and evaluation of treatments. After a survey of eight typical plants showed that the crushing and screening process was the primary cause of overexposure, retrofit treatments were installed in three different plants. Table 19 describes these treatments and summarizes their effectiveness.

As shown in table 19, the treatments were very effective in two of the three processing plants. In the first plant (which utilized a primary jaw crusher), an independently mounted air-conditioned operator's booth replaced an ineffective

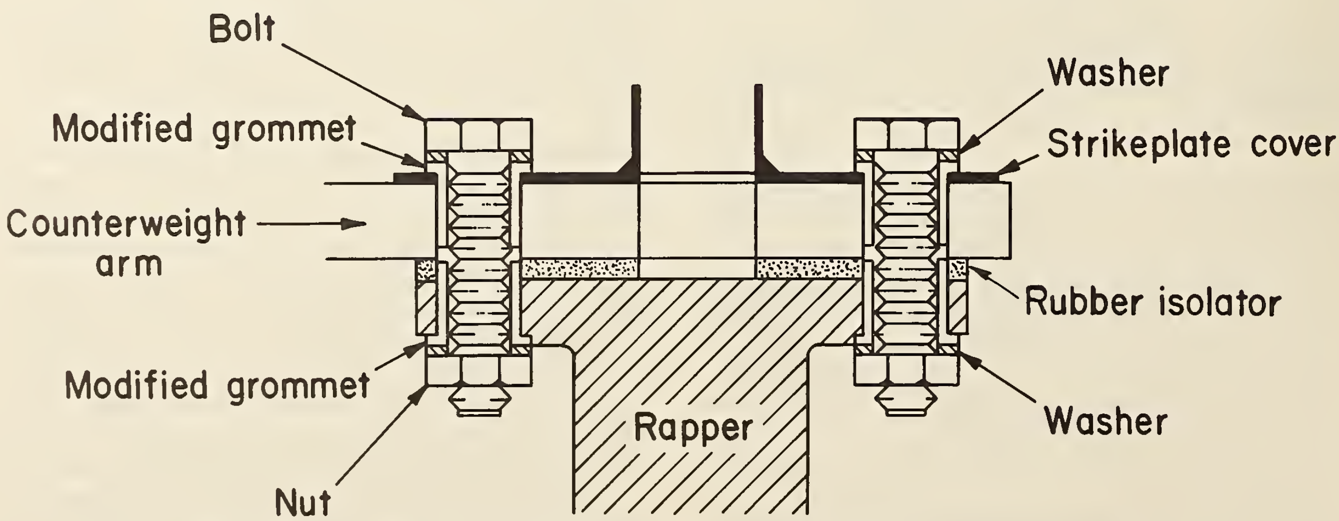


FIGURE 63. - Noise-control treatments for rapper on taconite fines screen.

TABLE 19. - Noise-control treatments installed in three nonmetallic processing plants

Treatment	Result	Cost	
		Materials, 1981 dollars	Labor, h
PRIMARY JAW CRUSHER			
Air-conditioned control booth on steel structure next to crusher, with door to catwalk to permit operator inspection of crusher.	80-dBA noise level in booth (compared to 97 dBA on catwalk).	5,000	40
INCLINED SCREEN AND SECONDARY CONE CRUSHER			
Resilient screen components (feedbox liner, top deck, wing liners, discharge lip), resilient crusher components (feed hopper liner, feed plate, feed cone liners), and flexible curtain around crusher.	3- and 7-dBA overall noise reduction. Treatments showed only minor wear problems over 7 months (198,000 tons of crushed stone, sand, and gravel).	14,000	66
HORIZONTAL SCREEN AND SECONDARY CONE CRUSHER			
Resilient screen (impact pads on feed chute, feedbox liner, top and bottom decks, wing liners, discharge lip) and resilient crusher feed hopper liner.	No significant noise reduction.[1]	17,000	69

[1]Treatment ineffectiveness was directly traceable to operator's change of equipment models after completion of original treatment designs.

crusher-mounted booth that was not air-conditioned. The only treatments showing significant wear in the second plant (inclined screen and secondary cone crusher) were the resilient crusher feed cone liners and feed plate; however, the latter failure was corrected when the original, undersized feed plate was replaced with a properly sized plate. Improperly sized components were also responsible for the ineffectiveness of the noise-control treatments at the third plant (horizontal screen and secondary cone crusher). Since the plant operator had changed both the models of the equipment used and the nature of the crusher feed after the original retrofit treatments were designed, extensive field modifications and remanufacturing were necessary. For example, the resilient impact pad on the screen feedbox failed before the discharge lip could be installed.

Despite the failure of the retrofit treatments at the third plant, the Bureau's program showed that retrofit noise-control treatments could be applied successfully to portable nonmetallic crushing and screening plants. Treatment costs were only 5 to 7 pct of the purchase price of a new plant (with a capacity of 200 to 300 tons/h); this is roughly equal to the annual repair and replacement costs of a reasonably well-maintained plant. Since crusher and screen performance was not adversely affected by the retrofit treatments, they appeared to be a cost-effective means of noise control.

Additional Research on Screen-Noise Abatement

Resilient, nonmetallic screen decks have been utilized extensively as a means to reduce noise generated by impacts of material (coal, rock, etc.) on the screen surface. Two other promising screen noise-abatement techniques are isolation of the screen drive mechanism and damping of the screen sidewalls. The Bureau and a major screen manufacturer conducted a joint research effort to determine the effects of these three treatments on screen performance, durability, and noise reduction (20). This effort involved the testing of six different commercially available nonmetallic screen decks using three different products--coal, granite and dolomite. The results of this research corroborated the results of previous studies. It was found that (1) coal screening is a quieter process than granite or dolomite screening because coal is a softer material; (2) vibration isolation and sidewall damping are durable, cost-effective methods of controlling the portion of screening noise that is unrelated to material impacts; and (3) resilient screen decks can be about 2 to 7 dBA quieter (and more durable) than all-steel decks, but can cause up to a 10-pct reduction in screening efficiency (i.e., 10 pct more blinding).

In order to investigate the blinding problem more closely, a digital computer model was developed to evaluate screening efficiency under a wide variety of operating conditions (21). A unique feature of this model was its use of explicit fundamental relationships rather than empirical quantities (percent oversize and undersize) to predict screening efficiency. The phenomena that affect the approach of a single particle toward the screen deck (particle size, hole size, bed depth, etc.) were investigated in order to derive a mathematical expression for the probability that it would pass through. "Probability-of-passage" equations simulated the percentage of material passing through the screen on a given approach, and the number of approaches on a given screen was used to determine screening efficiency. Figure 64 is the generalized flow chart of the screening-simulation algorithm.

Input to the computer program consisted of detailed information on the screen and the material being processed. Output consisted of the predicted screening efficiency and the size distribution of the overproduct and underproduct. Laboratory tests with actual screens verified that

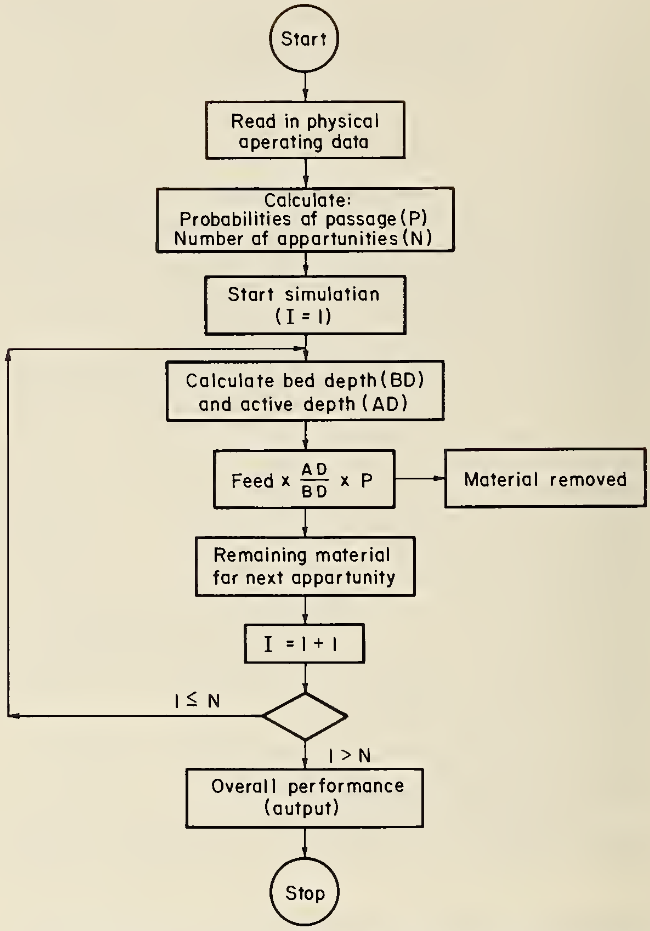


FIGURE 64. - Flow chart of screening simulation algorithm.

the computer-predicted values were accurate to within ±3 pct, although discrepancies were greater for screens with nonstandard shaking strokes and frequencies. To allow interested parties to make quick estimates of screening efficiency without running the entire program, a handbook consisting of the basic program elements was developed. Users of this handbook can make quick comparisons between the efficiencies attainable with standard versus nonmetallic screen decks for the same type of material.

USE OF HEARING PROTECTORS IN THE MINING ENVIRONMENT

As explained in part 1, the Bureau views hearing protectors (earplugs, earmuffs, etc.) as only a partial, temporary solution to mining noise problems.

Historically, it has been more effective to control industrial health problems at their sources than to require workers to use personal protective devices. For example, early attempts to reduce coal miners' exposure to dust through the use of respirators did not prevent coal workers' pneumoconiosis. Although large dust particles were trapped by the respirator, respirable dust particles (those smaller than 5 μm) passed through and around the respirator and were inhaled by workers. The same is true of hearing protective devices; unless they achieve a perfect seal around the ear (earmuffs) or ear canal (earplugs), noise will pass through the openings and render them ineffective.

However, Federal regulations do provide for the use of hearing protectors by requiring mine operators to make them available to miners in situations where engineering or administrative noise controls are not available, have not yet been developed, or fail to reduce noise to within levels of compliance. Therefore, the Bureau has conducted research to investigate the noise-reducing characteristics of personal hearing protectors and assess their potential usefulness in the mining environment.

Limitations of Hearing Protector Effectiveness

No hearing protective device can eliminate all sound transmission to the ear. Figure 65 shows the four most common noise pathways: (1) air leaks around the protector, (2) transmission of external sound through the protector material, (3) vibration of the protector in response to external noise, and (4) bone and tissue conduction--sound transmitted directly through the skull. Even if a "perfect" hearing protector could be developed to eliminate the first three pathways, bone and tissue conduction would still be present. Although the amount of bone and tissue conduction varies among individuals and different sound frequencies, the maximum noise reduction attainable with a "perfect" hearing protector would be about 50 dB (18). Even under well-controlled laboratory conditions, the maximum noise reduction achieved through the use of presently available hearing protectors has been about 35 dB. Furthermore, these maximum reductions would occur only in the frequency range of 2,000 to 4,000 Hz. In real-world situations (with non-perfect protector fit, etc.), actual

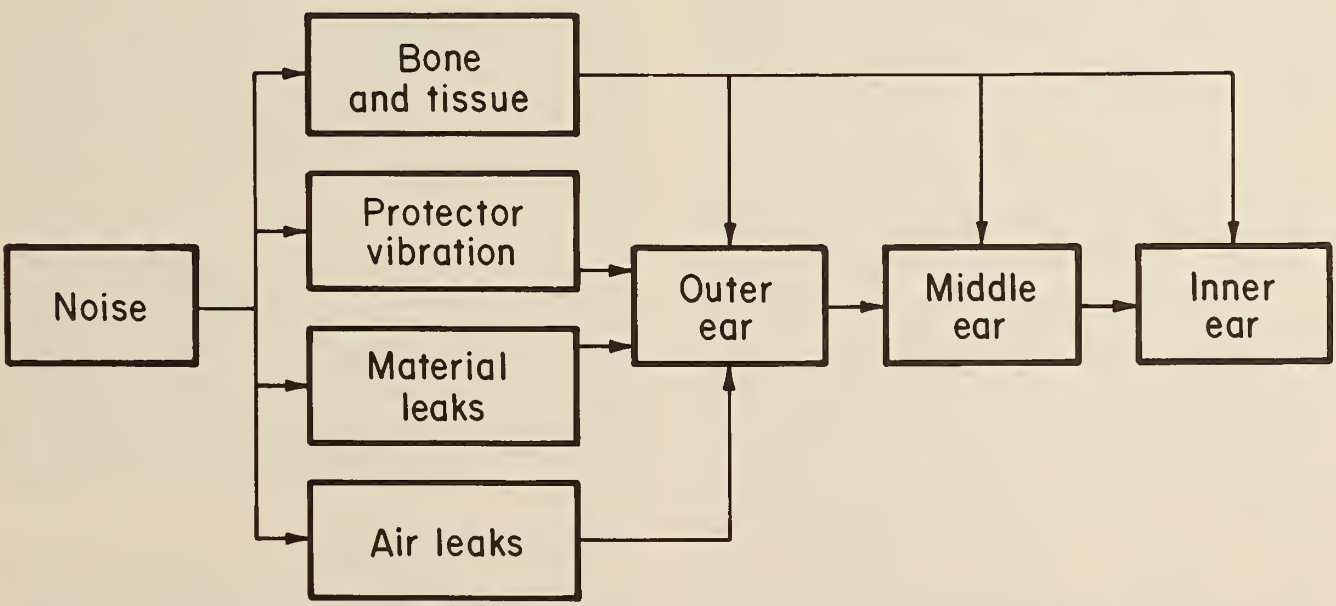


FIGURE 65. - Noise pathways to ear protected by hearing protective device.

noise reductions were found to be 20 dB or less (4), again depending on the frequency examined.

Assessing Earmuff Attenuation

Two basic techniques have been widely accepted for measuring the noise-reducing properties of hearing protective devices. The "real-ear" method (American National Standards Institute (ANSI) standard S3.19-1974) measures the hearing threshold of a human subject both with and without hearing protection. The difference in the hearing threshold of the protected and unprotected subject indicates the effectiveness of the hearing protector. Although the real-ear and other "psychophysical" methods of this type are used most often, several nonsubjective, "physical" methods are also used. Physical methods often involve two microphones, one outside the hearing protector and one between the protector and the subject's eardrum.[12] The difference in sound level at the two microphone locations is then measured. In both the psychophysical and physical approaches, the noise-reducing properties of the hearing protectors are measured over the entire audible frequency range. After applying corrections for A-weighting and the frequency spectrum of the incident noise, a noise-reduction rating (NRR) is assigned to the hearing protective device.

The psychophysical (real-ear) method is undoubtedly more accurate than the physical (microphone) method of measuring hearing protector effectiveness. However, the psychophysical method requires the use of a laboratory and is very time consuming, so the physical method is preferable for field evaluation of hearing protectors. In order to determine the exact differences between the two methods, the Bureau conducted a series of controlled laboratory experiments on earmuffs commonly worn by miners (36). First, real-ear attenuations were measured for 5 different types of miners' earmuffs, worn by 12 different subjects with normal hearing "Unprotected" measurements (without muffs) were also recorded. Microphones were then placed inside and outside the muffs, and the same 12 subjects were tested.

At sound frequencies below 2,000 Hz, the measured earmuff attenuations were approximately the same in both the physical (microphones) and psychophysical (real-ear) tests. Above 2,000 Hz, however, greater attenuations were measured in the psychophysical tests than in the physical tests (3- to 7-dB difference). These results were consistent among all 12 subjects and for all 5 types of earmuffs. The differences probably resulted from the inherent differences in the two test procedures. In the "unprotected" portion of the psychophysical tests, the high-frequency external sounds caused a standing-wave resonance phenomenon to occur within the subjects' ear canals, thus increasing the per-ceived sound levels.[13] In the "protected" portion of the psychophysical tests, both the exterior noise and the standing-wave phenomenon in the ear canal were drastically reduced. In contrast, the standing-wave phenomenon did not occur in the "unprotected" portion of the physical test because the unprotected microphone was completely outside the muff. The attenuation measured at the protected microphone, therefore, included only the reduction of exterior noise.

The existence of the standing-wave resonance phenomenon in the ear canal points out an important limitation of the physical method of measuring earmuff effectiveness; in fact, this limitation is common to almost all conventional methods of sound measurement: Since the protected microphones could not be placed

[12]ANSI standard S3.19-1974 specifies a test procedure in which a dummy head with a simulated human skin is the "subject."

[13]The standing-wave resonance phenomenon was prominent only at high frequencies because these sounds had wavelengths that were similar to the lengths of the subjects' ear canals.

inside the subjects' ear canals, they did not record the sound produced by the standing waves. Therefore, the two-microphone earmuff system actually underestimated the earmuffs' ability to attenuate high-frequency noise.

In order to compensate for the differences between the psychophysical and physical methods of measuring earmuff attenuation, the Bureau designed a correction filter for the protected microphone and used a microphone with linear response outside the muff. When tested in the laboratory, this system produced results that were similar to the results of the psychophysical tests (37). However, the system would not reliably measure actual earmuff attenuation in the field because the protected microphone and its cable would undoubtedly move around and contact the subject's body, thereby producing a misleadingly high sound level under the muff. Exterior sound levels would have to be at least 100 dB at all audible frequencies to override this under-the-muff noise. In most field situations, exterior sound levels would not exceed 100 dB at higher frequencies; therefore, applications of the "corrected" physical technique would be extremely limited.

The Bureau is still engaged in research to devise a reliable physical method for measuring the effectiveness of miners' hearing protectors as worn in the field. Even if the two-microphone muff system described above could be perfected, the same technique would be extremely difficult to apply to earplugs. The Bureau plans to attempt to improve the earmuff system and devise a physical measuring system applicable to earplugs and other types of hearing protectors. Until such systems are developed, the true benefits of hearing protectors in the mining environment cannot be determined.

Hearing Protector Interference With Required Acoustical Cues

One of the miners' greatest concerns about hearing protectors is the potential elimination of sounds they need to hear, such as verbal communications and "roof talk"--the noise preceding an impending roof fall. For this reason, the Bureau conducted research to determine the amount of interference caused by hearing protectors. One study (35) showed that when the ambient noise level in the mine was less than 90 dBA, hearing protectors did indeed inhibit the miners' ability to discriminate speech and roof talk from other noises. However, when the ambient noise level in the mine was greater than 90 dBA, discrimination of speech and roof talk was the same or slightly better when hearing protectors were used. The basic conclusion of this study was that hearing protectors would benefit miners only when overall noise levels exceed 90 dBA.

In an effort to provide a hearing protector that would work only when noise exceeded 90 dBA, the Bureau developed a "discriminating earmuff" (12). An electrical system incorporated into the muff allowed all sounds lower than 83 dBA to pass unattenuated to the ear. Sounds louder than 83 dBA were progressively attenuated up to a maximum attenuation of 30 dBA (90 dBA under the muff at 120 dBA exterior noise). In underground tests, subjects wearing the discriminating earmuff were able to hear low-level sounds such as speech and roof talk more easily than subjects wearing standard muffs. The discriminating muffs and standard muffs provided equal attenuation in high-noise environments. The only disadvantage of the discriminating muffs was that their electronics made them rather expensive and too fragile for in-mine use.

PART 4.--FUTURE BUREAU NOISE-CONTROL EFFORTS

Parts 2 and 3 documented the most significant and beneficial results of past Bureau noise-control research programs and illustrated their broad scope. Most of these programs were directed toward solving the immediate noise problems of the mining industry and involved field demonstrations of retrofit techniques whenever possible. When redesign of equipment appeared to be a more viable long-term solution, the end product sought by the Bureau was usually a field demonstration of a prototype "quiet" machine or process.

Recently, however, the scope and nature of Bureau research in all areas, including noise control, has changed dramatically. Demonstration projects such as those described in part 3 have been deemphasized in favor of long-term in-house programs in basic noise studies and applied noise-control research. The reasons for this change in emphasis were both philosophical and monetary. Limited resources have made it necessary for the Bureau to adopt the point of view that since a successful field demonstration of an inherently quieter piece of equipment requires substantial assistance from its manufacturer and user, these parties, rather than the Government, should take the leading role. Furthermore, inherent design differences between different models of the same type of mining equipment make it nearly impossible for the Bureau to design a "generic" noise-control treatment suitable for any single equipment type. Although past Bureau noise-control projects have successfully addressed specific models, the cost of developing numerous model-specific treatments is prohibitive. Unfortunately, this is exactly the type of effort needed to achieve widespread, immediate solutions to the many noise problems in mining, but neither the Bureau nor private industry can afford this effort at the present time. Therefore, the Bureau is now pursuing long-term strategies that will use its limited resources more effectively.

Until recently, the desire to achieve immediate noise reductions in many mining areas forced the Bureau to rely heavily on contracting firms, mostly noise specialists and equipment manufacturers. This approach helped introduce noise-control technology to the mining industry but did not allow Bureau personnel to pursue basic, long-term goals in noise control. However, the Bureau has now begun to concentrate on acquiring the capability to perform most of its noise-control research in-house. Research efforts will consist of long-term studies of mining noise problems that cannot be solved by the industry itself and will focus only on those problems that require in-depth scientific study.

FACILITIES AND EQUIPMENT

High-quality facilities and equipment are essential in any noise-research program, and the Bureau is now establishing these at its Pittsburgh Research Center. The centerpiece of the in-house facility is a large reverberation building[14] capable of housing a piece of mining equipment as large as a continuous miner, jumbo drill rig, or bulldozer. The physical dimensions and interior surfaces of this building were designed specifically to allow precise measurements of the sound power levels of noise sources located within. A small anechoic chamber, a room whose walls, floors, and ceiling reflect almost no noise, has been built outside the larger reverberation room for experiments with personal hearing protectors. All laboratory instrumentation needed to conduct detailed acoustical experiments in these rooms (sound level meters, tape recorders, microphones, accelerometers, frequency analyzers, etc.) have been obtained.

In order to allow mining machines to operate "normally" (i.e., with all noise-generating mechanisms present) within the reverberation building, it will contain several different cutting media. Noise produced by coal-cutting machines will be investigated by cutting into a synthetic coal seam similar to the one shown in figure 13 (part 3). Noise produced by rock drills will be investigated by drilling into replaceable blocks of extra-hard concrete. Specific tests to be conducted in the reverberation building are summarized below.

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[14]Scheduled for completion by the end of 1984.

RESEARCH PROGRAMS

Because of the relatively recent change in emphasis from contract to in-house research, the programs described below are still in their early stages. The four major areas of emphasis--coal cutting, conveying, percussion drilling, and hearing protectors--were chosen because contract research efforts have shown that long-term studies are still needed in these areas.

Coal Cutting

Although machine components for quieter coal cutting and conveying were designed and developed under Bureau contracts (part 3), only the sand-filled auger-miner cutting head received extensive testing under operating conditions in underground coal mines. Quieter cutting heads for drum-type continuous miners and longwall shearers are now being tested underground under two remaining Bureau contracts. Future work in this area will include basic studies into the effects of bit lacing and geometry on noise and the investigation of alternative, quieter cutting technologies (e.g., water jetting).

Conveying

The "quiet" chain conveyor components that performed well in aboveground tests could not be tested extensively underground due to problems in locating cooperating mines, manufacturers' reluctance to incorporate the unproven components in their product lines, and the short-term nature of the contract under which the components were developed. The long-term durability and acoustical performance of these "quiet" components are now being tested in a closed-loop conveying setup. In the future, the Bureau plans to conduct detailed, quantitative studies of the impacts that generate conveyor noise. It is believed that a better understanding of these phenomena is needed to achieve further conveyor noise reduction.

Percussion Drilling

Future Bureau work on percussion drill noise will consist of basic studies to gain a better understanding of the percussion drilling process and its relationship to noise. Work is planned in the following areas:

Drill Sound-Power Studies

Sound-power measurements of drills and their noise-producing components should provide a simple, accurate indication of how drill operating parameters (hammer pressure, feed thrust, etc.) influence the overall noise level. Relationships between sound power and drill size, power source (pneumatic versus hydraulic), and internal design (valveless versus valved, etc.) will be explored. Noise diagnostic work is expected to be made much easier through these studies.

Drill Energetics

Laboratory experiments will be conducted to determine the relationships between noise and blow energy, blow frequency, off-centered impacts, bit sharpness, etc.

Drill-Body Noise

Preliminary studies of hydraulic drills indicate that drill-body noise is equal to or greater than drill-steel noise. The effects of drill-body design and materials on drill-body noise levels will be investigated.

Small-Diameter In-the-Hole Drill

Placing the percussive tool inside the drill hose will obviously reduce the amount of noise reaching the operator. Work is now underway to explore the feasibility of extending down-the-hole drilling technology to smaller size tools (2 in diam or less).

Alternative Drilling Technologies

At some point in the future, the Bureau plans to investigate new drilling technologies that would perform the same function as percussion drills (i.e., drilling small holes in hard rock) in an inherently quieter manner. Candidate technologies include rotary drilling and water jets.

Perhaps the most promising drill-steel noise-control concept now being investigated by the Bureau is the "concentric drill steel." The two-piece concentric steel consists of (1) an inner pulse-transmission rod to deliver the blow to the bit and (2) an outer torque tube to rotate the bit and attenuate the noise produced by the inner pulse-transmission rod. The outer tube is acoustically isolated from the inner rod by elastomer inserts, and hole-flushing water passes through an annulus between the two sections. Although the prototype concentric steel is being developed under contract (39), much of the testing and evaluation will be done in-house, using the pneumatic and hydraulic jumbo drills.

Hearing Protectors

The goal of the Bureau's hearing protector research program is to develop a reliable, reproducible method of evaluating the effectiveness of hearing protectors worn by miners in the field. The previous Bureau efforts discussed in part 3 showed that much work remains to be done in this area. Future Bureau research will attempt to define (1) the theoretical minimum noise level attainable through the use of hearing protectors, (2) the ability of hearing protectors to attenuate impact noise, and (3) the exact effects of "noise leaks" (air gaps, etc.) on hearing protector effectiveness. Plans are for MSHA to cooperate closely with the Bureau, and the in-house anechoic chamber will be a valuable tool in these investigations.

TECHNOLOGY TRANSFER

Technology transfer is one Bureau activity that will continue during the shift from short-term contracts to long-term in-house research. The only anticipated difference between past and future practices is that contract final reports will be replaced by in-house Reports of Investigations (RI's) and Information Circulars (IC's) as the primary technology-transfer vehicles. As before, Bureau personnel will continually review new noise-control developments in mining and other industries and apply them to in-house programs.

In addition, information concerning the mining equipment noise-control technology described in part 3 will be supplied to the industry in a more usable form. Although the contract final reports covering the projects described in part 3 contain substantial amounts of information, most are much too detailed for potential users of the technology. Therefore, the Bureau has published a handbook (2) covering all its mining machinery noise-control programs in a clear and concise format. Figures 66 and 67 have been taken from this handbook; they summarize the current noise-control technology for underground mining equipment (fig. 66) and preparation and processing plants (fig. 67). Some of the "quieted" noise levels of the machines in these figures resulted from Bureau efforts, some resulted from manufacturers' efforts, and others represent the noise levels that could be achieved if currently available noise-control techniques were applied to previously untreated machines. The Bureau's handbook also contains extensive, easy-to-use listings that tell how the noise-control treatments are applied, how noise-control materials can be obtained, and where to go for further information.

SUMMARY

Hearing loss due to noise in the mining environment is a very serious occupational health hazard. The Bureau of Mines has addressed this problem by

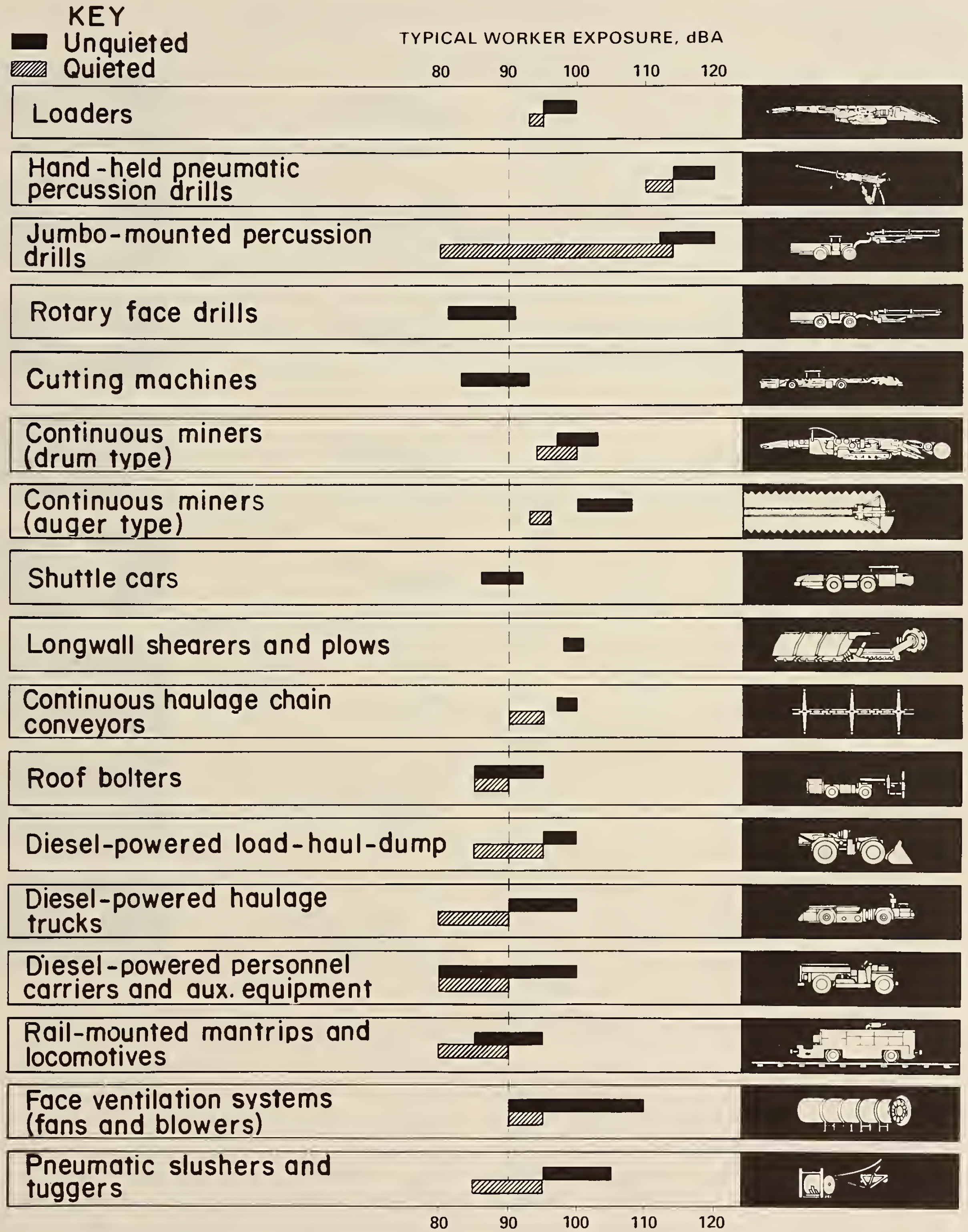

FIGURE 66. - Quieted versus unquieted noise levels of underground mining equipment.

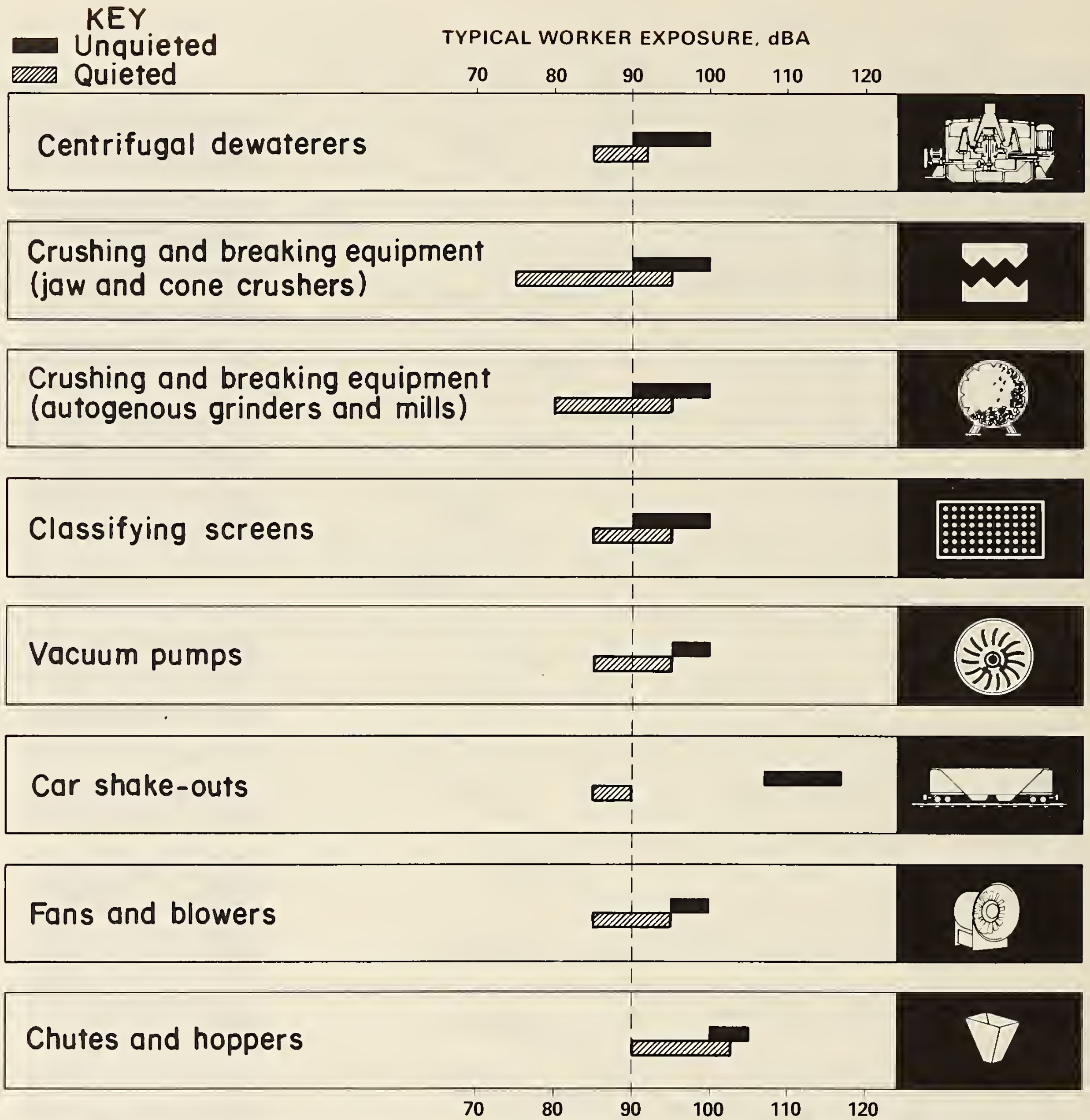

FIGURE 67. - Quieted versus unquieted noise levels of preparation and processing plant equipment.

conducting a wide variety of noise-control research programs. During the past 10 yr, these programs have involved all four major segments of the mining industry--underground coal mining, hard-rock mining, surface mining, and coal and mineral processing.

Mining machinery is primarily responsible for the high noise levels in the mining workplace. For this reason, and beause the workplace cannot be easily treated to reduce noise levels, Bureau research has focused on noise-control treatments for the machines used in mines. Retrofit techniques for existing equipment have been pursued whenever possible; however, in many cases equipment redesign has been found to be a more effective approach.

Retrofit treatments have been developed for (1) the cutting heads of auger-type continuous miners, (2) chain conveyors,

(3) handheld and jumbo-mounted pneumatic percussion drills, (4) diesel-powered LHD vehicles, (5) bulldozers and front-end loaders, and (6) coal and taconite processing plants. Redesign efforts have been directed toward (1) pneumatic percussion drills, (2) LHD vehicles, and (3) preparation plants. Basic studies of coal-cutting dynamics have provided valuable information that is now being used to design reduced-noise cutting heads for drum-type continuous miners and longwall shearers. Studies of the effectiveness of hearing protectors in the mining environment are underway.

The Bureau's emphasis in the past 2 yr has shifted from field demonstrations and contract research to long-term basic in-house research. A reverberation building has been constructed to provide Bureau personnel with a well-controlled acoustical environment in which detailed studies of the noise-generating mechanisms of mining equipment can be conducted. This approach is expected to be more cost-effective than field demonstrations and should yield results that can be implemented in the future by equipment manufacturers and users to create a quieter mining environment.

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