In-cab noise reduction on an air-rotary drill rig

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The National Institute for Occupational Safety and Health (NIOSH) has investigated engineering noise controls to reduce sound levels in cabs on air-rotary drill rigs. A recent investigation revealed that some drillers are exposed to A-weighted sound levels exceeding 85 dB even though a cab is used. NIOSH studied the in-cab sound levels of one such rig. First, preliminary tests were conducted in a controlled environment using accelerometers and microphones with spectral analysis to identify the dominant noise sources for in-cab sound levels. The results indicate that vibration transmitted from multiple hydraulic pumps to the control panel produces a dominant spike in the sound level spectrum in the 400 Hz 1/3-octave band. Next, field tests were performed in a production environment to evaluate noise controls to reduce in-cab sound levels. It was found that utilizing hydraulic noise suppressors reduces the structure-borne noise transmitted to the control panel. Further, using hydraulic noise suppressors and enhancing soundproofing reduced the in-cab A-weighted sound levels by as much as 4 dB.

1 INTRODUCTION

Exposure to excessive noise over time can cause permanent hearing loss. In 1996, NIOSH published the National Occupational Research Agenda, which identified hearing loss as the most common job-related disease in the United States.[1] The 1998 NIOSH publication, "Occupational Noise Exposure, Revised Criteria" recommends limiting exposure to A-weighted sound levels no greater than 85 dB for 8 hours.[2] However, federal and most state regulatory guidelines are written such that workers should not be exposed to A-weighted, time-averaged sound levels above 90 dB for 8 hours. In either case, risk assessment research confirms that exposure to sound levels in excess of 90 dB for 8 hours a day increases the risk of noise-induced hearing loss (NIHL). NIHL is painless, occurs over long periods of time, and cannot be corrected medically.

NIOSH investigations of the sound levels near drill rigs during production drilling identified air-rotary rigs as some of the loudest drill rigs used today.[3] These are high-production drilling machines that utilize compressed air to hammer-drill and to remove cuttings from the hole. Many air-rotary rigs are outfitted with a diesel engine, an air compressor, a large cooling fan, and numerous hydraulic pumps. Interest in the sound levels in the cab on air-rotary rigs resulted from previous NIOSH investigations of drill rig noise, which showed the in-cab A-weighted sound levels exceed 85 dB, and the growing concern about noise-induced hearing loss within the mining industry.

It has long been recognized that hydraulic systems or components on equipment are potential sources of noise or vibration.[4,5] One type of engineering control used with much success to reduce hydraulic noise and vibration is a hydraulic noise suppressor. Studies by Beck and Martin[6] and Wilkes and McLean[7] show that hydraulic systems are significant contributors to equipment noise and vibration. Noise and vibration generated by hydraulic systems has prompted the development of hydraulic mufflers and noise suppressors. The implementation of these devices has produced favorable noise reductions in many working environments that have hydraulic systems. Based on these successful results, NIOSH has investigated the application of hydraulic noise suppressors on air-rotary drill rigs to reduce the in-cab sound levels. This report describes the findings on the installation of hydraulic noise suppressors on one air-rotary drill rig.

2 TESTING AND PROCEDURES

The test rig (see Fig. 1) is a track-mounted rig having a mass of 19,389 kg, a 347-kilowatt diesel engine, and an air compressor which delivers

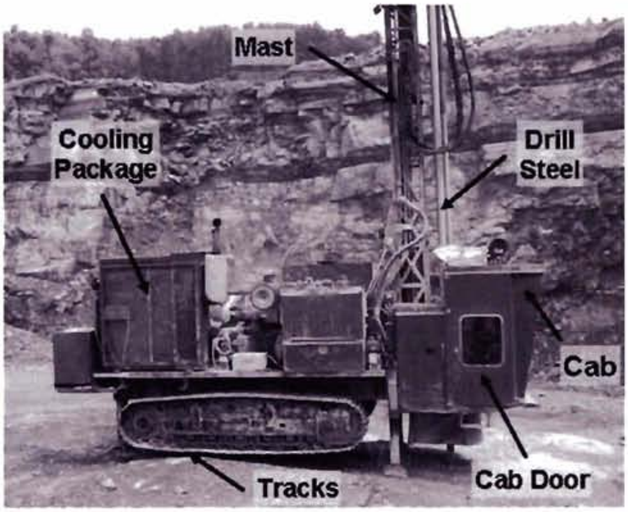

Fig. 1—Track-mounted, air-rotary drill rig.

$0.425\ m^3/s$ of air at a pressure of 2.4 MPa. In addition, the test rig has a 1.6-meter-diameter cooling fan, a dust collector, and a vibration-isolated cab. Several hydraulic pumps driven by the diesel engine are used to operate the drill rig. The hydraulic pumps are controlled by mechanical valves mounted directly to the control panel which forms the front of the cab. The cab has two sliding doors: an inner door near the drill steel and an outer door on the opposite side of the cab.

Pilot tests involved measuring the in-cab sound pressure level along with the sound levels near exterior noise sources. The in-cab sound level at the operator's ears was dominated by the sound energy in the 400 Hz 1/3-octave band as shown in Fig. 2. The narrowband spectrum of the in-cab microphone signal revealed a prominent spike at approximately 381 Hz. This 381 Hz spike was not observed in the sound spectra of the external microphones.

It was suspected that the 381 Hz spike was due to transmission of vibration into the cab. Vibration could be felt on both the hydraulic lines and the control panel. These observations led to the hypothesis that the high sound level in the 400 Hz 1/3-octave band was due to transmission of hydraulic noise into the cab via the hydraulic lines with subsequent radiation of noise by the control panel. Two batteries of tests, referred to as the Preliminary and Field Tests, were conducted to investigate the hydraulic noise.

2.1 Preliminary Tests

The preliminary testing, which was performed on a sealed asphalt test pad with the drill rig at high idle, consisted of five tests designed to determine if the dominant source of in-cab noise was hydraulic-related. Table 1 shows the test descriptions for the five preliminary tests. The main objective of these tests was to determine with certainty that the tandem gear pump was the source of the 381 Hz spike in the sound level spectrum.

The drill rig was placed on the test pad and allowed to warm up to stabilize fluid temperatures. Two accelerometers were mounted on the control panel inside the

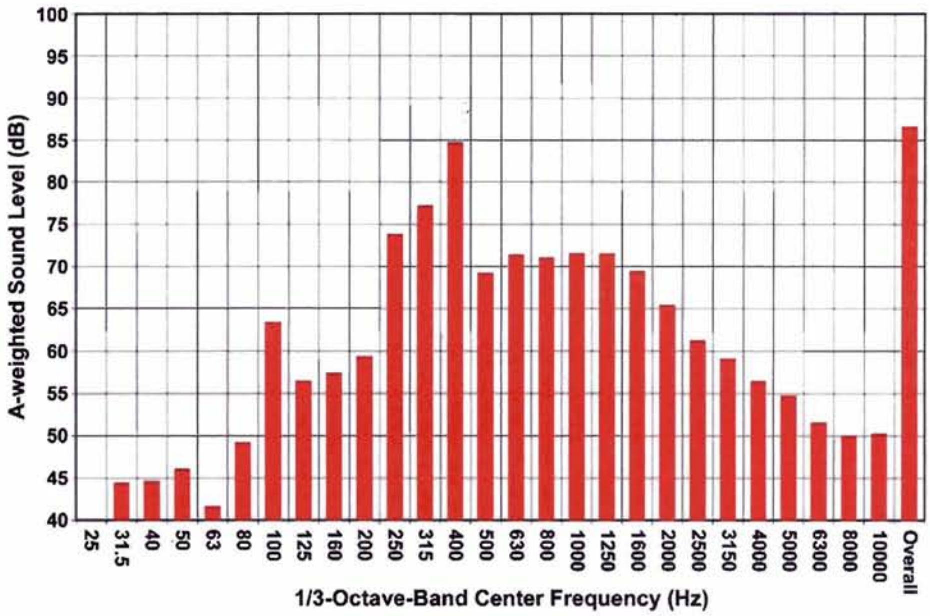

Fig. 2—Average A-weighted 1/3-octave-band sound level spectrum at operator's left and right ears for baseline test with drill rig at high idle.

Table 1—Preliminary tests on the drill rig.

Test Number	Test Description
1	Baseline test.
2	Hydraulic line from tandem gear pump suspected as source of tonal noise disconnected from control panel.
3	Thermal valve by-passed.
4	Two 0.3-meter-long steel hydraulic lines added in series with existing lines to tandem pump.
5	Two 0.3-meter-long steel hydraulic lines added in series with existing lines to tandem pump plus 0.1-meter-thick layer of sound-absorbing foam added to roof of cab.

cab. One accelerometer was positioned near the middle of the control panel while the other was placed near the bottom of the control panel below several hydraulic control levers. Two microphones were secured to a hard hat so that the microphones would be approximately 0.1 meters from the side of the operator's ears. The signals from the transducers were recorded with a portable data acquisition system. The data were post-processed to calculate the A-weighted 1/3-octave band sound level spectra and un-weighted 1/3-octave band acceleration spectra with filters meeting IEC-225-19668[8] and ANSI S1.11-19869.[9] The average 1/3-octave band sound level spectrum was then calculated using the spectra from the left-ear and right-ear microphones.

For the baseline test, the overall average A-weighted sound level was found to be 87 dB with an 85 dB spike in the 400 Hz 1/3-octave band as shown in Fig. 2. A corresponding spike with an acceleration level of 1 dB was observed in the spectrum of the lower accelerometer signal as shown in Figure 3. This indicates that the spike in the 400 Hz 1/3-octave band sound level spectrum is probably vibration-related.

The narrowband spectra of the time signals from the baseline tests were then computed using a Hanning window with overlap processing (75% overlap) and a spectral resolution of 1.5625 Hz. The resulting average narrowband sound level spectrum from 0 to 1000 Hz is shown in Fig. 4. A dominant spike with a sound level of 82 dB is present at approximately 381 Hz. This spike corresponds to the fundamental frequency for the hydraulic noise produced by the tandem gear pump, which has 10 teeth per gear and a rotational speed of 2286 RPM with the drill rig at full idle.

The vibration measurements showed that the lower accelerometer had higher accelerations than the upper accelerometer, particularly near 381 Hz. Therefore, the lower accelerometer signal was used with the in-cab microphones for vibration-noise coherence analysis. The coherence between the left and right microphone signals and the accelerometer signals was calculated by

$$\gamma_{xy} = \left[\frac{|G_{xy}|^2}{G_{xx}G_{yy}} \right] \qquad (1)$$

where γ_{xy} is the coherence, G_{xy} is the cross-spectrum between the microphone and accelerometer signals,

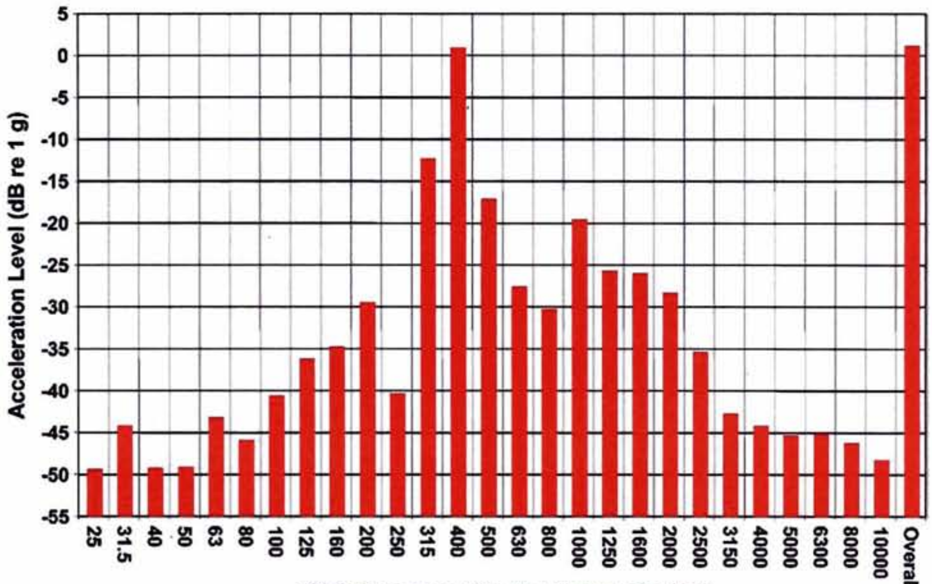

Fig. 3—One-third-octave-band acceleration level spectrum for lower accelerometer for baseline test with drill rig at high idle.

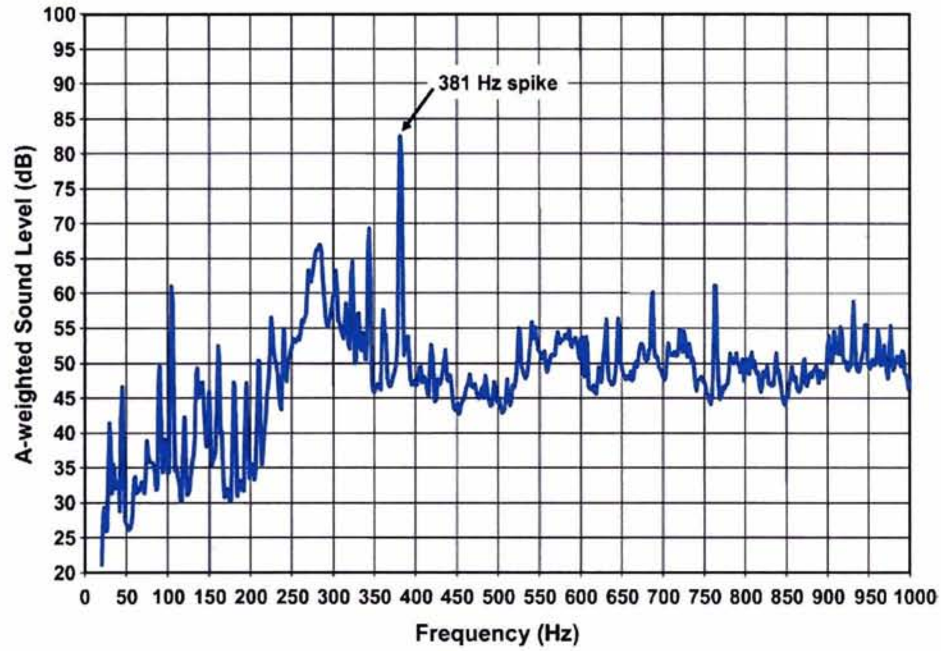

Fig. 4—Baseline in-cab narrowband average sound level.

G_{xx} is the auto-spectrum of the accelerometer signal, and G_{yy} is the auto-spectrum of the left or right microphone signal.[10] The coherence function has a value bounded by 0 and 1. Coherence values approaching unity indicate a strong relationship between the assumed source (control panel vibration) and the receiver (the microphone). The upper plot in Fig. 5 shows the acceleration spectrum for the lower accelerometer, while the lower plot shows the coherence with the lower accelerometer signal as the input and the right

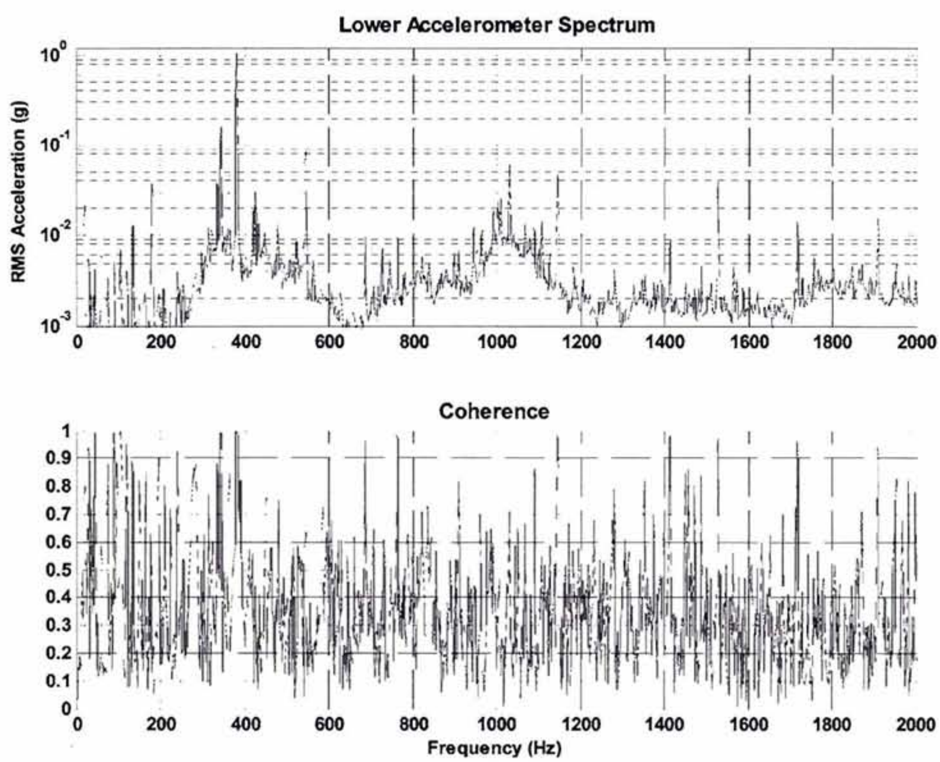

Fig. 5—Lower accelerometer narrowband RMS acceleration spectrum and coherence between lower accelerometer and right microphone for baseline test.

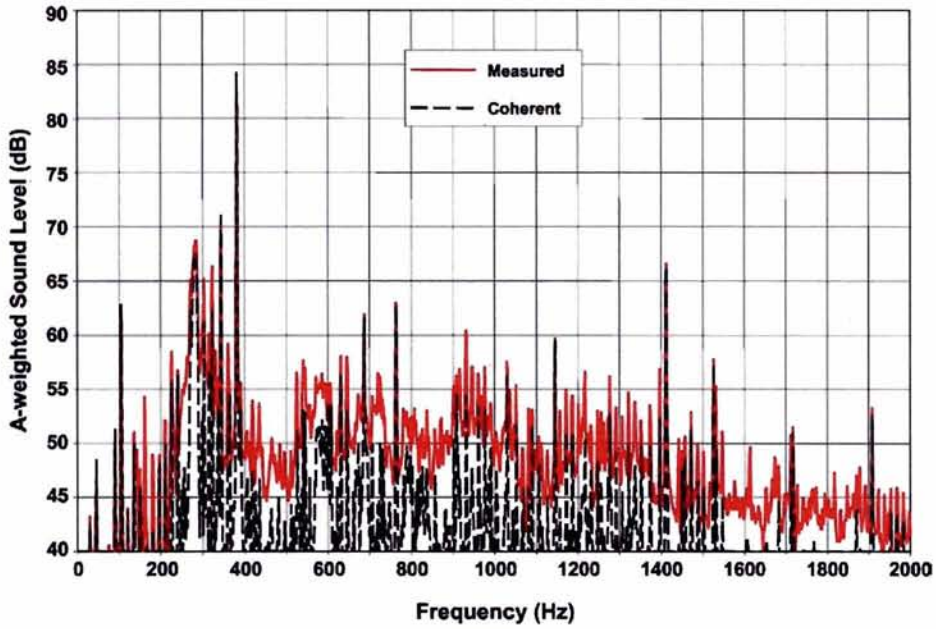

Fig. 6—Measured narrowband sound level and calculated coherent sound level with lower accelerometer as the reference.

microphone signal as the response. The lower plot indicates that the coherence approaches 1 at 381 Hz and several other peaks, indicating a strong relationship between the in-cab sound level and control panel vibration at these frequencies.

The coherence function was then used to calculate the coherent sound level for both the left and right microphones by

$$G_{vv} = \gamma_{xy}^2 G_{yy} \quad (2)$$

where G_{vv} is the coherent output spectrum between either microphone and the lower accelerometer.[10] The average coherent and measured sound levels are shown in Fig. 6. The data show that the coherent sound level is nearly equal to the measured sound level at the 381 Hz peak. This finding supports the hypothesis that the path of the noise from the hydraulic pump to the operator's ear is mechanical via the connection of the lines to the control valves and the control panel. Since the coherent sound levels match the measured sound levels at the most significant peaks throughout the frequency range, the data indicate that a strong relationship exists between the in-cab noise and structural vibration.

During the second test, the sound and vibration measurements were repeated with the flow from one output of the tandem gear pump disconnected from the control valves and re-routed to the hydraulic tank. The data were analyzed in the same manner as the baseline test data. Figure 7 shows the A-weighted, 1/3-octave band sound level spectra for both the baseline test and the test with the line re-routed (Test 2). With the hydraulic line disconnected from the control panel, the average sound level in the 400 Hz 1/3-octave band dropped from 85 dB to 74 dB, and the overall sound level dropped from 87 dB to 83 dB. Figure 8 shows the 1/3-octave band acceleration spectra for the lower accelerometer for the first and second tests. The acceleration level in the 400 Hz 1/3-octave band decreased from 1 to −21 dB with the hydraulic line disconnected. These results indicate that the dominant noise source for the 400 Hz 1/3-octave band is the tandem 10-tooth hydraulic pump.

The third test consisted of re-connecting the pump output to the control valves and bypassing a thermal valve at the suggestion of the drill rig manufacturer. With the thermal valve bypassed, neither the overall sound level nor the sound level in the 400 Hz 1/3-octave band decreased. Clearly, bypassing the thermal valve was ineffective.

Two 0.3-meter-long steel hydraulic lines were added in series with the existing hydraulic lines 0.48 meters from the tandem pump outlet for the fourth test. It was thought that adding a stiff section in series with the existing flexible lines could reduce the vibration transmitted to the control panel due to an impedance mismatch. Sound and vibration measurement and analysis was performed as before. Figure 9 shows that the 400 Hz 1/3-octave band sound level was 83 dB for the fourth test compared to 85 dB for the baseline test. In addition, the overall sound level was 86 dB, a 1 dB decrease from baseline conditions. The acceleration

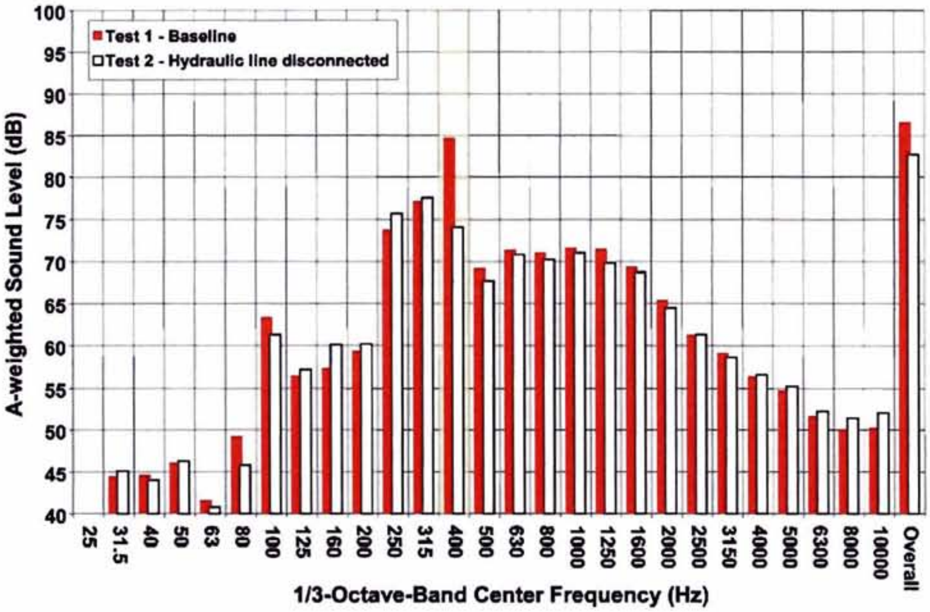

Fig. 7—A-weighted 1/3*-octave band sound level spectrum w/pump output lines disconnected from valve.*

level in the 400 Hz 1/3-octave band dropped from 1 dB for the baseline test to −6 dB with the steel lines added as shown in Fig. 10. However, the acceleration level in the 400 Hz 1/3-octave band with the line disconnected was −21 dB, indicating that the added stiff lines do not achieve the maximum possible reduction in transmitted vibration. Experimentation would have to be performed to determine the optimal length and location of the steel hydraulic lines.

Finally, Test 5 consisted of the steel lines added for Test 4 with an additional 0.1-meter-thick layer of sound-absorbing foam on the ceiling of the cab. Once again, sound and vibration measurements and 1/3-octave band analyses were performed. Neither the sound level in the 400 Hz 1/3-octave band nor the overall sound level changed with the additional acoustic foam. This result was not unexpected since the

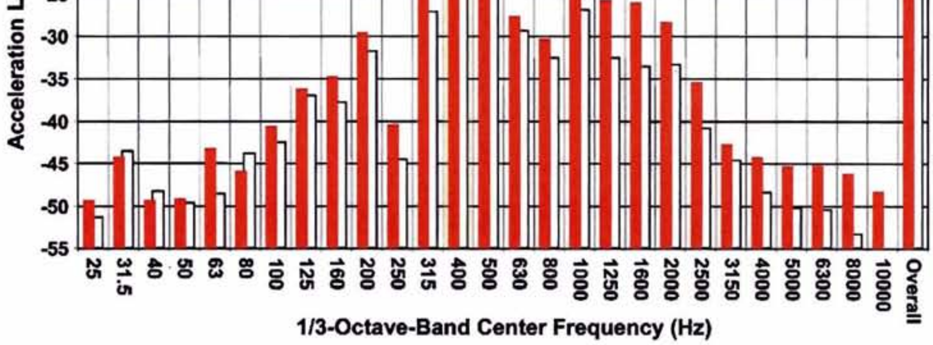

Fig. 8—One-third octave band acceleration level spectrum at lower accelerometer w/pump output lines disconnected from valve.

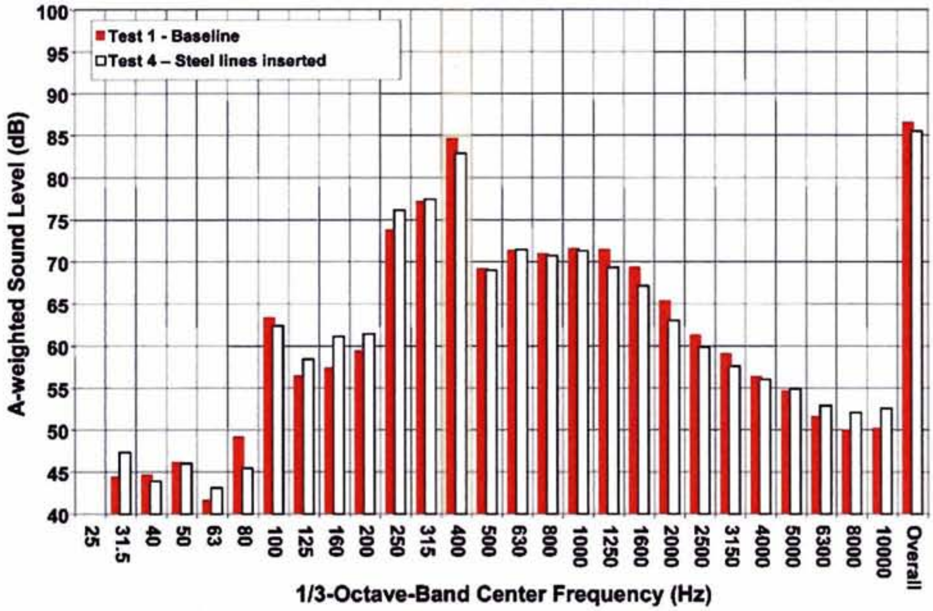

*Fig. 9—One-third octave band sound level w/*0.4-meter-*long steel hydraulic lines added* 0.48 meters *from tandem pump outlet.*

microphone location near the operator's ear is probably within the direct field of the noise radiated by the control panel.

The 400 Hz 1/3-octave band acceleration levels at the lower accelerometer and the 400 Hz 1/3-octave band and overall sound levels for Test 1, Test 2, and Test 4 are summarized in Table 2. The data indicate that the best means of reducing the 400 Hz 1/3-octave band sound level is by addressing the vibration transmitted from the tandem gear pump to the control panel.

2.2 Field Tests

After several other options were considered, hydraulic noise suppressors, which decrease pump ripple, were selected to reduce the vibration transmitted to the cab. A hydraulic noise suppressor is an in-line device

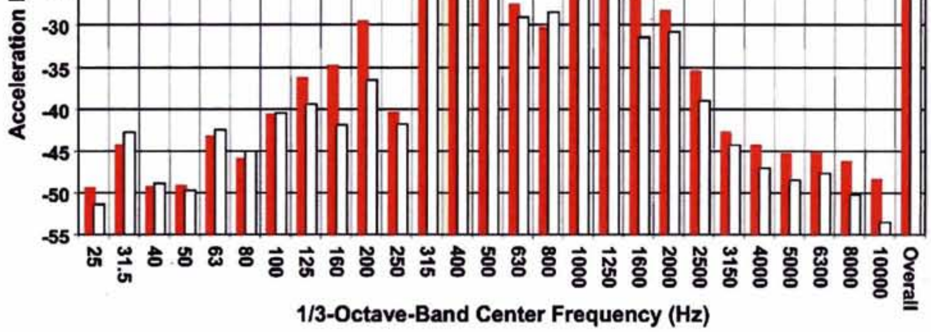

*Fig. 10—One-third octave band acceleration levels w/*0.4-meter-*long steel hydraulic lines added* 0.48 meters *from tandem pump outlet.*

Table 2—Summary of Test Results for Test 1, Test 2 and Test 4.

Measurement	Test 1-Baseline	Test 2-Hydraulic line disconnected from control panel	Test 4-0.4-meter-long steel lines added
Accel. Level in 400 Hz 1/3-octave Band at Lower Accel. (dB re 1 g)	1	−21	−6
A-wtd Sound Level in 400 Hz 1/3-octave Band (dB re 20 μPa)	85	74	83
A-wtd Overall Sound Level (dB re 20 μPa)	87	83	86

consisting of a steel body which houses several perforated tubes surrounded by a nitrogen-pressurized rubber bladder. To achieve the maximum noise reduction, the charge pressure of the bladder is adjusted based on the operating pressure in the attached hydraulic line.

While the Preliminary Tests focused on the in-cab noise with the drill rig's engine at full idle without drilling, most of the time during production is spent hammer drilling with the engine at full idle. Therefore, field testing was conducted at a production site to examine the in-cab sound level spectrum under normal operating conditions.

For a typical blasthole drilling cycle, the rig is moved to the desired hole location, the mast is raised, and the drill steel is positioned over the desired location. The machine is leveled using hydraulically-actuated outriggers. The cab door may be opened to enable the operator to see the drill rod position relative to the hole location. Next, hammer drilling commences and the cab door is closed. The dust collector system is used to minimize the operator's exposure to dust while drilling. When the drill rod is at its maximum depth, a second drill rod may be added to the first. Again, the rig is at high idle while a drill rod is added and the cab door may be opened. Prior to adding a drill rod, the rig operator may use the drill rod to flush debris from the hole. After adding the second drill rod, hammer drilling continues and the cab door is closed if it was opened. This process is repeated until the desired depth is reached. After drilling with the last rod is completed, the operator flushes the hole, removes the drill rods, lowers the mast, and moves the rig to the next location.

Two microphones were positioned near the operator's ears as with the Preliminary Tests. In addition, two accelerometers were mounted to the control panel at similar locations as those used during the Preliminary Testing. The microphone and accelerometer signals were recorded while drilling a blasthole with the rig's engine at full idle. The recorded microphone signals were subsequently post-processed to calculate the A-weighted sound levels with a slow response. In addition, the narrowband sound and acceleration level spectra were calculated. It is important to note that, in addition to the hammer drilling, other noise sources such as the dust collector, air compressor, and other hydraulic components that are used during drilling were not operating during the Preliminary Tests. These sources may be significant to the in-cab sound levels observed during production drilling.

Examination of the narrowband in-cab sound level spectrum revealed that two spikes, one at 390 Hz and the other at 350 Hz, were now the main contributors to the sound level in the 400 Hz 1/3-octave band (see Fig. 11). Recall, the Preliminary Testing showed that the tandem gear pump was a significant contributor to the

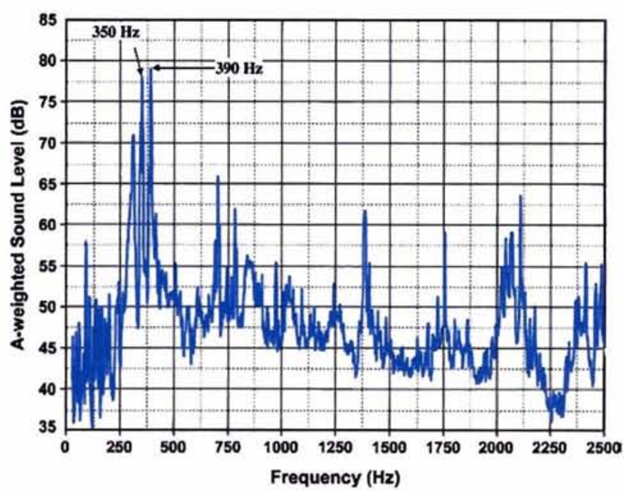

Fig. 11—In-cab narrowband sound level spectrum for high idle portion of blast hole drilling cycle.

overall sound level, producing a spike at 381 Hz with the drill rig's engine operating at 1800 RPM. For the Field Tests, the engine speed at full idle was observed to be approximately 1840 RPM. All pumps on the drill rig had an input speed of approximately 2300 RPM. The 10-tooth tandem gear pump would, therefore, produce its fundamental tone near 390 Hz.

Identifying the source of the 350 Hz tone was more difficult. Several piston pumps on the drill rig have nine pistons, and each piston pump produces its fundamental tone at 350 Hz. By examining the hydraulic schematic the dust collector pump was identified as the piston pump most likely to create the 350 Hz tone. Since the dust collector can be turned on or off via a lever in the cab, a simple on/off test was conducted to verify that the 350 Hz tone originated at the dust collector pump. The 350 Hz peak was observed to appear with the dust collector on and to disappear with the dust collector off, verifying that the dust collector pump was the source of the 350 Hz tone.

With the main sources of the in-cab hydraulic noise identified, three noise suppressors were installed: one suppressor at each of the tandem gear pump outlet ports and another at the dust collector pump outlet port. Since the attenuation depends on the noise suppressor charge pressure, a series of vibration measurements were performed with various charge pressures for each suppressor. The real-time frequency spectra of the accelerometer signals were measured, and the acceleration levels at the tandem and piston pump fundamental frequencies were monitored. The most effective charge pressures for the slow feed and outrigger ports suppressors of the tandem pump were found to be 210–410 kPa and 410–1,240 kPa, respectively. The best attenuation of the dust collector fundamental frequency occurred with the dust collector suppressor charged to 6,200 kPa.

Sound and vibration measurements were conducted without and with the noise suppressors installed. Three holes were drilled without and with the suppressors installed and charged to the previously discussed charge pressures. A Personal Digital Assistant (PDA) was used to record the drill rig operations (hammer drilling, setting up, rig at high idle, etc.) and whether the cab doors were opened or closed. The drill rig was located on a bench such that the rig was parallel to the high wall at a distance of approximately 15 meters. It is important to note that drilling this close to the highwall may increase the sound level in the cab while drilling due to the reflections from the highwall.

After acquiring the data, each recording for a single hole was split into multiple files according to the drill rig operation and whether the doors were opened or closed. The PDA data were used in conjunction with listening to the recordings to categorize each recording as follows:

- hammer drilling, doors closed
- hammer drilling, door(s) opened
- high idle, doors closed
- high idle, door(s) opened.

After the recordings were categorized, the average 1/3-octave band sound levels and the un-weighted 1/3-octave band acceleration levels were calculated for each resulting data file that was longer than 10 seconds. Finally, a global average for each of the four categories was calculated by weighting each spectrum according to the percentage of time for the specific file relative to the total time for the category in question. For example, if a single file accounted for 10 seconds of the total time spent hammer drilling with a door open, and the total time spent hammer drilling with a door open was 1800 seconds, the resulting spectrum would account for 0.56% of the average spectrum for hammer drilling with a door open.

Figure 12 shows a comparison between the 1/3-octave band acceleration levels at the lower accelerometer when hammer drilling without and with the suppressors. The figure shows that the acceleration level in the 400 Hz 1/3-octave band decreased slightly whereas the acceleration level in the 315 Hz 1/3-octave band increased by a few dB with the suppressors. These changes may be due to differences in drilling conditions between the measurements without and with the noise suppressors. Significant reductions in the acceleration levels occurred in the 630 Hz to 6300 Hz 1/3-octave bands with the noise suppressors installed. The resulting 1/3-octave band acceleration levels with the rig at high idle with the doors closed without and with the hydraulic suppressors is shown in Fig. 13. The figure indicates that the acceleration level in the 400 Hz 1/3-octave band increases slightly and the acceleration level in the 315 Hz 1/3-octave band increased by a few dB. These changes may be due to a small variation in the engine RPM for each measurement. The vibration levels in the 1000 Hz to 5000 Hz 1/3-octave bands are significantly reduced with the noise suppressors installed. The reductions at the higher frequencies are probably due to attenuation of harmonics of the tandem pump fundamental frequency.

The 1/3-octave band acceleration levels near the dust collector control lever without and with the suppressors for hammer drilling and high idle are shown in Figs. 14 and 15, respectively. Both figures show that a substantial reduction in acceleration occurs

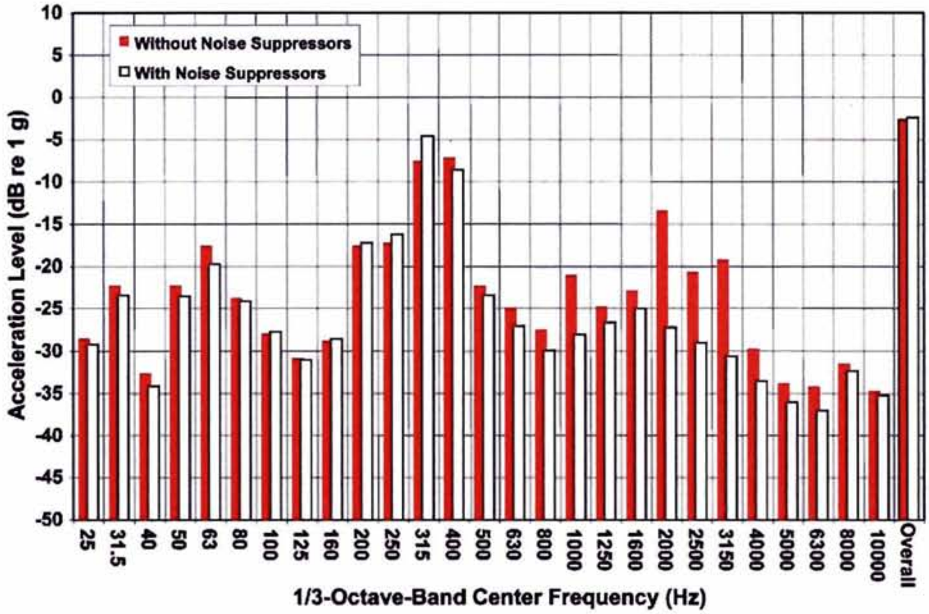

Fig. 12—Comparison of 1/3*-octave band acceleration levels on lower control panel w/o and w/noise suppressors during hammer drilling.*

in the 315 Hz through 630 Hz 1/3-octave bands. In addition, significant attenuation is shown for the higher frequency bands.

Figures 16 and 17 show the average 1/3-octave band sound levels without and with the suppressors during hammer drilling with the doors closed and at high idle with the doors closed. Figure 16 shows that a 6-dB reduction occurs in the 400 Hz 1/3-octave band with a 1-dB reduction in the overall sound level. Due to hammer drilling, the sound level spectra in Fig. 16 exhibit a hump from the 630 Hz to 3150 Hz 1/3-octave band which dominates the spectrum. For these tests, the drill rig was within 15 meters of a highwall causing the drilling noise to be reflected back to the cab, thereby increasing the significance of the drilling noise. If the drilling noise entering the cab

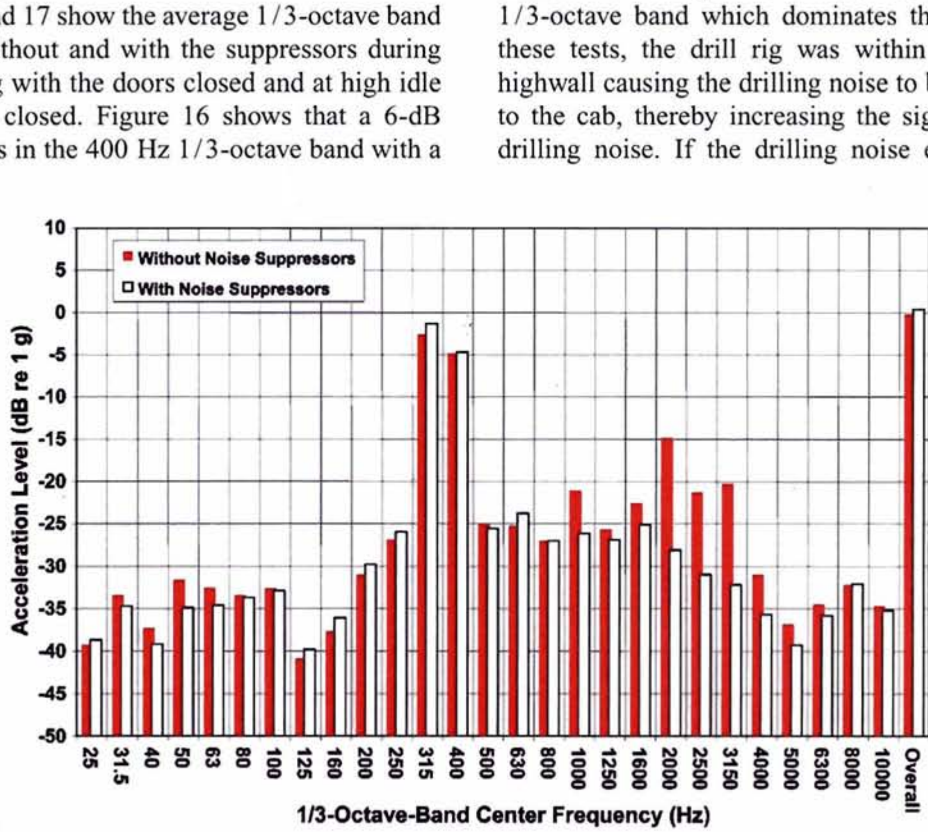

Fig. 13—Comparison of 1/3*-octave band acceleration levels on lower control panel w/o and w/noise suppressors at high idle.*

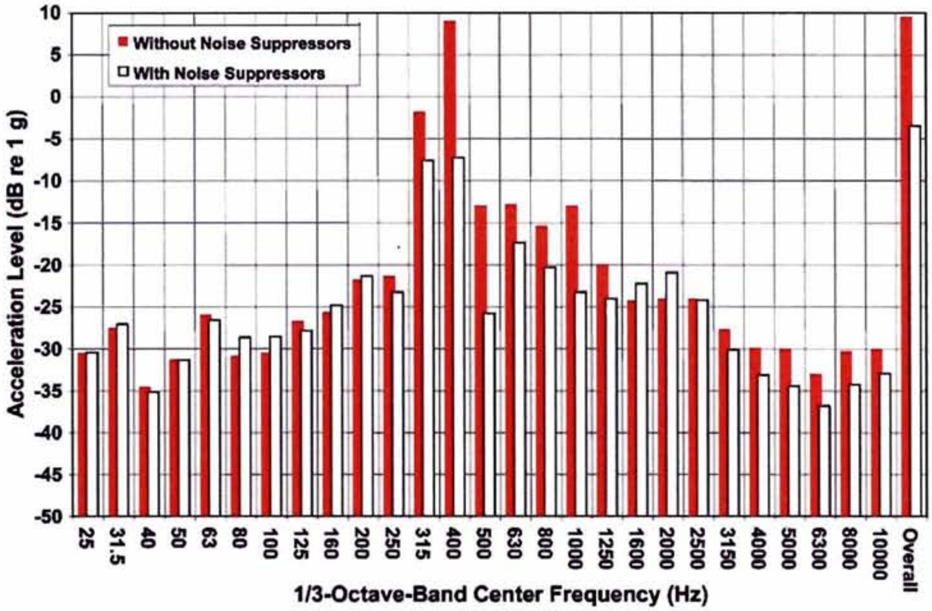

Fig. 14—Comparison of 1/3-*octave band acceleration levels near dust collector control lever w/o and w/noise suppressors during hammer drilling.*

could be blocked by improving the cab design or if the noise generated by drilling could be reduced, using the suppressors has the potential to reduce the overall sound level by more than 1 dB while drilling. Figure 17 indicates that using the noise suppressors reduces the 400 Hz 1/3-octave band sound level by 7 dB and the overall sound level by 4 dB with the rig at high idle. In addition, significant reductions occurred in the 630 Hz to 6300 Hz 1/3-octave bands.

During testing, a gap of approximately 1 cm in width that allows drilling noise to enter the cab was noticed between the inside door and the cab. The rubber seal in this area was not compressed even when the inside door was closed and latched. A quilted fiberglass blanket with a lead septum was draped over the cab/inside door interface to determine if the gap was a significant sound transmission path. Figures 18 and 19 show comparisons of the average 1/3-octave band

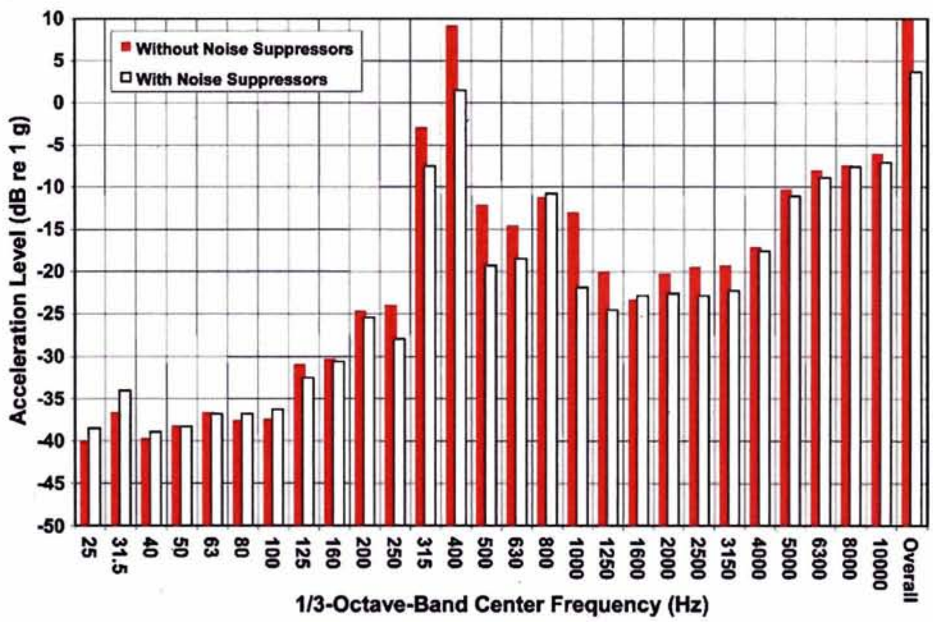

Fig. 15—Comparison of 1/3-*octave band acceleration levels near dust collector control lever w/o and w/noise suppressors at high idle.*

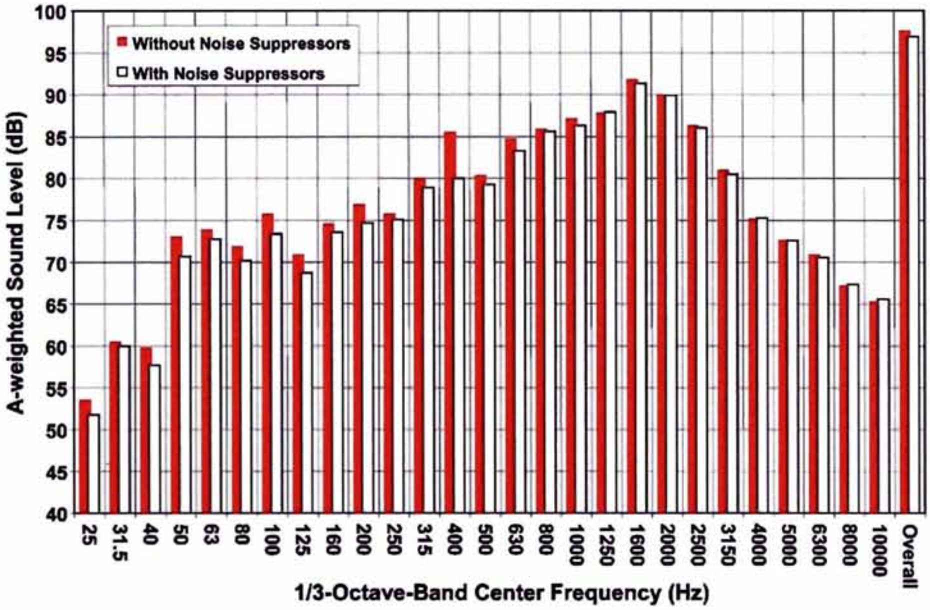

Fig. 16—Comparison of 1/3*-octave band sound levels w/o and w/noise suppressors during hammer drilling with cab doors closed.*

sound levels without the hydraulic suppressors, with the hydraulic suppressors, and with the hydraulic suppressors plus the lead-fiberglass blanket during hammer drilling and high idle with the cab doors closed. Figure 18 shows that using the lead-fiberglass blanket significantly reduced the sound levels in the 500 Hz through 10 kHz 1/3-octave bands. In addition, adding the blanket reduced the overall sound level during hammer drilling by an additional 2 dB. Figure 19 shows that the sound levels in the 1 kHz through 10 kHz 1/3-octave bands with the drill rig at high idle with the doors closed were substantially reduced by adding the lead-fiberglass blanket. However, the overall sound level was only reduced by 1 dB since the 315 Hz and 400 Hz 1/3-octave bands dominate the spectrum. The results of these tests are summarized in Table 3.

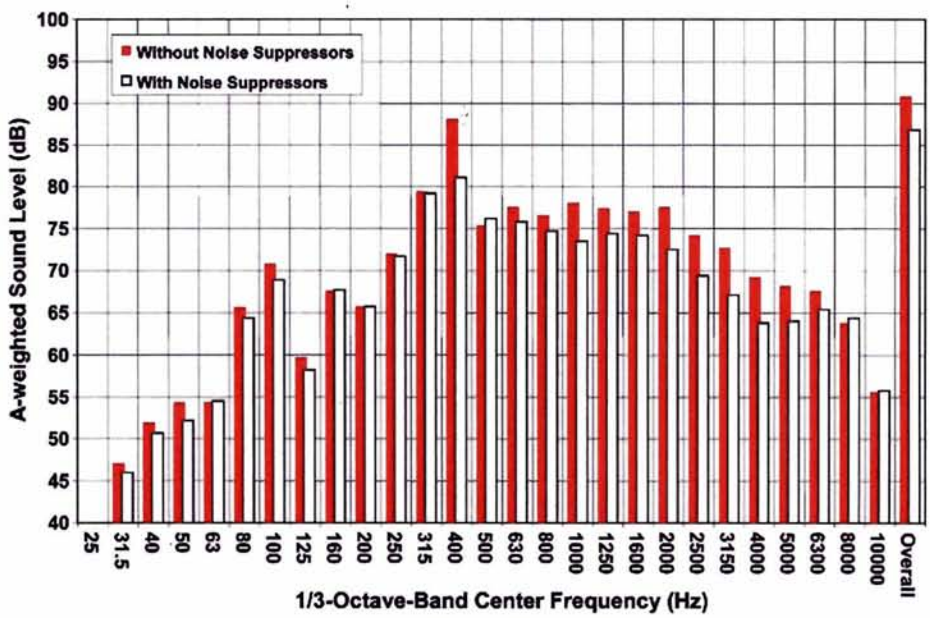

Fig. 17—Comparison of 1/3*-octave band sound levels w/o and w/noise suppressors at high idle with cab doors closed.*

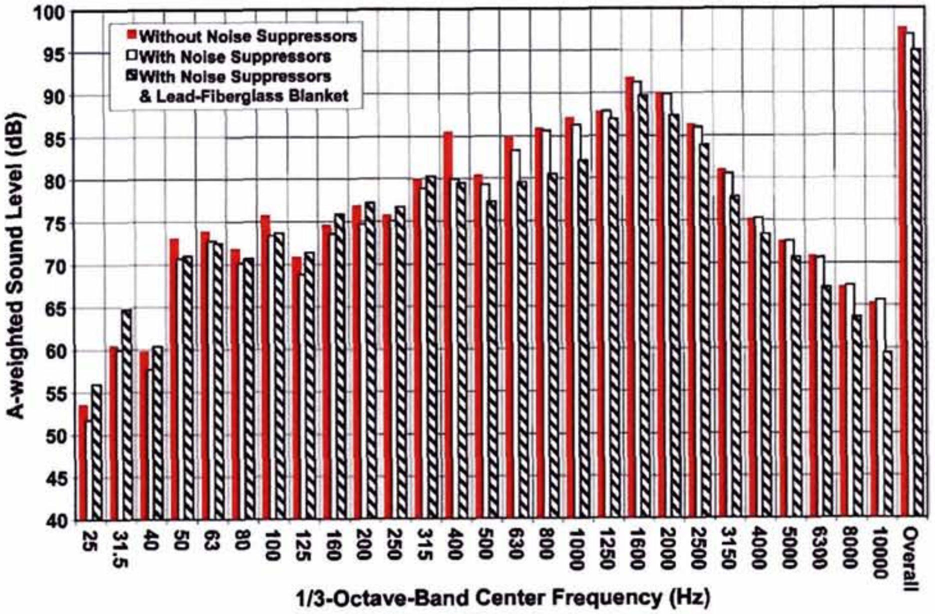

Fig. 18—Comparison of 1/3*-octave band sound levels w/o and w/noise suppressors and w/noise suppressors and lead-fiberglass blanket during hammer drilling with cab doors closed.*

3 DRILL RIG OPERATOR'S NOISE EXPOSURE

The results from the Preliminary and Field Tests show that multiple hydraulic pumps on the tested air-rotary rig are the dominant contributors to the in-cab noise during drilling operations. In addition, a gap between the inner door and the cab was shown to be a path for drilling noise to enter the cab. Further, the test results show that installing hydraulic noise suppressors and eliminating the gap will reduce the overall in-cab sound levels, thereby reducing the drill rig operator's noise exposure. The cab on this drill rig used sliding doors with a rubber seal. It appeared that the inside door was bent on this machine creating a gap along the cab-door interface. Gaps around doors are highly detrimental to the ability of a cab to block

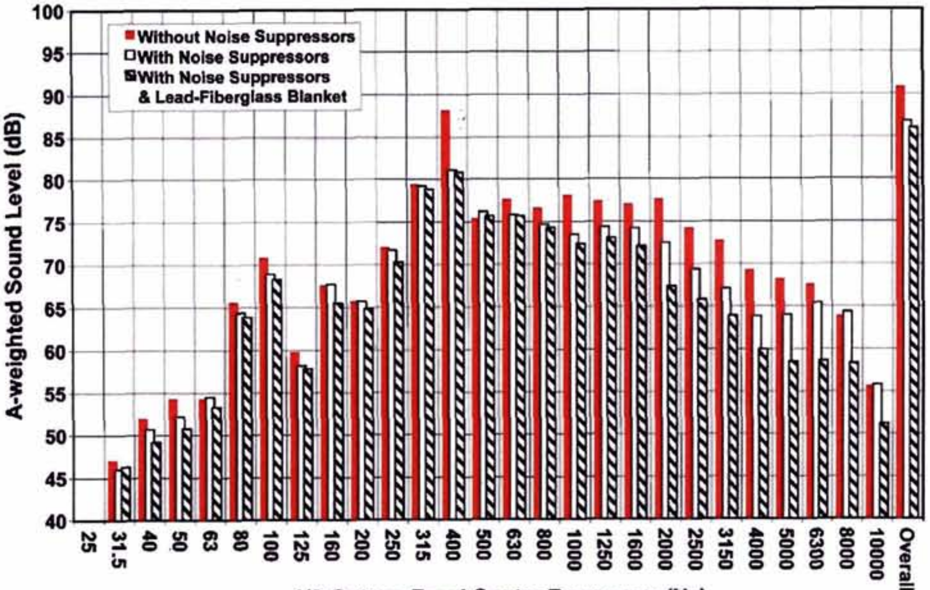

Fig. 19—Comparison of 1/3*-octave band sound levels w/o and w/noise suppressors and w/noise suppressors and lead-fiberglass blanket at high idle with cab doors closed.*

Table 3—Comparison of acceleration and sound levels without noise suppressors, with noise suppressors, and with noise suppressors plus lead-fiberglass blankets for high idle and hammer drilling with the cab doors closed.

	High Idle-Doors Closed		Hammer Drilling-Doors Closed	
Measurement	Without	With	Without	With
Accel. Level in 400 Hz 1/3-octave Band at Lower Accel. (dB re 1 g)	−5	−5	−7	−9
Accel. Level in 400 Hz 1/3-octave Band at Accel. Near Dust Collector Control Lever (dB re 1 g)	9	1	9	−7
A-wtd Sound Level in 400 Hz 1/3-octave Band (dB re 20 μPa)	88	81	86	80
Accel. Level in 630–6300 Hz 1/3-octave Bands at Lower Accel. (dB re 1 g)	−12	−17	−11	−18
Accel. Level in 630–6300 Hz 1/3-octave Bands at Accel. Near Dust Collector Control Lever (dB re 1 g)	−3	−12	−8	−14
A-wtd Sound Level in 630–6300 Hz 1/3-octave Bands (dB re 20 μPa)	86	81	97	94
Overall, A-wtd Sound Level (dB re 20 μPa)	91	86	98	95

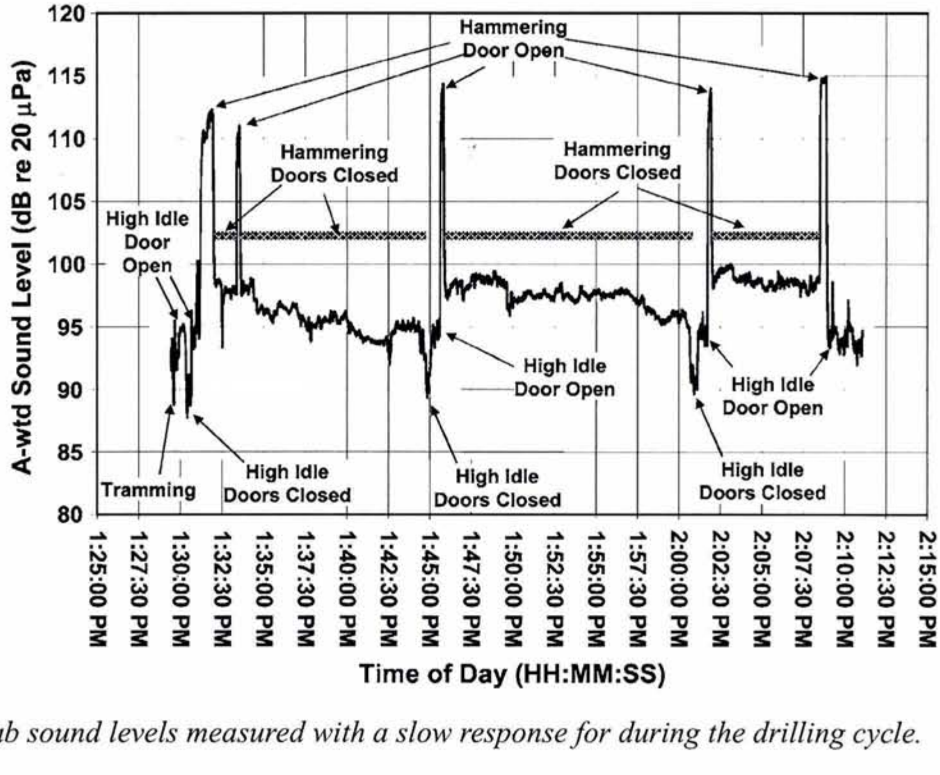

Fig. 20—In-cab sound levels measured with a slow response for during the drilling cycle.

Table 4—A-weighted sound level and percentage of time at each mode of operation.

Mode of Operation	A-wtd Sound Level (dB re 20 μPa)	% of Time
Hammering, doors closed	98	82%
Hammering, door open	112	5%
High idle, door closed	91	8%
High idle, door open	95	5%

sound. For example, consider a 0.6-meter-wide × 1.2 meter-high door with a sound transmission loss of 25 dB at a particular frequency. A 1-cm gap along the width of the door would reduce the overall transmission loss of the door by more than 4 dB. Therefore, elimination of gaps around doors and windows is essential to achieve a cab with a high sound transmission loss.

Figure 20 shows an example of the sound level time history measured using a slow response while drilling a blasthole with no added engineering noise controls. The tramming, setting-up, flushing, and drill rod removal processes are referred to as 'high idle' in Fig. 20, since no drilling is taking place, the engine is at full idle, and the sound levels and spectra are similar for these processes. 'Hammering' refers to when the rig is being used to drill the hole. The horizontal bars labeled 'Hammering Doors Closed' indicate the time the operator spent hammer drilling with the cab doors closed. As expected, the sound levels are highest while drilling with the door open, reaching sound levels as high as 115 dB. When hammer drilling with the doors closed, the sound level varied from about 93 to 99 dB for this particular hole.

Table 4 shows the average in-cab sound levels and the percentage of time spent with the drill rig operating at high idle with the door(s) open, at high idle with the doors closed, hammer drilling with the doors open, and hammer drilling with the doors closed. As the table shows, the majority of time was spent with the drill rig hammering with the doors closed. However, the sound level for hammer drilling with the door open is substantially higher than it is with the doors closed. Therefore, it remains difficult to know which mode of operation is the most significant contributor to the operator's noise exposure because noise exposure is a function of both the sound level and the duration of exposure.

Noise exposure is measured in dose and is a function of the threshold sound level, criterion sound level, criterion duration, and exchange rate in addition to the sound level at the worker's ear and the actual exposure time. The dose may be calculated by

$$D = 100\frac{T}{T_c}10^{(L_i-L_c)(10LOG_{10}2)/Q} \qquad (3)$$

where D is the percentage of the allowable dose, T is the exposure time in hours, T_c is the criterion duration, L_i is the sound level for the ith event, L_c is the criterion level, and Q is the exchange rate in dB.[11] Sound levels below the threshold sound level do not add to the dose.

Typically, worker noise dose is measured using a noise dosimeter with settings corresponding to the MSHA Permissible Exposure Level (PEL) or MSHA hearing conservation program (HCP) settings. Both the MSHA PEL and HCP settings use a criterion level of 90 dB, a criterion time of 8 hours, and an exchange rate of 5 dB per doubling (or halving) of time. The MSHA PEL settings use a threshold level of 90 dB whereas the MSHA HCP settings use a threshold of

*Table 5—Estimated noise dose for MSHA PEL (*90 dB L_T, 90 dB L_C, 5-dB *exchange rate), MSHA HCP (*80 dB L_T, 90 dB L_C, 5-dB *exchange rate), and NIOSH (*80 dB L_T, 85 dB L_C, 3-dB *exchange rate) dosimeter settings, assuming* 6 hours *of drilling and* 2 hours *of quiet time during an* 8-hr *work shift without noise suppressors.*

Mode of Operation	% of Drilling Time	Hours in 8-hr shift	AVG Sound Level, dB	MSHA PEL Dose	MSHA HCP Dose	NIOSH Dose
Hammer drilling, doors closed	82%	4.92	98	186%	186%	1240%
Hammer drilling, door open	5%	0.30	112	79%	79%	1920%
High idle, doors closed	8%	0.48	91	7%	7%	24%
High idle, door open	5%	0.30	95	8%	8%	38%
Non-drilling activity	0%	2.00	<80	0%	0%	0%
	Total Dose			280%	280%	3222%

Table 6—Estimated noise dose for MSHA PEL (90 dB L_T, 90 dB L_C, 5-dB exchange rate), MSHA HCP (80 dB L_T, 90 dB L_C, 5-dB exchange rate), and NIOSH (80 dB L_T, 85 dB L_C, 3-dB exchange rate) dosimeter settings, assuming 6 hours *of drilling and* 2 hours *of quiet time during an* 8-hr *work shift without noise suppressors.*

Mode of Operation	% of Drilling Time	Hours in 8-hr shift	AVG Sound Level, dB	MSHA PEL Dose	MSHA HCP Dose	NIOSH Dose
Hammer drilling, doors closed	82%	4.92	97	162%	162%	984%
Hammer drilling, door open	5%	0.30	112	79%	79%	1920%
High idle, doors closed	8%	0.48	87	0%	4%	10%
High idle, door open	5%	0.30	95	8%	8%	38%
Non-drilling activity	0%	2.00	<80	0%	0%	0%
	Total Dose			249%	253%	2951%

80 dB. NIOSH recommends using a threshold of 80 dB, a criterion level of 85 dB, and a 3-dB exchange rate.

The estimated noise dose due to each operating condition and the total dose for the drill rig operator settings were calculated based on these dosimeter readings, assuming that drilling was performed for 6 hours during an 8-hour work shift and that no additional dose was accumulated in the remaining 2 hours. The results of these calculations are shown in Table 5. As the table shows, in this instance the drill rig operator was overexposed no matter which metric was used. Due to the use of a 3-dB exchange rate and an 85-dB criterion level, the dose calculated using NIOSH settings is significantly higher than the dose calculated with either MSHA setting. For the MSHA settings, hammer drilling with the doors closed accounts for the majority of the operator's noise exposure. Hammering with the door open is the most significant mode of operation in terms of noise exposure with the NIOSH settings.

The dose for each drilling operation and the total dose were calculated using the results of the testing with the noise suppressors installed and with the noise suppressors plus the lead-fiberglass blanket blocking the gap between the inside cab door and the cab body. Tables 6 and 7 show the calculated dose with the noise suppressors installed and with the noise suppressors

Table 7—Estimated noise dose for MSHA PEL (90 dB L_T, 90 dB L_C, 5-dB exchange rate), MSHA HCP (80 dB L_T, 90 dB L_C, 5-dB exchange rate), and NIOSH (80 dB L_T, 85 dB L_C, 3-dB exchange rate) dosimeter settings, assuming 6 hours *of drilling and* 2 hours *of quiet time during an* 8-hr *work shift with noise suppressors installed and a lead-fiberglass blanket covering the gap between the inside door and the cab frame.*

Mode of Operation	% of Drilling Time	Hours in 8-hr shift	AVG Sound Level, dB	MSHA PEL Dose	MSHA HCP Dose	NIOSH Dose
Hammer drilling, doors closed	82%	4.92	95	123%	123%	620%
Hammer drilling, door open	5%	0.30	112	79%	79%	1920%
High idle, doors closed	8%	0.48	86	0%	3%	8%
High idle, door open	5%	0.30	95	8%	8%	38%
Non-drilling activity	0%	2.00	<80	0%	0%	0%
	Total Dose			210%	213%	2585%

installed with the lead-fiberglass blanket covering the gap. With the suppressors, the calculated noise dose dropped by 31% for the MSHA PEL settings, 27% for the MSHA HCP settings, and 271% for the NIOSH settings. The calculated noise dose with the suppressors and lead-fiberglass blanket decreased by 70% for the MSHA PEL settings, 67% for the MSHA HCP settings, and 637% for the NIOSH settings. With the treatments installed, hammer drilling with the doors closed remained the main contributor to the noise dose calculated with the MSHA settings. With the NIOSH settings, hammer drilling with a door open remained the most significant contributor to the noise dose. A further reduction of the noise dose would require either a reduction in the drilling noise or an improvement in the cab attenuation.

4 SUMMARY

A series of tests was conducted to identify the dominant noise sources for the in-cab sound levels of an air-rotary drill rig. A tandem gear pump and a piston pump were identified as significant sources of in-cab noise. Three hydraulic noise suppressors, one on each outlet port of the tandem pump and one on the output of the dust collector piston pump, were installed in-line with the existing hydraulic lines. Field measurements with the drill rig at high idle showed that the in-cab A-weighted sound level near the operator's ear was reduced by 4 dB with the noise suppressors installed. When the rig was hammer drilling, however, the in-cab sound level was reduced by only 1 dB. In this instance, drilling noise within the cab is dominant. Both reflections from the nearby highwall and the presence of a gap at the cab/inside door interface increase the significance of drilling noise relative to the in-cab sound level. Covering the gap with lead-fiberglass blankets with the noise suppressors installed reduced the in-cab sound level while hammer drilling by 3 dB compared to baseline conditions. This indicates that eliminating the gap is critical to reduce the sound level inside the cab.

The percentage of time spent during each drill function and the A-weighted sound levels for each rig function were used to estimate the operator's noise dose based on MSHA PEL, MSHA HCP, and NIOSH-recommended dosimeter settings for an 8-hour workday with 2 hours of quiet time when no dose was accumulated. For the baseline machine, the estimated noise doses according to the MSHA PEL, MSHA HCP, and NIOSH settings were 280%, 280%, and 3222%, respectively. With the hydraulic noise suppressors installed these values were reduced to 249%, 253%, and 2951%. Finally, adding the lead-fiberglass blanket to seal the gap with the suppressors reduced the estimated noise doses to 210%, 213%, and 2585%. These reductions correspond to reductions of 25% for MSHA PEL settings, 24% for MSHA HCP settings, and 20% for NIOSH settings. The reductions may have been higher if the drill rig was not positioned as close to a highwall, since reflections of drilling noise from a highwall significantly increase the contribution of drilling noise to the in-cab overall A-weighted sound level thereby decreasing the importance of hydraulic noise. If the hydraulic noise is reduced by installing the hydraulic noise suppressors, improving the sound transmission loss of the cab to block airborne drilling noise may reduce the operator's noise exposure below the MSHA PEL settings.

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