PRACTICAL APPLICATION OF A PARTIAL CAB TO REDUCE THE A-WEIGHTED SOUND LEVEL AT THE OPERATOR'S STATION ON SURFACE DRILL RIGS

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Abstract

The National Institute for Occupational Safety and Health (NIOSH) identified hearing loss as the most common job-related disease in the United States in its 1996 National Occupational Research Agenda. Previous studies by NIOSH have shown operators of surface drill rigs without cabs are commonly exposed to A-weighted sound levels exceeding 90 dB. During hammer-drilling, A-weighted sound levels exceeding 100 dB were recorded at the operator station. NIOSH collaborated with a local drilling company to design and install a partial cab between the operator and the drill steel in an effort to reduce the sound level at the operator station. Sound level measurements in the field show the partial cab reduces the A-weighted sound level by 5-9 dB at the operator's left ear and 2-5 dB at the operator's right ear while hammer-drilling. This paper will briefly discuss the preliminary design of a cab and the testing of materials for construction of the prototype. Explanation of the ideas behind the prototype design and fabrication will be covered. Finally, the field test method and results will be discussed in detail.

Introduction

Noise, which is any unwanted sound, is present throughout the mining industry. Continued exposure to high noise levels can cause damage to the inner ear. The eventual result is a permanent shift in hearing thresholds, known as noise-induced hearing loss (NIHL). NIHL is the most common occupational disease in the United States today, with 30 million workers exposed to excessive sound levels or toxicants that are potentially hazardous to their hearing (1). For noise dosimetry, NIOSH recommends using a criterion level of 85 dB(A) and a 3-dB exchange rate whereas the Mine Safety and Health Administration (MSHA) uses a criterion level of 90 dB(A) with a 3-dB exchange rate (2,3)

Surface drill rigs are used for a variety of purposes including the installation of water wells, environmental monitoring wells, gas wells, and pilings. Additionally, they are commonly used in the mining industry to drill blast holes at surface mines, and access holes for underground mines. When used on mine property, drill rigs are subject to MSHA regulations. Prior NIOSH research concluded air-rotary rigs produced the highest sound levels at the operator station when compared to cable tool rigs, auger rigs, and probe impact rigs. Typically, this type of rig uses a pneumatic/hydraulic hammering device which is either located at the bottom of the drill string (down-hole hammer) or at the top of the drill string (top hammer). The hammering action is needed to break up hard materials to expedite the drilling process. After the rock is fractured, air-rotary rigs use high pressure air to force the drill cuttings from below the drill bit and out of the hole.

Field investigations identified the drill steel as the major noise source on the drill rig during hammer-drilling. One particular study involved three different air-rotary drill rigs with three different drill rig operators (4). Results of this study indicated all three drill rigs produce A-weighted sound levels above 90 dB during the development of domestic water wells. In two of the three cases, the drill rig operators exceeded their recommended daily allowable noise exposure limits within four hours of drilling activity. The operators' noise dosimeters projected dose readings of 276%, 268%, and 130% if the drilling activity were to continue for eight hour shifts. These dose values equate to time-weighted averages (TWA) of 97.3 dB, 97.1 dB, and 91.9dB respectively, based on the MSHA criteria. In general terms, the TWA is the constant sound level that would result in the same noise dose as the time-varying sound level (5). This study also found A-weighted sound levels exceeding 100 to 110 dB at the operator station during hammer-drilling and particularly during the hammering of well casing.

Many of the air-rotary rigs used for blast hole drilling are equipped with cabs to protect the operator from dust and noise. However, rigs used for mine support services such as access holes, dewatering holes, and degas holes do not usually have operator cabs. Additionally, a large percentage of the air-rotary rigs used in non-mine-related work do not have cabs. These rigs are sometimes owned and operated by family businesses in the water well and gas drilling industries which are regulated by OSHA.

Rig designs vary based on manufacturer and model. However, the air-rotary rigs NIOSH observed in this research were similar. The rig controls used by the operator were located in close proximity to the drill steel and no barrier existed between the drill steel and the operator's platform (Figure 1). Additionally, some operators spent a large percentage of their day at the operator's platform. As can be seen from Figure 1, the operators of drill rigs of this style are in very close proximity to the major noise source of the rig. The goal of this research was to design an effective barrier to reduce the operator's exposure to noise radiated by the drill steel. In order to be fully accepted, the barrier would have to be easy to use, un-cumbersome, and economical.

Many of the rigs without cabs do not have automated drill steel handling equipment which is typically installed on rigs used for blast hole drilling. The operators of the non-cab rigs who were observed by NIOSH have to add and remove drill steels by hand during the process of completing a hole. While adding a drill steel, a jib crane on top of the mast is used to move the drill steel directly through the area in front of the control panel. Therefore, any barrier located near the operator's platform would have to allow the operator to reach the drill string when adding and removing drill steels. In addition, the presence of a full cab could impact the size and maneuverability of the rig and thus limit the location of drilled holes. The overall cost of the barrier needed to be considered as well. According to a manufacturer of air-rotary drill rigs, a full operator's cab could cost approximately $20,000 depending on the rig, cab options, and cost of materials at the time the rig was manufactured. This high cost could be one reason why only five

percent of the rigs sold by the manufacturer included operator cabs as an option. NIOSH concluded that a partial cab design could be retrofitted to these rigs to help protect the operator from the sound emitted from the drill steel.

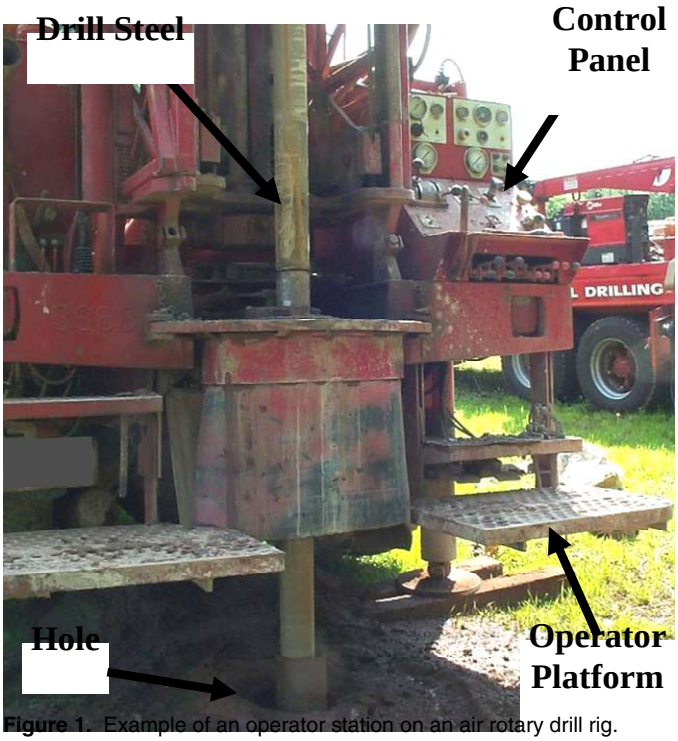

Figure 1. Example of an operator station on an air rotary drill rig.

Concept and Testing of the Initial Partial Cab

After researching the sound levels around air rotary rigs, the idea of a partial cab was discussed by researchers at NIOSH. The partial cab was envisioned as a small, lightweight, inexpensive barrier that could be added to almost any drill rig on the market. The detailed design of the partial cab would vary between rigs, but the overall effect of the cab would be to protect the drill rig operator from direct exposure to sound emitted from the drill steel. A concept cab was tested to see if a simple partial enclosure could reduce the sound levels at the operator location.

The first concept of the partial cab was a five-sided box (Figure 2). The box would screen the operator down to the shoulders and would be equipped with windows to allow the operator to view the control panel and drilling deck. The cab could be quickly and easily retracted using a winch to allow the drill operator to move around the drill rig.

This basic concept was tested in the lab using a representative layout of an air rotary rig (Figure 3). For the initial tests, the concept partial cab consisted of a box constructed with 6-mm-thick plywood for the left, right, top and back and acrylic sheet for the front. The box measured approximately 61-cm long by 100-cm wide by 61-cm high. Barrier-absorber material, with a thickness of 3.18-cm, was added to the interior of the box on the four plywood surfaces for the secondary testing. The materials selected were used because they were available at the time of the initial testing. Loudspeakers were placed in the locations where the cooling fan and drill steel would be positioned on the rig. A Bruel & Kjaer 4188 microphone was then placed on a tripod where the operator station would be on a drill rig. During prior research, the sound pressures near the drill steel and cooling fan were simultaneously recorded while hammer-drilling with a drill rig in the field. Since the sound pressures at these locations were recorded simultaneously, the relative contributions of the individual noise sources are maintained. These recordings were used for the laboratory testing. The testing was conducted in a large open building at the Pittsburgh Research Laboratory (PRL). The test set up was positioned as far as possible from large objects to reduce the potential for sound reflecting off of the objects and affecting the sound levels recorded at the operator position. The set up described above was also used to test later cab designs.

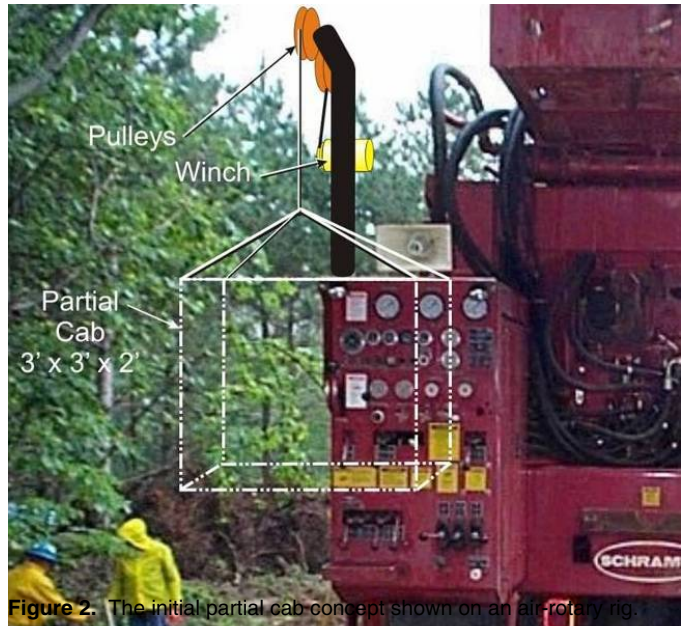

Figure 2. The initial partial cab concept shown on an air-rotary rig.

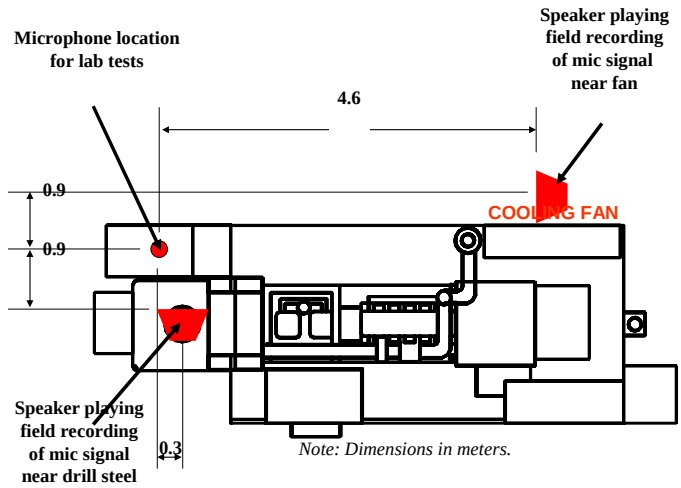

Figure 3. Laboratory test set up of speaker and microphone locations. Rig outline shown to display locations of speakers relative to equipment on the rig. Rig not used during testing.

Using a laptop computer, the recorded signals were fed from the laptop's soundcard to an amplifier that drove the two loudspeakers The signal recorded near the drill steel was played through the speaker positioned where the drill steel would be and the signal recorded near the fan was played through the other speaker. An LMS Pimento portable data acquisition system was used to record the resulting sound pressure at the microphone using the Time Data Acquisition Module with a sample rate of 25,000 samples per second and 16-bit resolution. While playing the recordings without the concept partial cab covering the microphone, the volume for the loudspeakers was adjusted to produce an overall un-weighted sound pressure level of 100 dB at the microphone. This level was considered the baseline level to measure the attenuation of the partial cab concept. Figure 4 shows the A-weighted 1/3-octave-band sound levels near the drill steel from the field data (plotted on the left y-axis) and at the A-weighted 1/3-octave band sound levels at the microphone resulting from playing the field recordings (plotted on the right y-axis). Although the A-

weighted sound levels for the lab testing are lower than what was observed in the field, the frequency content of the sound generated by the loudspeakers is similar to that of the field data. Since the goal of the testing was to determine changes in sound levels due to using the concept partial cab, the sound generated by the speakers is sufficient for the laboratory testing.

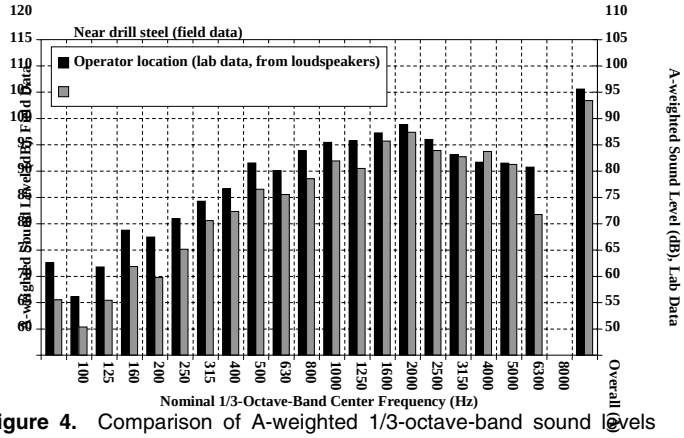

Figure 4. Comparison of A-weighted 1/3-octave-band sound levels from field data on a drill rig with lab sound levels generated from playback of field recordings in the lab.

After the baseline sound level was established, the concept cab was positioned to cover the microphone and the attenuation tests were conducted. The sound pressure at the microphone was measured without the partial cab, with the partial cab, and with the lined partial cab using the recordings made with the rig at high idle and while hammer-drilling. For each measurement, the data were post-processed to calculate the overall A-weighted sound level and the A-weighted sound levels in 1/3-octave bands. The plywood cab reduced the A-weighted sound level at the microphone by 8.0 dB. The attenuation increased to 11.6 dB when the barrier-absorber material was added. The reductions in the A-weighted 1/3-octave-band sound levels resulting from the tests are presented in Figure 5. The figure shows the cab was not effective at reducing the low frequency sound levels below 400 Hz. This can be expected since the thickness of the partial cab is not sufficient to block low frequency sounds and low frequency components diffract around partial barriers more easily than high frequency components (6). However, Figure 5 shows the partial cab was effective at reducing the sound levels in the 400 Hz through 8000 Hz 1/3-octave bands. Since drilling noise is the most significant contributor to the A-weighted sound level at the operator's location, and drilling noise is dominated by high frequencies (refer to Figure 4), the testing proved that a partial cab could be an effective noise control for non-cab drill rigs. Therefore, a more detailed design for a partial cab was pursued.

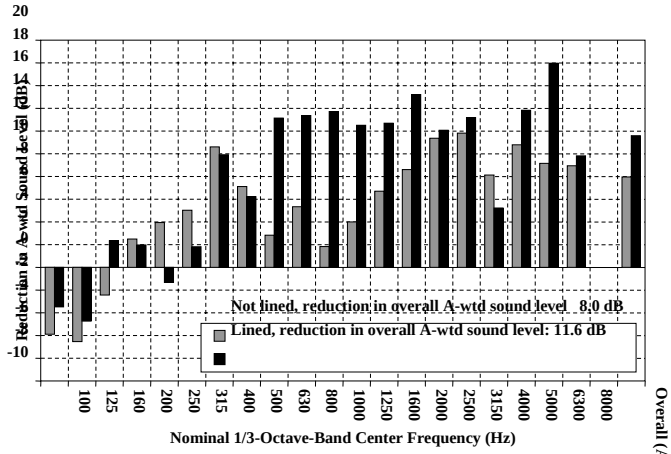

Figure 5. Reduction in A-weighted 1/3-octave-band sound levels with partial cab concept without and with a barrier-absorber lining.

Research and Design for Prototype

Determination of required panels.

Subsequent to the findings discussed above, a new research effort was initiated at PRL to design and fabricate a functional partial cab for installation on a working air rotary rig. The first step in this process was to determine some of the fundamental design characteristics of a functioning partial cab including the number and heights of the sides necessary to substantially reduce the A-weighted sound level at the operator's ear. Since the final version of the partial cab would not consist of a full enclosure, choosing a material with the highest transmission loss was not necessary since the maximum attenuation of a partial enclosure is limited due to flanking paths (7). For convenience, 18-mm-thick plywood sheets were used to form the sides of the structure.

Using the previously described test set up (see Figure 3), a series of tests were conducted at PRL. The test configurations included adding 18-mm-thick plywood panels, which represented the sides of a partial cab, to a wooden framework placed around the microphone. The microphone was placed to the left of the speaker playing the sound recorded near the drill steel. This location was similar to the operator station of several rigs studied earlier by NIOSH. Plywood panels were then added to the faces of the wooden framework. The panels were categorized as front, back, left, right, and top depending on the relationship of the operator facing forward at the operator station. For reference, the panel located between the microphone and rear speaker was the right-side panel (see Figure 6).

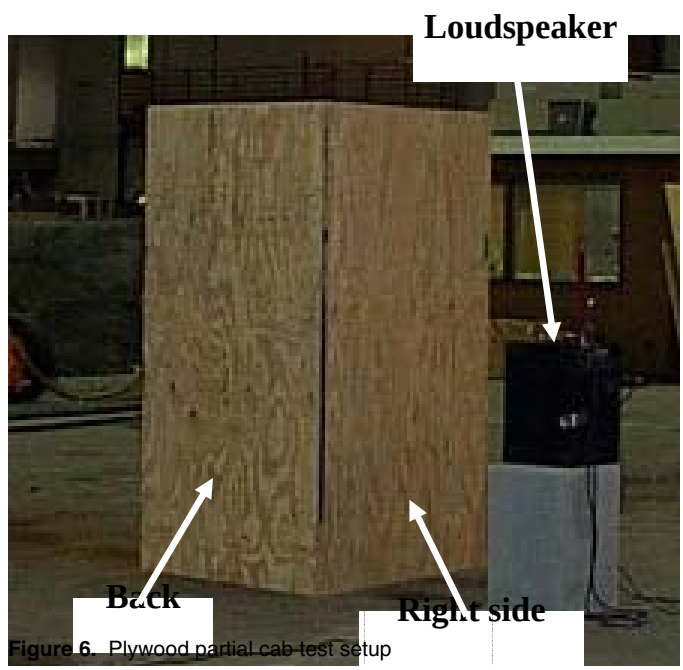

Figure 6. Plywood partial cab test setup

After completing the tests with various heights and sides consisting of plywood (see Figures 7a, 7b, 7c), two additional series of tests were conducted using some of the configurations from the first series of tests in conjunction with a layer of 25-mm-thick urethane acoustic foam attached to the inside surface of the plywood. For one series of these tests, the entire surface of the plywood was covered with foam (see Figure 7d) while the other tests were performed with foam only around the perimeter of each panel, simulating windows. (see Figure 7e).

For this series of tests, the LMS Pimento Octave Acquisition Module was used to measure the A-weighted 1/3-octave-band sound levels in the 20 Hz through 10 kHz 1/3-octave-bands. Using the Octave Acquisition Module eliminated the need to post-process the data. In addition to the microphone signal, the voltages used to drive each loudspeaker were measured to ensure that the noise generated was consistent for each test. At the beginning of each test sequence

the microphone was placed at the operator station without the plywood partial cab and the speaker output was adjusted until the sound pressure level at the microphone was 100 dB.

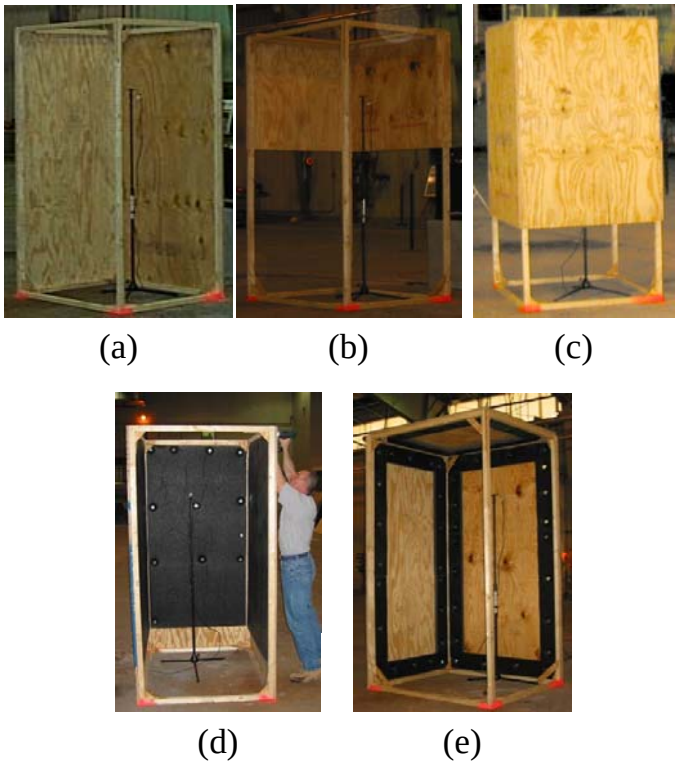

Figure 7. Panel test configuration examples - (a) full height, front and right panels, no foam; (b) shoulder height, front and right panels, no foam; (c) waist height, front, right, top, back, and left panels, no foam; (d) full height, front, left, and right panels, full foam; (e) full height, front, right, and top panels, perimeter foam.

For each sequence of tests, the initial configuration had panels on the front and right (see Figure 7a). A top panel was added for the second configuration. For the third configuration, a panel was added to the back of the frame. Finally, the last test in a sequence had a panel added to the left side (see figure 7c). The first, second, and third test sequences used full height, waist height, and shoulder height plywood panels, respectively. Due to the frame resting on the floor, the full height configuration with panels on all sides formed a complete enclosure. A fourth sequence of tests was conducted with configurations similar to the third sequence using shoulder height panels except that a 0.15-meter-wide L-shaped panel was used in place of a full top panel. Additional test sequences were conducted to evaluate the improvement in the plywood partial cab performance due to using acoustic foam to line the inside surfaces of the structure. Four sequences of tests were conducted with configurations similar to sequences one through four and a few additional variations in the configuration were tested as well. These tests were completed with acoustical foam covering the entire interior surface of the panel ("Full Foam") and with a narrow strip of foam installed around the perimeter of the panels were called "Perimeter Foam". This configuration was designed to simulate a panel with a window in the center. Any of the panels, either with or without a window, could represent a door for operator access to the partial cab. In all, thirty-six configurations were tested.

Figure 8 shows the reduction in A-weighted sound level for the ten best configurations. The full height panels covering all sides of the framework using full interior foam or perimeter interior foam provided the highest attenuation, 22 dB. Full height panels covering the top, front, and right sides with full foam or perimeter foam were the next best configurations (18-dB reduction). The best unlined configuration used full height front and right side panels with a top panel (16-dB reduction). Waist height with top, front, and right panels with full or perimeter foam is the best partial height configuration (12-dB reduction). The unlined, five-sided enclosure reduced the sound level by 12 dB. The unlined configurations approaching a full enclosure had poor results due to the reverberant conditions created within the enclosure. Adding either full foam or perimeter foam to this configuration increased the sound level reduction to 22 dB.

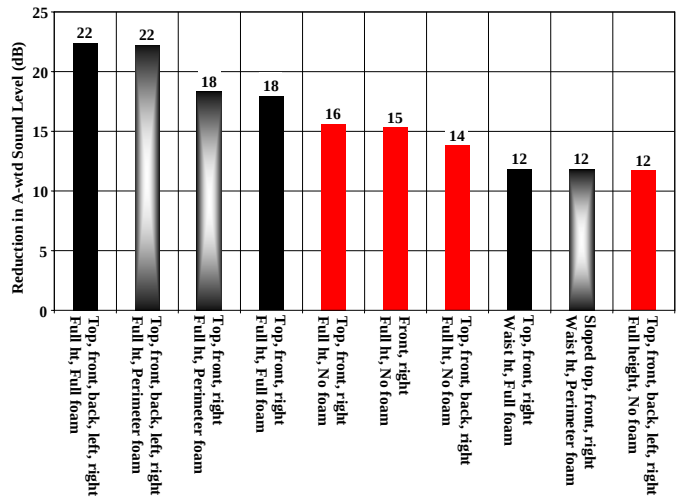

Figure 8. Reduction in A-weighted sound level for the ten most effective cab configurations.

The "3-Sided" configurations (front, top, right) with full height panels seem to be the best compromise between noise reduction and worker mobility. The rear panel and left (or panel opposite the drill steel) would not be installed on the prototype cab. This layout would give the operator protection from direct exposure to sound emitted from the drill steel while allowing the operator free ingress and egress to the enclosure without moving the cab panels. The "Front" panel would include the operator control panel. Additional height or length could be added as needed. Since flanking around the cab would be the limiting factor for attenuation, the transmission loss of the barrier was not as important as its location relative to the drill steel and operator. Even if a barrier with a high transmission loss were used, flanking would limit the maximum attenuation achievable from the partial cab (7).

Aluminum mock-up testing

Based on the findings of the plywood panel tests the overall layout of the cab had been decided. A three-sided enclosure would be the basis for the design. The next step was to determine what materials to use for the prototype design. Clearly plywood was not an acceptable material for a robust design. The panels for the cab to be installed on a working rig would need to be lightweight, strong, and require little maintenance. Also, windows would be necessary for observation of the drill steel and drill mast. Originally, it had been planned to test a variety of materials for the panels. However, the researchers discussed the possibilities and decided to use panels constructed of powder-coated aluminum sheets installed on a steel framework. The powder-coated sheets would provide a lightweight, rustproof, maintenance-free covering for the cab. Steel sheet was also considered. But, after taking into account the potential for rusting and the additional weight, the team decided to rule out using steel sheets. The researchers contemplated using acrylic plastic sheet or polycarbonate thermoplastic for the windows. However, the decision was to use laminated glass for the windows due to its superior scratch resistance compared to the other materials. To support the cab, the researchers chose to use a painted steel framework.

The objective of these tests was to determine how several design choices affected the attenuation provided by a partial cab constructed of aluminum panels attached to a square-tube-frame. An aluminum mock-up cab was constructed and placed on the same wooden framework used for the plywood panel testing. Once again, the test

setup and procedures using the recorded drilling noise played through loudspeakers were followed. An OROS OR38 Multi-analyzer was used for these tests to measure the resulting A-weighted 1/3-octave band sound levels. The goal of this testing was to determine if using two layers of aluminum sheets for each panel would improve the attenuation and to verify that the aluminum sheet with windows installed would provide as much attenuation at the operator station as the plywood panel designs. A three-sided, waist height cab with a single layer of aluminum sheet attached to the outside of the steel frame with no windows or acoustical foam was used for the initial tests (Figure 9a). Further tests on the aluminum mock-up included the addition of acoustical foam, a second layer of aluminum sheet attached to the inside of the steel frame, and windows. A rubber skirt was also added to block reflections from the ground from reaching the microphone (Figure 9b). Since the use of a rubber skirt was not in the original test plan for the aluminum cabs, a roll of rubber floor mat was used. A full length panel was not desirable due to the added weight of the framework and panels. Also, the drill rigs are commonly used on uneven ground. Under these conditions a full length door could hit obstructions and not be usable. For one configuration, acoustic foam was added to the inside surface of the single layer of aluminum. In another configuration, acoustic foam was encapsulated by the layers of aluminum attached to the steel frame.

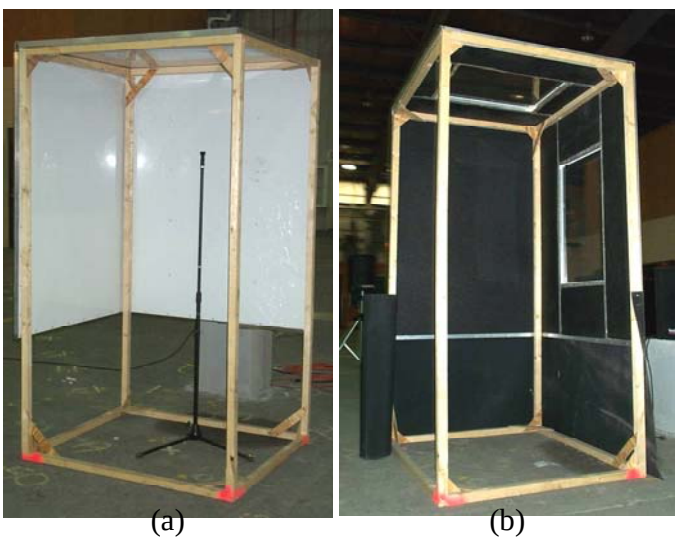

Figure 9. Test arrangement showing (a) three-sided double-layer aluminum cab with no windows or foam and (b) three-sided cab with windows, acoustical foam, and rubber skirt.

In all, eleven aluminum mock-up configurations were tested and the resulting reductions of the A-weighted sound level were determined (see Figure 10). The single-layer and double-layer aluminum with encapsulated foam configurations each provided the lowest attenuation, 8.3 dB. The double-layer aluminum configuration resulted in an attenuation of 8.9 dB. Examination of the results for the single-layered configurations highlights the importance of adding sound-absorbing foam and blocking ground reflections from reaching the operator location. The maximum attenuation, 15 dB, was achieved with the mock-up consisting of a single layer of aluminum lined with acoustic foam and with the added rubber skirt. Adding the rubber skirt to the single-layer, foam-lined configuration improved the sound level reduction by almost 5 dB. Clearly, the partial cab would have to protect the operator from sound which emanates from the hole, or is reflected by the ground. Full length doors were not practical due to the additional weight of the door. Also, since the rig often works in areas with uneven ground, a flexible material was necessary to allow the door to slide without catching on objects at ground level. Several additional configurations were performed to determine if two panes of acrylic sheet would result in a higher sound level reduction than a single pane. A few tests were conducted with a 3-mm-thick pane of acrylic sheet attached to the outside of the frame. More tests were conducted with a 1.6-mm-thick pane of acrylic sheet on the inside of the frame with the 3.2-mm-thick pane of acrylic sheet on the outside of the frame. As Figure 10 shows, the three-sided, single-layer aluminum, waist height configuration with the rubber skirt, using two panes of Acrylic sheet improved the attenuation of the cab by less than 1 dB.

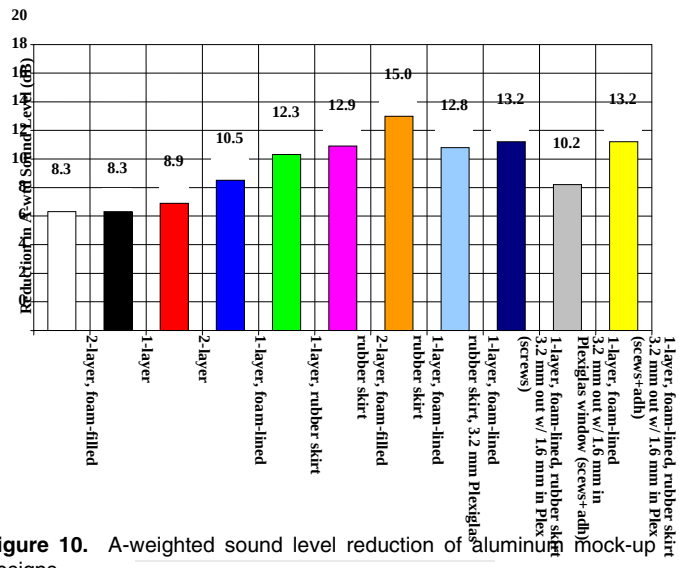

Figure 10. A-weighted sound level reduction of aluminum mock-up designs.

Figure 11 shows the reductions in the A-weighted 1/3-octave band sound levels for the mock-up cab tests. The results for the mock-up were similar to the results observed with the concept design (refer to Figure 5). The aluminum mock-up designs achieved reductions of 10 dB or more in the 1000 Hz 1/3-octave band and beyond. At 125 Hz, the sound level reductions were less than 1 dB. The sound levels were amplified with the mock-ups at 100 Hz and below. However, since the sound level at the operator's station is dominated by high frequencies, a partial cab similar to the aluminum mock-ups should provide a significant reduction in the sound level at the operator's station.

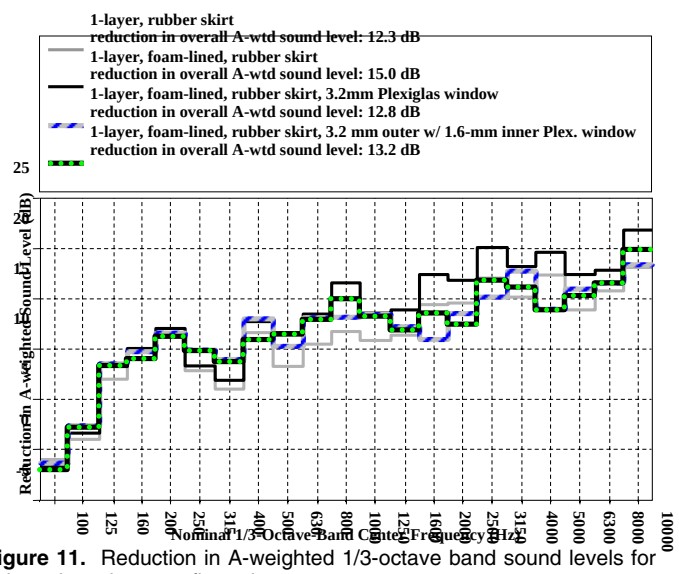

Figure 11. Reduction in A-weighted 1/3-octave band sound levels for selected mock-up configurations.

Based on the mock-up test results, it was concluded that the partial cab prototype would be constructed of a single layer of aluminum attached to a steel frame. Large single-pane windows made from laminated safety glass would be installed on the side of the partial cab facing the drill steel and on the top surface of the partial cab. To

add absorption, acoustical foam would be installed wherever possible around the windows and inside the compartment. A dense vinyl barrier would be hung from the bottom of the partial cab where possible to block noise emanating from ground level. A dense vinyl barrier with a surface mass density of 4.84 kg/m^2 was used instead of the rubber skirt for field testing because the vinyl barrier had a much higher surface mass density. Since the sound transmission loss, which is a measure of a materials ability to block sound, increases with surface mass density, the vinyl barrier would be better than the rubber skirt at blocking noise from entering the bottom of the partial cab (8).

Design and Fabrication of the Prototype Partial Cab

Using the information gathered from the testing above, the design of a working prototype partial cab could begin. The researchers collaborated with a local drilling company which was willing to have the cab installed on one of their production drill rigs. The selected rig was a truck mounted air rotary rig. The rig had an onboard air compressor and would use a second or third skid-mounted air compressor to help flush cuttings when large or deep holes were drilled. The operator station for the selected rig was located to the right of the drill mast (Figure 12). The rig's operators indicated the partial cab should not add any width to the rig or reduce ground clearance. The rig operator commonly needs to access the drill steel and drill deck while standing at the control panel. The operator grabs the drill steel when adding pieces of drill steel to the drill string. The operator also needs to slide the thick steel plate (Figure 12) that is used to tighten or loosen the drill steels. Therefore, the researchers decided the operator must be able to quickly and easily retract the partial cab. Also, depending on the layout of the drill rig, the operator would need to retract the cab so it was not in the way when adding and removing drill bits, or adding drill steels to the drill rig.

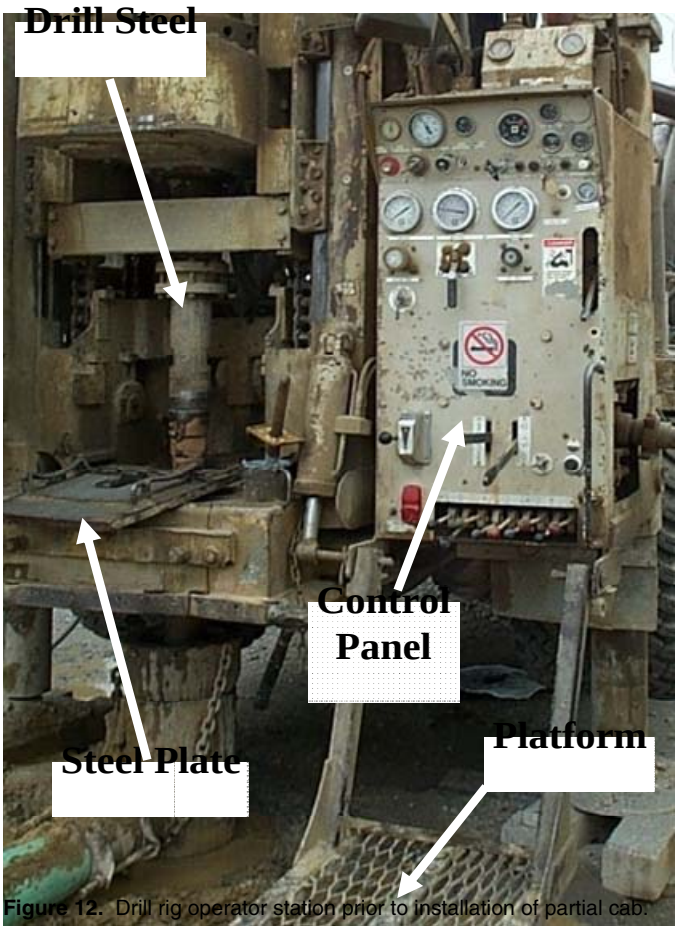

Figure 12. Drill rig operator station prior to installation of partial cab.

After examining the rig in detail it was determined that the basis for the cab would include a sliding canopy covering the left side and top of the operator station. The control panel would make up the majority of the front panel. The cab would be constructed of a one-piece door that would slide between the control panel and the drill platform and over the top of the control panel. The biggest obstacle to overcome was the limited space to the left of the control panel (Figure 13). The distance between the drill mast and control panel was approximately 63.5-mm. This meant the one-piece door would have to be approximately 38-mm in overall thickness to reliably clear any obstacles.

Figure 13. Available clearance between control panel and drill platform (approximately 63.5-mm).

Thorough measurements were taken of the drill rig's control panel and operator platform. The measurements were then used to complete a three-dimensional model of the control panel using a computer-aided design (CAD) program. Using the model, the design for the partial cab was completed (Figure 14). The design of the cab consisted of a one-piece cantilevered door constructed from 25.4-mm steel tubing and covered with 1-mm thick aluminum sheet. The door would be supported on a 25.4-mm steel tubular framework added to the drill rig's control panel. The door would slide forward and backward using liner bearings. Laminated glass windows measuring were added to the door on the top and sides. Where necessary, areas of the support framework would be covered with aluminum sheet to block direct paths from the drill steel to the operator. All available surface area inside the partial cab would be covered with acoustical foam to reduce reflected noise. The existing supports for the operator platform would be modified to make room for the door between the control panel and drill mast.

Arrangements were made with the drilling company to have the drill rig available at PRL for one week for installation of the partial cab. Prior to the rig's arrival, the majority of the components for the cab were constructed. After the rig was delivered to PRL, the components were fitted to the machine and final fabrication was completed. Components were then painted and installed. The one-piece door was then taken to a local glass shop for installation of the laminated glass. When the door returned, the final steps, including adding aluminum to the support framework and control panel, were finished. An acoustic barrier made from a dense filled vinyl-based polymer was added to the bottom of the door and control panel (Figure 15).

The cost of materials for the partial cab was less than 10% of the estimated cost of purchasing a complete operators cab from the manufacturer. The total material cost and material list is included in Table 1. The cab was installed at no cost to the drilling company collaborating with NIOSH for this project. The estimated design and fabrication time for the project was approximately 200 personnel-hours. The door and support framework was constructed of steel tubing. All welding was completed using a MIG wire feed welder. All construction materials were readily available from either on-line or local suppliers. The most expensive components for the cab were the precision guide blocks and guide rails which support the cab and allow it to move. These rails and bearing blocks need to be strong enough to support the entire weight of the cantilevered door estimated at 75 kg. The amount of time required to design and fabricate the NIOSH partial cab was adversely affected by the limited availability of the rig for

measurement and fabrication. A complete CAD model would not be required when constructed by the rig owner/operator. The cab could be designed and built during rig down-time and as time allowed during drilling operations. Using this method of design and fabrication the rig operator could install an effective partial cab without appreciable labor cost. The owner/operator could also save additional capital by choosing to install a partial cab without the retractable functionality requested by the company partnering with NIOSH for this research.

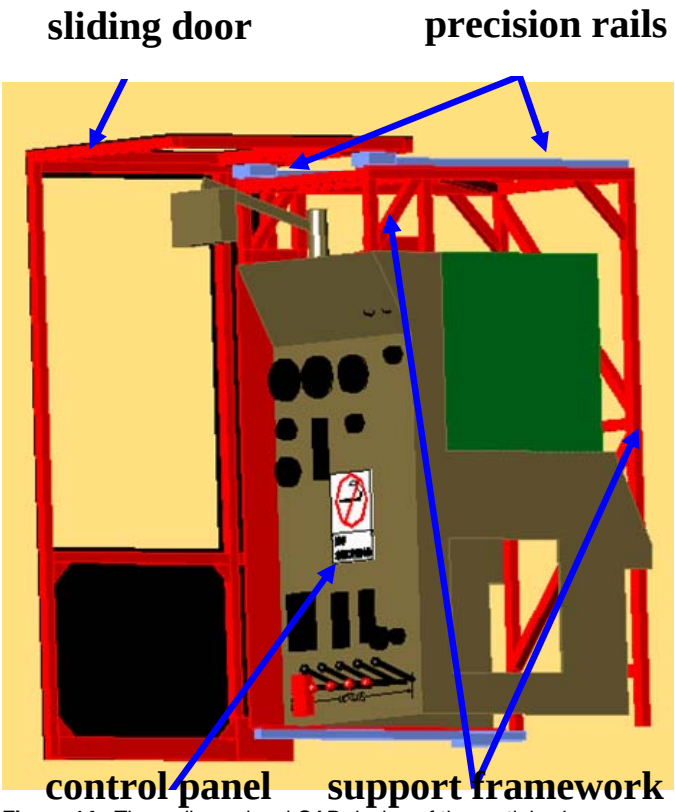

Figure 14. Three-dimensional CAD design of the partial cab.

Field Testing of the Prototype Partial Cab

After the partial cab had been successfully installed on the drill rig, researchers evaluated the attenuation provided by the cab under actual drilling conditions. While the testing completed at PRL was conducted in an area approximating a free-field environment, the conditions surrounding the drill rig during operation can vary greatly. The rig that the cab was installed on was primarily used to drill holes into underground mines for utility access or methane degassing operations. The rig would travel into both remote locations and mine operation yards. In remote locations the surrounding area resembled a free-field condition unless the rig was located near a high wall. When located on mine property sites the rig could be in a more complex acoustic environment having multiple reflections due to the presence of buildings and other large pieces of machinery. However, even in these locations, the researchers believed the partial cab would still reduce the sound level at the operator's station. The direct sound waves being emitted from the drill steel were expected to overshadow any noise reflected from the surroundings.

The researchers followed the drill rig to a variety of locations and performed both sound pressure time history and noise dosimetry measurements. The sound pressure measurements were later post-processed to determine the A-weighted sound levels in 1/3-octave bands. Much of the field testing was similar to an earlier investigation involving sound pressure measurements, dosimeter recordings, and time-activity study of four different air rotary drill rigs with mounted cabs (9). Two types of sound measurements were taken at each field site during this early investigation. One focused on the exterior sound pressure generated by the rig during hammer drilling, the loudest sound levels during hole development. The other measurements focused on the operators noise exposure during hole development. This prior research showed a factory installed full cab could substantially reduce the A-weighted sound levels at the operator's ear when properly used. Researchers observed a 17-dB reduction in the A-weighted sound level with the OEM cab. Furthermore, for drill rigs designed with the operator control panel adjacent to the drill steel, simply opening the OEM cab's door facing the drill steel would increase the A-weighted sound level by 15 dB, indicating the barrier blocking the direct sound waves between the drill steel and the operator is very important for this style of rig (10). During the field research associated with the partial cab the sound pressure levels at the operator's platform were measured to show the attenuation in sound level provided by the partial cab at the operator station. Noise dosimetry was conducted to review the impact of the partial cab on the drill operator's noise dose.

Figure 15. Completed partial cab installed on the drill rig.

While evaluating the partial cab in the field, sound pressure measurements were performed by placing Bruel & Kjaer 4188 microphones near the operator's left and right ears while the rig was hammer-drilling (Figure 16). An LMS Pimento portable data acquisition system was used to record the time waveforms of the microphone signals at a sample rate of 25,000 samples per second with 16-bit resolution. The sound pressure generated by the drilling process varies due to several factors including drilling depth, the hardness of the material that is being drilled, and whether an auxiliary compressor is being used to expedite drilling. Due to these variables, the overall A-weighted sound levels vary from measurement to measurement leading to differences in the attenuation of the partial cab. To account for this variability, several sets of sound pressure recordings were made with the partial cab pulled out to protect the operator and pushed in to the storage/transport (or unprotected) position. Three 15-second sound pressure recordings were made with the cab pulled out to block the direct path from the drill steel to the operator. Then, the partial cab was pushed back into its retracted position and three additional 15-second recordings were collected. The recordings for each set of measurements with the partial cab out and in were completed within a few minutes of each other to ensure

the drilling conditions had not significantly changed. A total of three visits were made to field sites resulting in nine sets of recordings.

Table 1. Material list with pricing for the partial cab installed by NIOSH.

Item	Unit	Quantity	Unit Cost	Total Cost
25-mm-thick square steel tubing	m	24	$5.00	$120.00
1-mm-thick aluminum sheet	Each	2	$100.00	$200.00
25-mm-thick open cell acoustic foam	m^2	1	$30.00	30.00
6-mm-thick laminated safety glass	m^2	0.8	$220.00	$176.00
3-mm-long rivets	Box	1	$15.00	$15.00
15-mm wide, 820-mm long precision rails	Each	2	$220.00	$440.00
57-mm length precision guide blocks	Each	2	$100.00	$200.00
Bellows cover for rails	Each	2	$45.00	$90.00
4.84 kg/m^2 Dense vinyl barrier	m^2	1.7	$20.00	$34.00
	TOTAL			**$1,305.00**

The recorded data was post processed to calculate the overall A-weighted sound level and the A-weighted sound levels in 1/3-octave bands. For each set of measurements, the average A-weighted sound level and 1/3-octave-band sound levels were calculated for the measurements with the cab pulled out (protecting the operator) and with cab pushed in (not protecting the operator). The attenuation was computed by simply taking the difference in the average sound levels for each set of measurements. The partial cab attenuated the A-weighted sound level by 5 to 9 dB at the operator's left ear and by 2 to 5 dB at the operator's right ear when used while hammer-drilling. Figure 17 shows a comparison of the A-weighted sound levels in 1/3-octave bands with the cab pushed in (operator not protected) and with the cab pulled out (operator protected) for one set of measurements. The data indicates that the partial cab reduces the sound levels by more than 10 dB at 1000 Hz and above. This is similar to the results from the mock-up testing conducted at PRL (refer to Figure 11).

The reduction in the overall A-weighted sound level using the installed partial cab was less than the reduction seen in the lab for the mock-up. Several possibilities for the lower reductions include the following. The recordings used for the mock-up testing were for a different drill rig and likely generated a slightly different spectrum than the rig the partial cab was tested on. For the lab tests, the noise emanates from only two locations which cannot replicate the full sound field around a drill rig which consists of many distributed noise sources. Additionally, the drilling noise does not come from a point location such as a speaker, it radiates from the entire drill steel, which is 12-m long, as well as the drill mast. Reflections from surrounding equipment at a drill site result in additional paths for sound to reach the operator. Finally, the partial cab installed on the rig did not have the same dimensions as the mock-up cab. Since the operator did not want the cab to block his access to the drill steel in any way, the depth of the door had to be reduced. The mock-up cab had a depth of 18.9-cm while the door for the cab installed on the drill rig was limited to a depth of 11.22-cm.

The attenuation achieved by the partial cab will be dependant on the drilling conditions as well as the environment surrounding the rig. For this rig, the A-weighted sound levels at the operator station increased by 3 to 5 dB when the auxiliary air compressors were turned on. The increased amount of air helps flush drill cuttings from the hole and causes the pneumatic hammer on the bottom of the drill string to impact harder, which in turn increases the noise emitted by the drill string.

Figure 16. Sound pressure measurements at operator's ears.

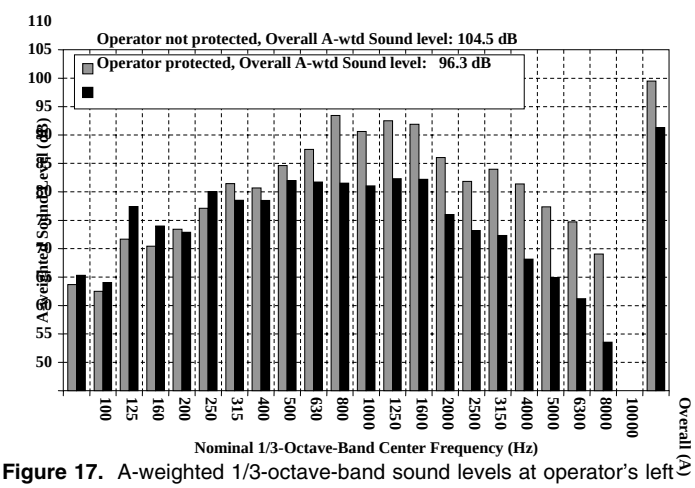

Figure 17. A-weighted 1/3-octave-band sound levels at operator's left ear when not protected and protected by the partial cab.

Further data collection and analysis was performed to assess the potential reduction in operator noise dose due to use of the partial cab. Two Larson Davis Spark dosimeters were used to measure the operator's noise exposure. During the initial visit to record the sound pressures using the LMS Pimento, dosimeters were placed on the left and right shoulder of the operator. Time-motion data for the operator was collected using a personal digital assistant (PDA) while observing the operator for several hours. The collected data indicates the partial cab has the potential to significantly impact the noise dose for the operator. Figure 18 shows the A-weighted equivalent continuous sound level (LEQ) in 5-second increments for twenty minutes of the dosimetry data. The data presented here was collected while the operator stood on the operator's platform while the rig was hammer-drilling. The figure indicates the A-weighted LEQ at the operator station while the operator is protected by the partial cab was approximately 90 to 93 dB at the operator's left ear and 91 to 94 dB at the operator's right ear. The levels increase dramatically twice during

the observations. The first increase, which was approximately 7 dB for the operator's left ear, occurred when the operator leaned around the partial cab toward the drill steel, exposing the left dosimeter microphone and the left side of his head to the noise radiated by the drill steel. The second increase, which was approximately 4 dB, occurred because the operator was asked to push the partial cab in while the data were collected for the unprotected position. Additionally, the data show the LEQ at the operator's left ear is typically lower than the LEQ at the right ear when the partial cab is pulled out to protect the operator from drilling noise. When the partial cab is pushed in to the storage, or unprotected, position the sound level is higher at the operator's left ear than at the right ear. For the protected position, the sound level at the right ear may be higher than the sound level at the left ear for several reasons. First, sound radiated from the drill string or other noise-generating components on the rig, such as the engine and cooling fan, could be flanking the partial cab and reaching the right ear. Secondly, sound waves could be reflecting from objects surrounding the drill rig and reaching the operator's right ear.

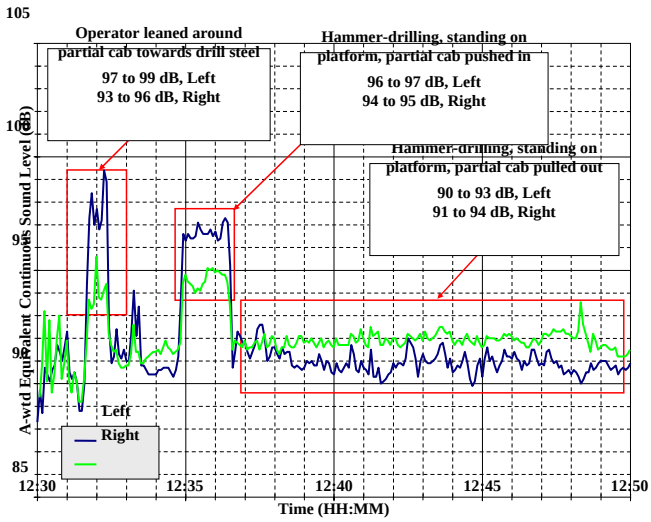

Figure 18. Five-second, A-wtd LEQ from dosimetry data for operator's left and right ear.

After examining the time-motion and dosimetry data, the team decided to add an additional side to the partial cab to reduce the levels at the operator's right ear. A removable partition constructed of overlapping clear vinyl noise barrier strips was added. Once again, the sound pressures at the operator's left and right ear were recorded using Bruel & Kjaer 4188 microphones and the LMS Pimento portable data acquisition system and post-processed to calculate the A-weighted overall sound level and 1/3-octave-band sound levels. Two recordings were made without the clear barrier followed by two recordings with the clear barrier. After approximately 20 minutes had passed, two additional recordings were made with and without the clear barrier. Analysis of the hammer-drilling data showed the sound level reduction due to adding the clear barrier was less than 1 dB for the left hear. However, the clear barrier provided a 2 dB sound level reduction at the right ear (see Figure 19).

Conclusions

Laboratory tests were conducted using recorded drilling noise played through loudspeakers to determine the required number and size of panels for a partial cab for an air-rotary drill rig. The data showed that a three-sided mock-up constructed of full height aluminum sheets, steel tubing, and acrylic sheet could reduce the A-weighted sound levels by approximately 13 dB. A partial cab fabricated using aluminum sheets, safety glass, steel tubing, acoustic foam, and vinyl barrier was attached to an air-rotary drill rig. Field testing showed that using the partial cab reduced the A-weighted sound levels at the operator's left ear and right ear by 5 to 9 dB and 2 to 5 dB, respectively. The sound levels in the 1000 Hz 1/3-octave band and above were reduced by more than 10 dB with the partial cab protecting the operator. Adding a clear barrier to the right side of the partial cab increased the sound level reduction at the operator's right ear by 2 dB.

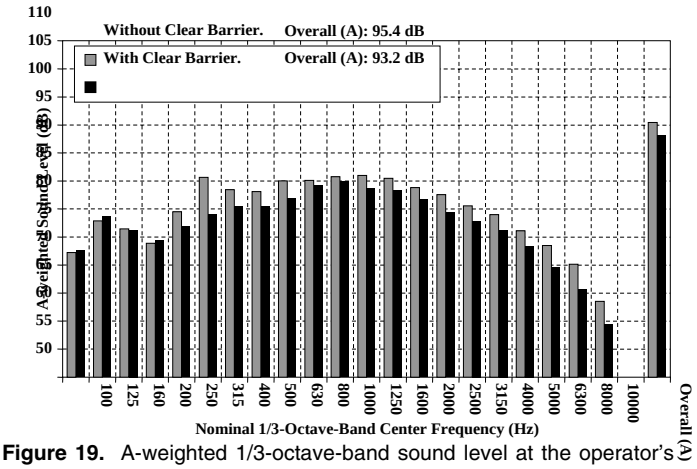

Figure 19. A-weighted 1/3-octave-band sound level at the operator's right ear without and with a clear barrier added to the right side of the partial cab.

In order to be effective at reducing noise and to be accepted by the operator, the partial cab must be small, lightweight, durable, and easy to use. The NIOSH cantilever design of the partial cab can be applied to many of the drill rigs with the operator station located adjacent to the drill mast. For other styles of drill rigs an effective partial cab can be installed by following the basic design principles discussed earlier. The partial cab installed by NIOSH was well received by the drilling company and the cab is still in place on the rig after more than a year. An effective partial cab can be installed for a small cost when compared to the cost of installing an OEM cab. Materials for the partial cab installed by NIOSH were estimated at $1,300. The estimated cost of adding an OEM cab to a drill rig is $20,000 according to a rig manufacturer. The cab can be fabricated and installed by the rig owner/operator, or by a local welding and fabrication shop. Additionally, the partial cab does not limit the maneuverability of the drill rig for use in tight locations, and adds limited weight to over the road drill rigs.

Commercially available full cabs can provide high reductions in sound levels. However, their initial cost, added size, added weight, and limited operator access make OEM cabs unattractive to many drill rig operators. The partial cab is an effective compromise for drill rig operators and owners who want lower sound levels at the operator station while maintaining the flexibility and maneuverability of their drill rig.

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