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A control suite to reduce roof bolting machine drilling noise

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Among underground coal miners, hearing loss remains one of the most common occupational illnesses. In response, the National Institute for Occupational Safety and Health (NIOSH) conducts research to reduce the noise emission of various underground coal-mining equipment, an example of which is a roof bolting machine. Field studies support the premise that, on average, drilling noise is the loudest noise that a roof bolting machine operator would be exposed to and contributes significantly to the operators' noise exposure. NIOSH has determined that the drill steel radiates a significant amount of noise during drilling. NIOSH, in collaboration with Corry Rubber Corporation and Kennametal, Inc., has developed a suite of controls to reduce drilling noise which consists of a bit isolator, chuck isolator, and a collapsible drill steel enclosure. This control suite effectively reduces the noise radiated by the drill steel. Laboratory testing confirms that the control suite reduces sound pressure levels generated during drilling by 13 dB(A) at the operator's location. As a result of this reduction in drilling noise, the noise exposure of the roof bolting machine operator is significantly reduced.

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1 INTRODUCTION

Hearing loss is one of the most common occupational illnesses in the United States[1]. As such, hearing loss prevention is one of twenty-one Priority Research Areas listed in the National Institute for Occupational Safety and Health (NIOSH) National Occupational Research Agenda[2]. In the mining industry, hearing loss is an even more serious issue— it is 2.5-3 times greater than what is expected for the average of the population that is not exposed to occupational noise. Additionally, the same NIOSH studies have shown that by the age of 50, 90% of coal miners have a hearing impairment versus only 10% of the population not exposed to occupational noise[3]. Department of Labor Mine Safety and Health Administration (MSHA) noise sample data collected from 2000 to 2005 show that only seven types of machines compose the bulk of the equipment whose operators exceed 100% noise dosage per the MSHA Permissible Exposure Level (PEL). Of these machines, the roof bolting machine (RBM) operator was the second-most likely to be over-exposed among operators of all equipment used in underground coal mining[4].

A roof bolting machine is a large, electrohydraulic machine used to temporarily stabilize the mine roof while installing roof bolts to support it after coal has been extracted. To install the bolts, the roof bolter drills holes into the mine roof using 25 or 35 mm diameter drill bits attached to drill steels with either hexagonal or round cross-sections (Fig. 1). The lengths of the drill steels normally vary from approximately 0.3 meters to 1.5 meters, or longer combinations thereof, depending on the mine and its roof conditions. After a hole is drilled, a roof bolt is inserted into the hole to secure the overlying strata, thereby supporting the roof. To spread the load across the roof, roof bolts are inserted through a steel plate prior to inserting the bolt into the roof. Fig. 2 shows a roof bolting machine in an underground coal mine.

Prior underground time-motion studies confirmed that RBM operators are exposed to the highest noise levels when drilling as opposed to bolting, tramming, and other tasks associated with their typical work day[5]. Therefore, an essential part of developing noise controls to reduce the occurrences of Noise Induced Hearing Loss (NIHL) for RBM operators is to find ways to reduce drilling noise. Prior research has shown that much of the noise from percussive rock drilling originates from bending vibrations in the drill rod[6-7]. NIOSH measurements coupled with beamforming analysis on the rotary drilling system used on RBMs found that the highest sources of drill steel noise were near the chuck and the drill bit[8].

Therefore, in order to meet our overall objective to reduce an operator's noise exposure to a time-weighted average (TWA) of 90 dB(A) or less for an eight hour shift per the MSHA PEL, NIOSH researchers developed a suite of controls to target drilling noise along the drill steel. These include bit isolators, chuck isolators, and a collapsible drill steel enclosure (CDSE).

2 TEST SETUP

All testing was conducted outdoors in free field conditions on a Fletcher model HDDR RBM drilling into granite. NIOSH used granite as the drill media to represent a high compressive strength roof and because of its homogeneity, which helps ensure test repeatability. A large steel stand was used to support the granite drill media, which was isolated from the stand by sheets of urethane. Additional design considerations to reduce the radiation of sound energy included filling several members of the support stand with sand[9].

Sound pressure levels (SPL) were measured using a Brüel & Kjær (B&K) PULSE data acquisition system and a B&K Type 4188 microphone, positioned at the operator's right ear location. Ambient noise levels were insignificant since they were over 10 dB below all SPLs measured with the roof bolter running. The roof bolter was run at a thrust of 12.6 kN and set at an average rotation speed of 230 RPM. These are the typical settings we use for drilling harder materials such as granite[9], since the higher rotation speeds and thrust settings used for coal would quickly dull the bits for this media. Drilling was conducted with 1.2 m (4 ft) long hex drill steels and 35 mm (1 3/8”) bits. A new bit was used for each hole to ensure measurement repeatability and data were taken for 30 seconds of drilling. Each configuration was measured three times and the results were averaged. The bit and chuck isolators were tested separately and in combination with each other and the CDSE to determine the improvement over the baseline configuration.

3 BIT AND CHUCK ISOLATORS

3.1 Bit and Chuck Isolator Design

The NIOSH bit and chuck isolators were developed in collaboration with Corry Rubber Corporation and Kennametal, Inc. to reduce the noise sources found near the drill bit and chuck in previous studies[8]. They consist of inner and outer steel members machined out of 4130/4140 steel and heat treated to 350 BHN that are isolated from each other by a layer of 75 durometer Shore A natural rubber (Figs. 3 and 4). This durometer was chosen because the fatigue life of the rubber was a concern. The 75 durometer elastomer is bonded to the inner steel member, pre-compressed, and assembled into the outer steel member. A post-vulcanization (PV) bond attaches the elastomer’s outer surface to the inner surface of the outer steel member. This type of “pre-compressed bonded joint design” has the advantage of improved durability since the pre-compression of the rubber ensures that the elastomer never goes into tension during operation.

The bit and chuck isolators are similar in design, except for having slightly different geometry in their steel components to connect to the chuck, drill steel, and bit. The bit isolator has one end machined to mate with a standard 35 mm (1 3/8”) drill bit and the other is machined the same as a standard drill steel coupling such that a bit isolator can fit on top of the drill steel. For the chuck isolator, one end is machined to the same dimensions as the bottom of a hex drill steel in order to fit into the chuck, and the other is the same as a standard drill steel coupling so a drill steel will fit on top of it.

An 11.4 mm gap exists between the inner steel component where it begins to neck down and the edge of the outer steel member. This is to protect the elastomer from overload since the outer sleeve will bottom out on the inner member shoulder at about 45 kN, thus allowing loads above this threshold to be reacted by the steel components.

Design requirements for the 35 mm isolator are summarized as follows:

1. Max torque: 410 N-m
2. Max axial load (thrust load): 35 to 45 kN
3. Isolator metals will bottom out at 11.4 mm deflection or approximately 45 kN thrust load
4. Preliminary life requirement: 2 weeks to 1 month of continuous operation
5. Estimated static axial stiffness (for noise attenuation): 2,600 kN/m to 5,200 kN/m
6. Estimated torsional static stiffness (for noise attenuation): 6.8 to 20.3 N-m/deg.

All of the above requirements have been met for the bit and chuck isolators. Maximum torque and axial loads were determined from the maximum torque and thrust outputs a typical roof bolting machine can provide. The life requirement was chosen to be at least as long as that of an average drill steel. The stiffness requirements were developed from testing the material properties of earlier prototype bit and chuck isolators that were successful at reducing noise[8].

3.2 Discussion of Bit and Chuck Isolator Results

As shown in Fig. 5, the bit isolator is effective at reducing noise above 1.25 kHz, but increases A-weighted SPLs in the 800 Hz – 1.25 kHz ⅓-octave bands. This yields an overall reduction in A-weighted SPL at the operator's ear of 4 dB. There is little to no reduction in the low frequencies because the RBM noise from the electric motor, hydraulic system, and vacuum dominates the noise in this range, making low frequency noise reductions difficult to achieve. Previous studies have shown that noise from these systems is prominent at the 1 kHz octave band and below[10].

As seen in Fig. 6, the chuck isolator causes slight improvements over the entire frequency range, again with the exception of the 800 Hz – 1.25 kHz ⅓-octave bands. Overall it yields a 2 dB improvement from baseline in A-weighted SPL at the operator's ear. While not as effective at reducing noise as the bit isolator, the fact that it reduces some lower frequency noise suggests that it could be used in combination with the bit isolator to gain even greater SPL reductions from the baseline configuration.

Combining the bit isolator and chuck isolator (Fig. 7), roof bolter noise at the operator's ear location is lowered by a total of 5 dB(A) from baseline. As was the case with the bit isolator and chuck isolator on their own, the ⅓-octave bands that were improved were mainly in the range from 1.25 to 10 kHz, with degradation from 800 Hz to 1.25 kHz.

4 CDSE

4.1 CDSE Design

An additional noise control is the CDSE, which serves as a barrier to block noise radiated by the drill steel from reaching the operator's ear. It consists of a bellows with a spring to support it, a hinge that allows the CDSE to move out of the way for roof bolt installation, a cap to help the CDSE seal against the roof, and customized mounting hardware to install the CDSE onto a specific RBM (Figs. 8 and 9).

The bellows is made of 0.864 mm-thick aluminum-coated fiberglass and has an extended length of 1.22 m, but lengths may vary depending on the specific needs of the application. Aluminum-coated fiberglass was chosen due to its heat resistance, ability to block noise, resistance to acids, oils, corrosive vapors, and many solvents, and its incombustibility.

Each CDSE bellows is supported by a straight cylindrical compression spring which keeps the bellows upright and collapses as the drill chuck of the roof bolter rises during drilling. The spring is made of zinc-plated steel wire 0.635 cm in diameter with a load of 303 N. The outside coil diameter is 15.82 cm, but again this could be varied for specific applications.

The top of the CDSE is made of PVC 203 mm in diameter and 31.8 mm thick. A conical ultra high molecular weight polyethylene (UHMW-PE) insert into a bottom made of 6061 aluminum accommodates either 25 mm or 35 mm drill steels as shown in Fig. 10. The funnel-like shape of the insert guides the drill steel into place in the chuck. A hinge connects the roof bolter chuck to the bottom of the CDSE.

Before drilling, the operator installs a drill steel through the top of the CDSE and into the chuck. At the beginning of the drilling cycle, the CDSE is fully extended. A gap between the cap and the roof allows the operator to see the drill bit-to-media interface and start the hole. The gap can be designed to the operator's preference to make the drill steel visible for a longer portion of the drilling cycle, but a larger gap will result in less noise reduction. As the drill chuck rises, the gap closes until the cap is flush with the roof, as in Fig. 9. The CDSE then collapses as drilling continues. When drilling is completed, the operator swings the CDSE to the side and installs the roof bolt as usual.

4.2 Results Using the CDSE

Previous testing has shown that the CDSE alone gives a 7 dB(A) reduction in SPL at the operator's ear from baseline[11] and reduces roof bolter drilling noise by 6 dB(A) during an operator's 8-hour time-weighted average in the field[12]. In combination with the bit isolator, it yields a 12 dB reduction in A-weighted SPL at the operator's ear location as shown in Fig. 11 and the results summary in Table 1. These improvements are seen in the ⅓-octave bands from 250 Hz to 10 kHz. The advantage of the bit isolator and CDSE combination is that there is no degradation from baseline in the range between the 800 Hz – 1.25 kHz ⅓-octave bands as is characteristic with the bit and chuck isolators on their own. Combining the bit isolator, chuck isolator, and CDSE provides one more dB(A) of reduction for a total of 13 dB(A) less than baseline. However, adding the chuck isolator to the bit isolator and CDSE combination does add back in the noise in the 200-400 Hz ⅓-octave bands.

5 FURTHER DEVELOPMENTS WITH BIT AND CHUCK ISOLATORS

Realizing that fatigue life of the metal components— rather than the elastomer layer separating them— is the limiting factor with the chuck and drill bit isolators, the research team found that a pre-compressed bonded joint design was not necessary to meet life requirements. Further, the variability in bond strength, concentricity, and stiffness inherently associated with these types of designs could be improved upon by using a fully-bonded design. Reducing this process variation would ensure that the load-carrying requirements of the isolators would consistently be met. Therefore, the bit and chuck isolator designs were modified to incorporate chemical bonds created during the molding operation (Figs. 12 and 13). To create them, metal components are sandblasted, degreased, phosphatized, and coated with Chemlok® adhesive prior to vulcanization to yield high bond strengths between the elastomer and metal components.

Additional studies with the new fully-bonded designs have been completed to optimize the durometer of the bit and chuck isolators[8], which should yield even greater noise reductions in the field than those discussed previously. An initial series of sound power level measurements were taken per ISO 3743-2 at the NIOSH Office of Mine Safety and Health Research Reverberation Chamber, located in Pittsburgh, Pennsylvania. Measurements were taken while drilling into granite for 30 seconds, and three runs for each configuration were averaged. The total length from the chuck to the drill bit was kept constant for this test at 1.2 m (4 ft) to eliminate potential differences in vacuum and drill steel noise radiation, and a new 35 mm (1 3/8") bit was used for each hole. Rotation speed was kept constant at 230 RPM, with a thrust of 2.2 kN (500 lbs). Since we wanted to prove the concept first, we chose a lower thrust for this study to avoid potential mechanical failure of the lower durometer isolators while testing. Three different durometers of bit isolator were tested: 58 durometer natural rubber, 50 durometer butyl rubber, and 68 durometer natural rubber.

All bit isolators tested showed a clear trend of noise reduction above the 630 Hz ⅓-octave band, with the lower durometer materials providing more reduction in sound power than the higher durometer materials (Fig. 14). The 50 durometer butyl rubber bit isolator provided the greatest reduction in A-weighted sound power level, which was 6 dB. This is significant because it suggests that the bit isolator alone could yield a SPL reduction of up to 6 dB(A) at the operator's ear. As discussed earlier, the highest sources of noise on the RBM is drilling noise at the drill steel interface to the chuck, and at the top of the drill steel near the bit. The operator is positioned close to these noise sources, so changes from baseline in overall SPLs at the operator's right ear location should be quite similar to changes in overall sound power levels.

Using this same logic, the combination of bit and chuck isolator could improve from a current reduction in A-weighted SPL of 5 dB up to 9 dB. As seen in Fig. 15, testing the best bit isolator (45 durometer) from a previous study[8] in combination with a 50 durometer butyl rubber chuck isolator yielded an overall reduction in sound power of 9 dB(A). Other combinations of bit and chuck isolator durometers may obtain even better results.

6 CONCLUSIONS

Each noise control reduces roof bolter drilling noise on its own, as summarized in Tables 1 and 2. The single most effective noise control presented herein is the collapsible drill steel enclosure (CDSE). The bit isolator, chuck isolator, and CDSE reduce overall A-weighted sound pressure level (SPL) at the operator's ear location by 4, 2, and 7 dB, respectively. In order to meet the MSHA Permissible Exposure Level (PEL), a combination of two or more controls may be necessary. Combining the bit and chuck isolators yields a total reduction of 5 dB(A) in overall SPL. The combination of two controls that is most effective is to combine the bit isolator and CDSE for an overall reduction of SPL by 12 dB(A). However, if a 13 dB(A) reduction is needed, all three controls may be combined. These reductions in sound pressure levels under controlled laboratory conditions may be less if drilling into softer materials when testing in the field. New developments in bit and chuck isolator designs focusing on durometer optimization for the elastomer show promise for even greater noise reductions.

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Table 1 – Summary of operator's right ear A-weighted sound pressure level results.

Configuration	**Overall SPL, dB(A)**	**ΔdB from Baseline**
Baseline	106	—
75 Durometer Bit Isolator	102	4
75 Durometer Chuck Isolator	104	2
Bit Isolator and Chuck Isolator	101	5
Bit Isolator and CDSE	94	12
Bit Iso, Chuck Iso, and CDSE	93	13

Table 2 – Summary of A-weighted sound power level results.

Configuration	**Overall Sound Power Level, dB(A)**	**ΔdB from Baseline**
Baseline	114	—
68 Durometer Natural Rubber Bit Isolator	111	3
58 Durometer Natural Rubber Bit Isolator	109	5
50 Durometer Butyl Bit Isolator	108	6
45 Duro NR Bit Iso & 50 Duro Butyl Chuck Iso	105	9

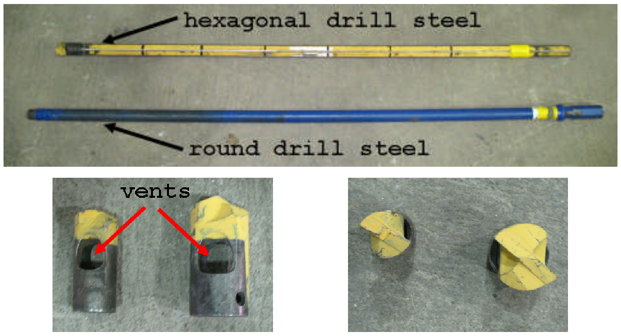

Fig. 1 – Hex and round drill steels for a 35-mm diameter drill bit (upper) and two examples of drill bits – 25 mm and 35 mm (lower).

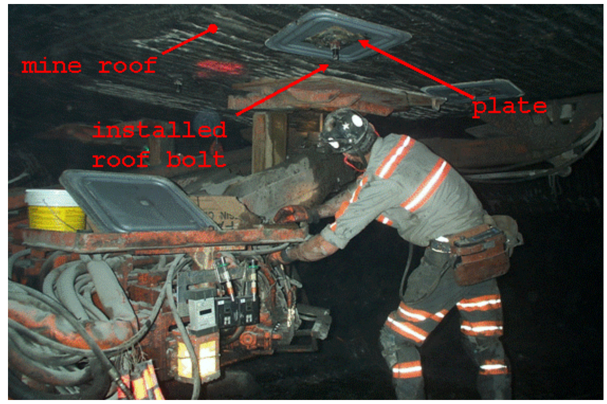

Fig. 2 – A roof bolting machine in an undergroundcoal mine.

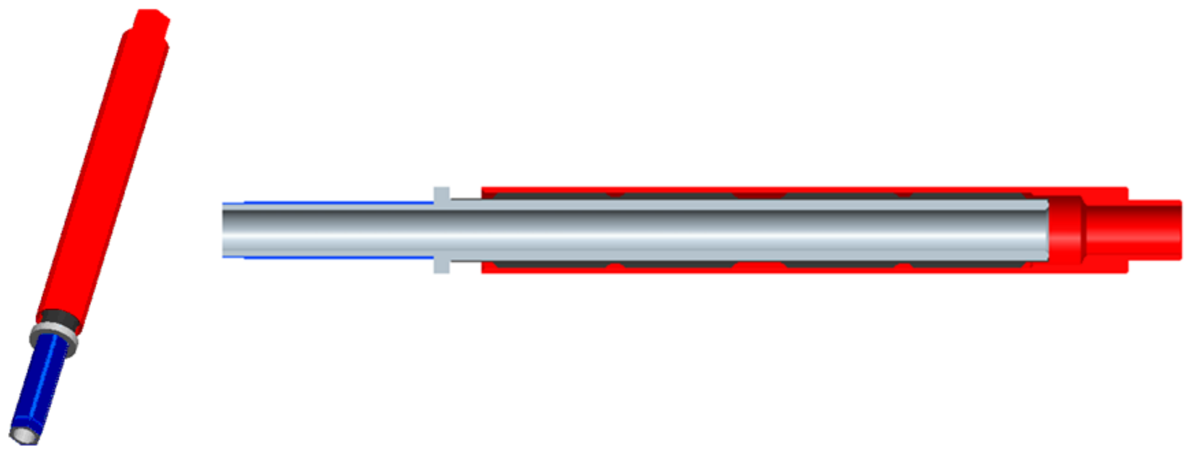

Fig. 3 – Model of bit isolator design. The blue color indicates the inner member, red indicates the outer steel member, and black indicates the elastomer layer.

Fig, 4 – Picture of bit isolator design, two units disassmbled.

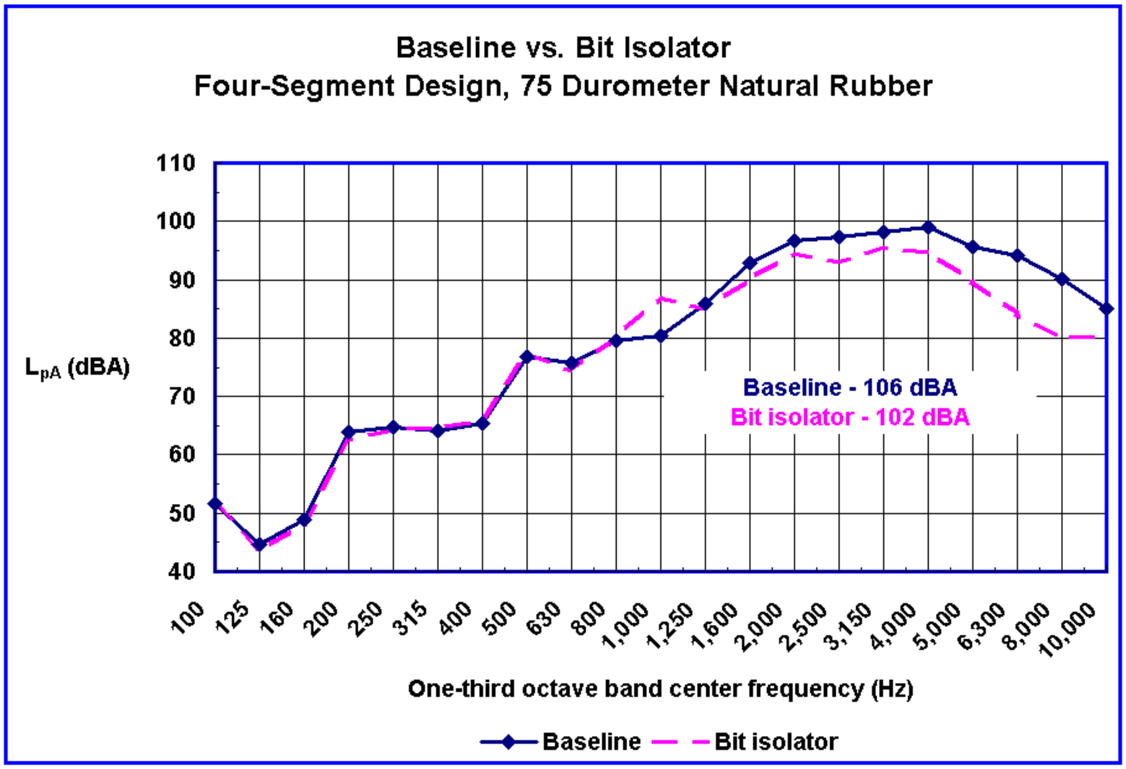

Fig. 5 – A-weighted SPL in ⅓-octave bands for baseline vs. the bit isolator.

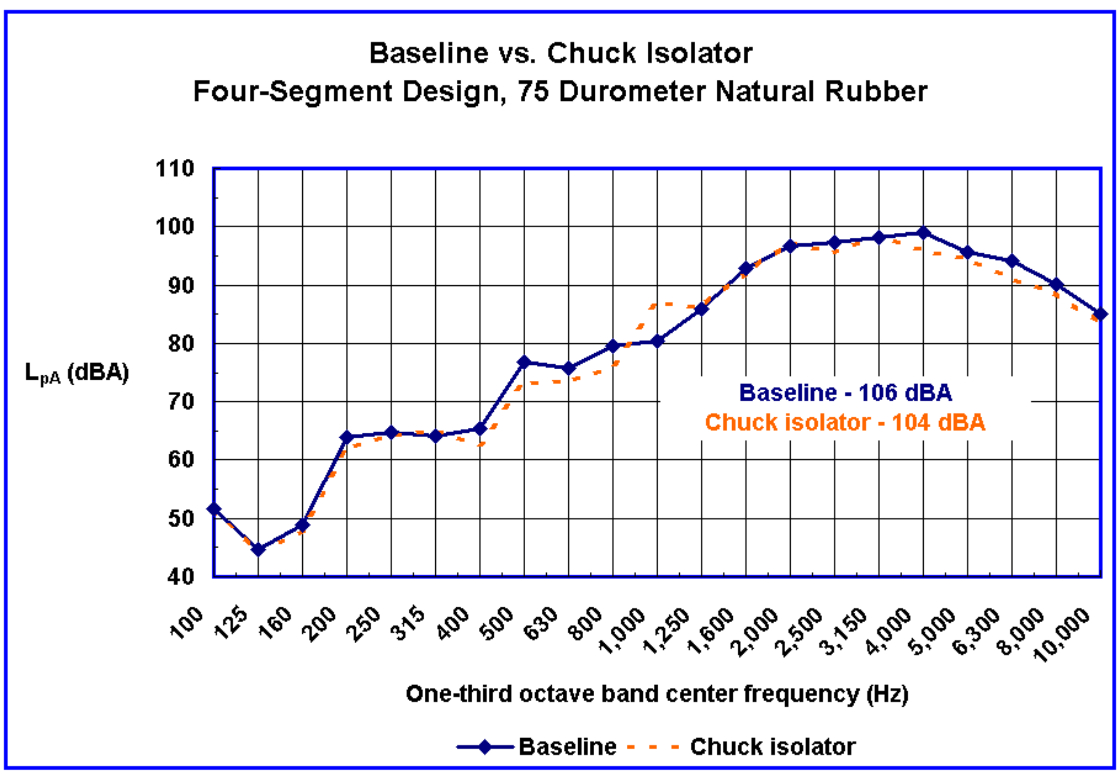

Fig. 6 – A-weighted SPL in ⅓-octave bands for baseline vs. the chuck isolator.

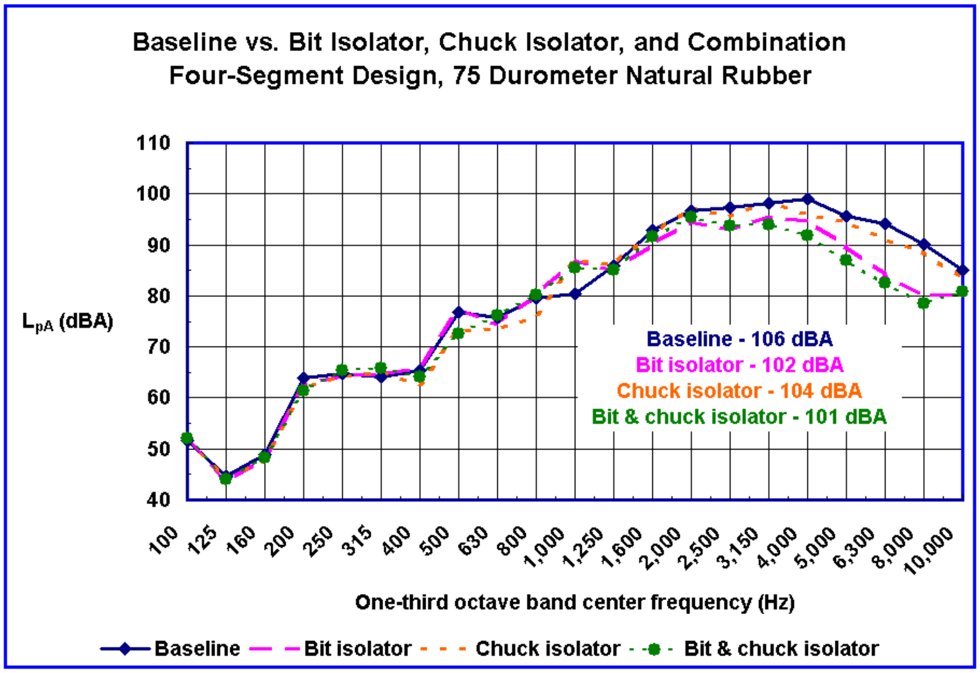

Fig. 7 – A-weighted SPL in ⅓-octave bands for baseline vs. the bit isolator, chuck isolator, and combination of bit and chuck isolator.

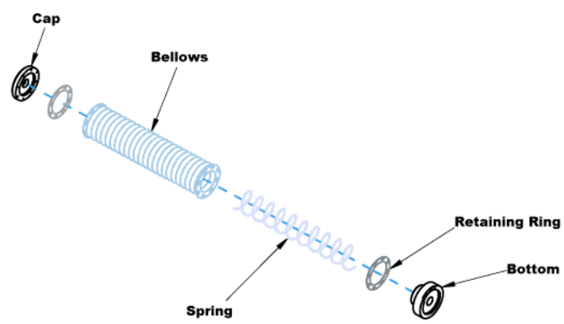

Fig. 8 – Exploded view of the CDSE.

Fig. 10 – Bottom of the CDSE, showing the conical UHMW-PE insert used to guide the drill steel into place when attaching it to the chuck.

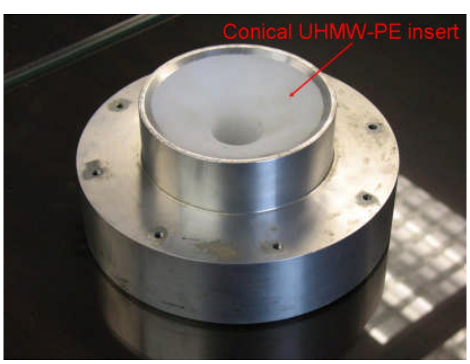

Fig. 9 – The CDSE installed on a roof bolting machine. At this point in the drilling process, the drill chuck has been raised far enough that the top of the CDSE has come into contact with the mine roof.

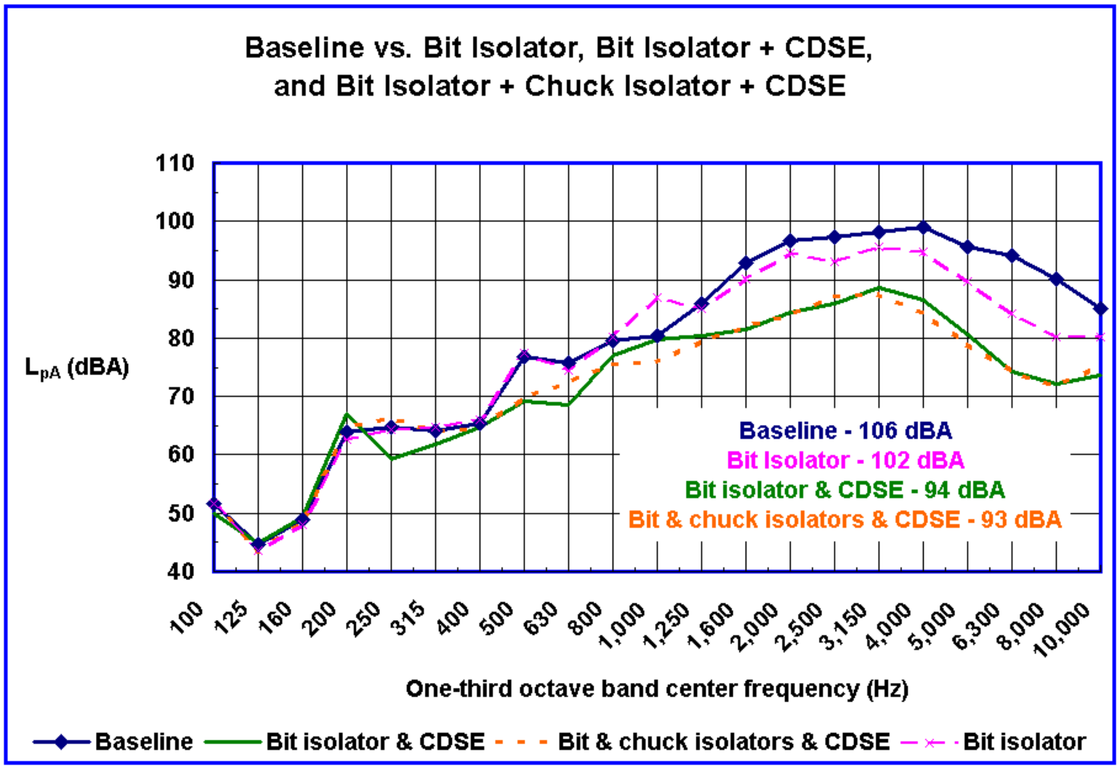

Fig. 11 – A-weighted SPL in ⅓-octave bands for baseline vs. the bit isolator, bit isolator combined with the CDSE, and combination of bit isolator, chuck isolator, and CDSE.

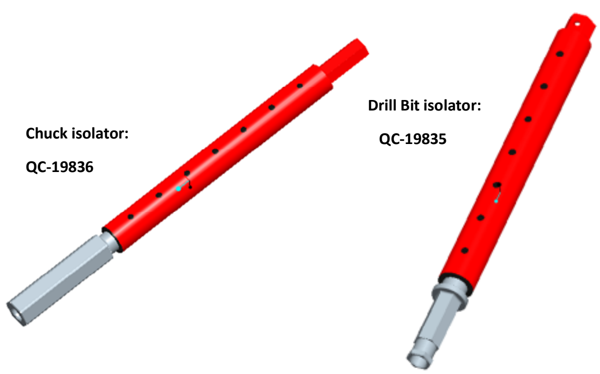

Fig. 12 – Final production designs of chuck and bit isolators for use with 35 mm-diameter drill bits. The gray color indicates the inner member and red indicates the outer member.

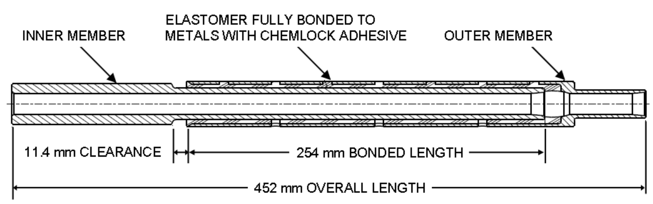

Fig. 13 – Cross-section of production design chuck isolator.

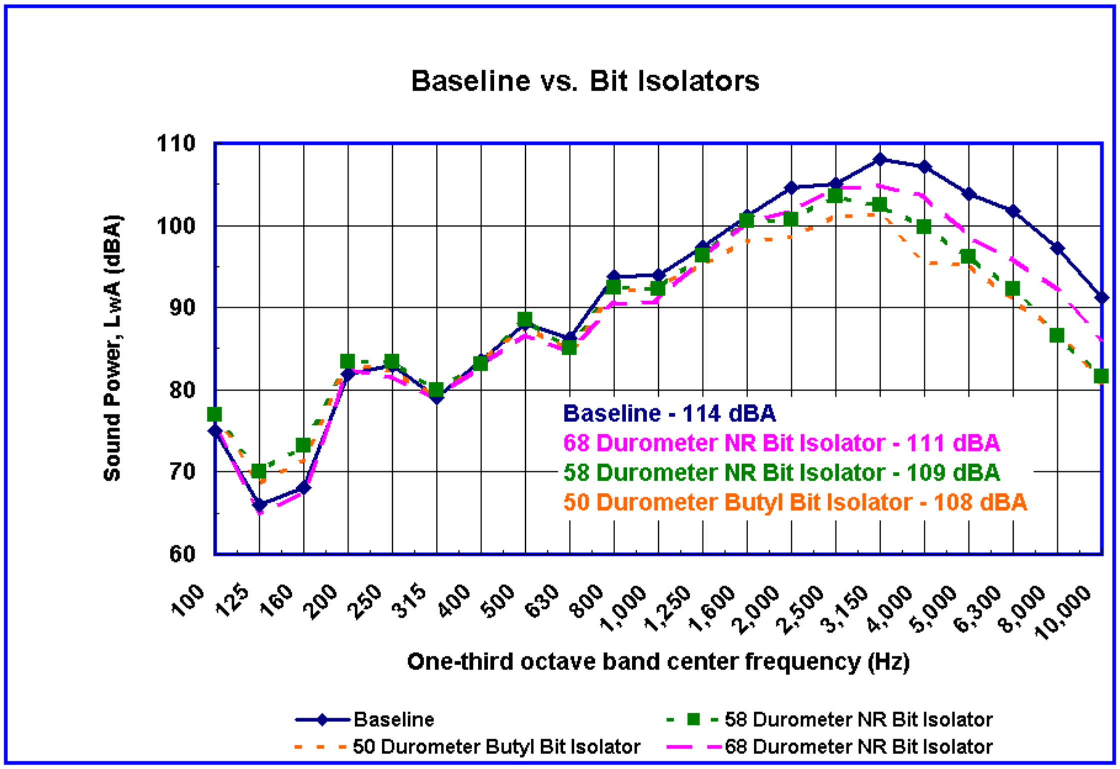

Fig. 14 – A-weighted sound power level in ⅓-octave bands for baseline vs. 50, 58, and 68 durometer bit isolators. The 68 and 58 durometer isolators are made of natural rubber, while the 50 durometer isolator is made of butyl.

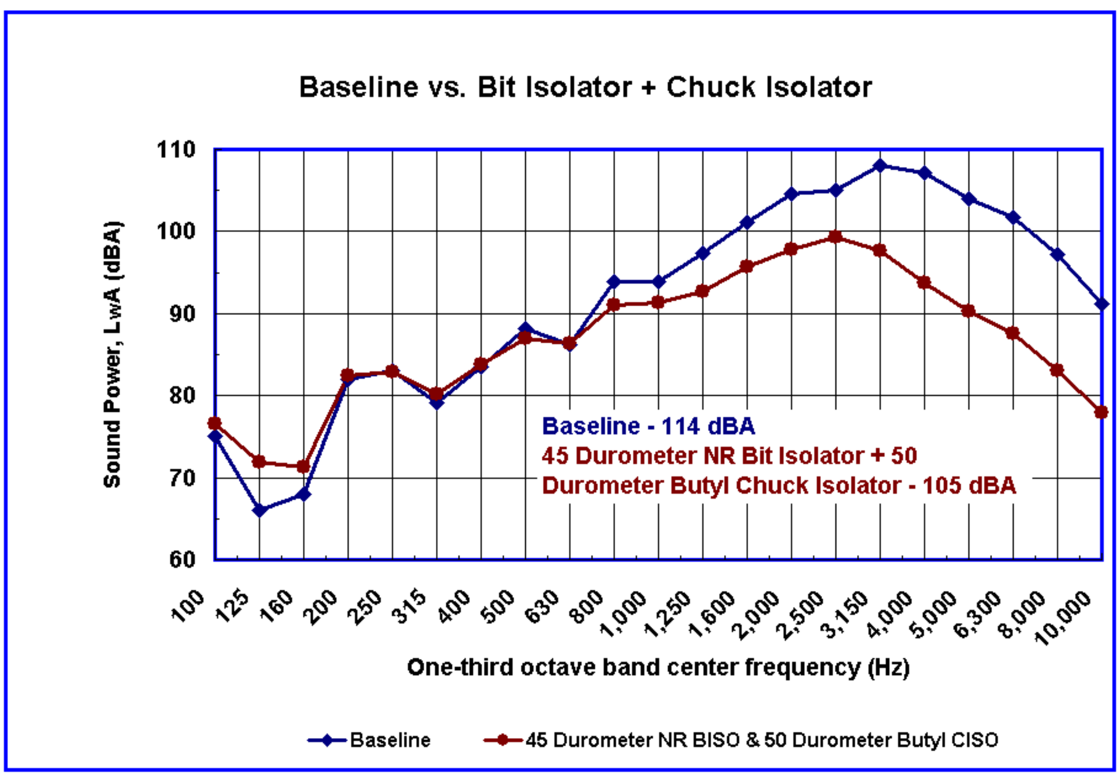

Fig. 15 – A-weighted sound power level in ⅓-octave bands for baseline vs. 45 durometer natural rubber bit isolator with a 50 durometer butyl chuck isolator.