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Laboratory evaluations of a redesigned collapsible drill steel enclosure to reduce noise from roof bolting machines

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ABSTRACT

Roof bolting machine (RBM) noise is a significant health hazard in underground coal mining because the sound levels at the operator's station often exceed 100 dB(A). Drilling the hole prior to installing a roof bolt is the most significant source of RBM operator noise exposure. Vibrations along the drill still generated by the bit-rock interface are the dominant noise source of the roof bolting machine. Researchers at the National Institute for Occupational Safety and Health (NIOSH) have developed an enclosure to surround the drill steel as it drills the hole to reduce the noise reaching the machine operator. The collapsible drill steel enclosure, or CDSE, is designed to collapse upon itself as the drill steel is further advanced into the mine roof so that the drill steel can remain enclosed during the entire hole-drilling process. Past NIOSH studies found this device to be effective at reducing noise exposure of the operator by 5-7 dB. However, the prototype was deemed unacceptable by the mining industry for various usability and durability issues. This paper describes a new design of the CDSE which is more acceptable because of improved operator usability and durability in harsh underground mining conditions. Laboratory testing of the redesigned CDSE at NIOSH's Office of Mine Safety and Health Research (OMSHR) revealed a noise reduction of 3-4 dB.

1. INTRODUCTION

Hearing loss is a significant health concern in the mining industry. A recent study involving the analysis of over 1 million audiograms found that the mining industry exhibits the highest prevalence of hearing loss of all industries surveyed.[1] Despite recent advances in noise control technology and hearing protector implementation, underground coal miners still exhibit the second highest rate of noise exposure of all industry sectors.[2] In fact, the underground coal mining sector has the highest self-reported rate of hearing loss.[3] A variety of factors contribute to the high hearing loss rates in this industry: Loud machinery, tight working quarters, extended shifts, and the need for clear communication exacerbate the noise exposure of the typical underground coal miner. Certain types of machinery are louder and therefore more hazardous to the operator. Mine Safety and Health Administration (MSHA) data[4] indicates that roof bolting machine operators have the second highest rate of noise overexposure of all underground coal machine operators. According to the Bureau of Labor Statistics, nearly 4,000 roof bolting machine operators are employed in underground coal mining.[5] To reduce noise-induced hearing loss in the mining industry, effective noise controls must be developed, evaluated, and implemented. To this end, this paper discusses both a prototype and an improved, redesigned version of a collapsible drill steel enclosure to reduce noise from roof bolting machines.

2. BACKGROUND

Roof bolting machines (RBMs) are used to drill and install roof bolts in specific, predetermined areas of an underground coal mine. Roof bolting is necessary to maintaining safe operating conditions. The purpose of this activity is to attach the multiple levels of rock strata to each other to prevent roof falls after the coal has been extracted. When the coal is removed from a section of a mine, the remaining rock above that area is vulnerable to collapse. A roof bolting machine operator will enter that section with the RBM to drill holes at a predetermined depth and spacing, and then install roof bolts into these holes. This process involves the use of drill bits, typically consisting of a steel body with a carbide insert brazed into the tip. The bit is placed on the end of various lengths of round or hexagonal drill steels to drill the bolt hole. After the hole is drilled the roof bolt is installed. There are multiple methods by which the roof bolt can be installed, each appropriate for specific mining conditions A roof bolting machine operator will perform the drilling and bolting action many times throughout a typical shift.

The roof bolting machine operator is exposed to various noise sources throughout the shift. Past research by the National Institute for Occupational Safety and Health (NIOSH) has shown that the vibration of the drill steel during the drilling part of the cycle is the dominant noise source.[6] The portion of the drill steel directly below the bit and the portion near the chuck interface are the primary noise-radiating areas.[7] The design of most RBMs requires the operator to stand in close proximity to the drilling and bolting mechanism; therefore the operator is at an increased risk for acquiring noise-induced hearing loss.

In response to this problem, the NIOSH Office of Mine Safety and Health Research (OMSHR) Hearing Loss Prevention Branch has developed several noise controls for the RBM drilling operation. One such control is the collapsible drill steel enclosure (CDSE). The CDSE is essentially a cylinder constructed of collapsible material that is placed over the drill steel as a barrier to the drilling noise. At the start of drilling, the CDSE is fully extended. As the boom of the RBM is raised to drill into the mine roof, the CDSE will collapse, allowing it to remain in use for the duration of each drilled bolt hole. During the course of OMSHR’s research into RBM noise exposure, two versions of the CDSE have been constructed: a prototype and a redesigned CDSE.

A. Prototype Collapsible Drill Steel Enclosure

The prototype collapsible drill steel enclosure as seen in Figure 1a was constructed of a round aluminum-coated fiberglass bellows with a spring enclosed inside the bellows. These materials were chosen for several reasons: Fiberglass serves as a good barrier material and is non-flammable. The aluminum coating resists moisture absorption which prevents decay of the material. Furthermore, acids, oils, and other corrosive agents that might be found in underground mines would not permeate the device. The fiberglass bellows was 1.905 cm (0.75 inch) thick with an outside diameter of 19.865 cm (7.8 inches). Details of the construction and evaluation of this device have previously been published.[8, 9, 10]

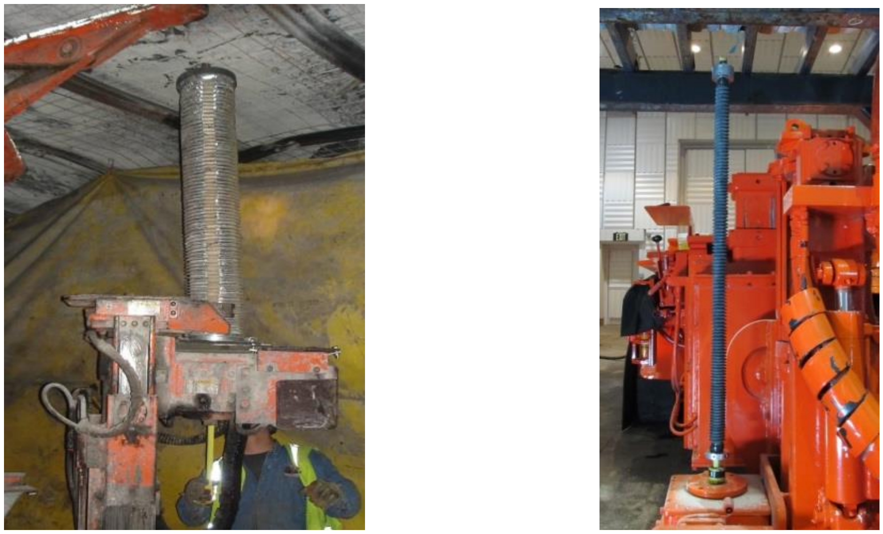

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Figure 1: a) Prototype CDSE installed on a roof bolting machine in an underground coal mine. b) Redesigned CDSE installed on a roof bolting machine in the NIOSH OMSHR hemi-anechoic chamber.

Laboratory evaluations of this prototype device successfully demonstrated a 5-7 dB reduction[8] in sound power level when drilling in granite in the OMSHR National Voluntary Laboratory Accreditation Program (NVLAP) accredited reverberation chamber. Noise dosimetry and time-motion studies determined that the 8-hour time-weighted average exposure was reduced from 97 to 91 dB(A) through use of the CDSE.[11]

Although the CDSE prototype was successful at reducing noise emitted during the drilling process, certain inherent design issues called into question its practicality for prolonged underground use. First, the design itself was bulky. It was designed to attach to the drill head with a hinge which allowed it to be pivoted out of the way when installing the roof bolt into the mine roof. Thus, when the device was installed on the RBM and a hole was not actively being drilled, it was flopped onto its side, lying across the ground while still attached to machine. This posed a potential tripping hazard and monopolized space in the typically tight quarters of an underground coal mine. Further, because of the attachment to the drill head, the drill steel had to be inserted into the chuck through the center of the CDSE. Therefore it was cumbersome to the operator to manipulate the device and complete the roof bolting tasks. Although the aluminum-coated fiberglass was water-resistant, the material did not hold up well under multiple uses. After one full shift of CDSE use underground, the material developed multiple small tears and it appeared that it might unravel or pull away from the inner spring. Last, the relatively large diameter of 19.865 cm (7.8 inches), compared to a drill steel size of 25-mm or 35-mm diameter(1 or 1.38 inch),did not allow for the RBM operator to see the drill steel as it advanced into the mine roof. Importantly, RBM operators pay attention to any bowing of the dill steel as a potential safety indicator—too much bow can cause the drill steel to snap. Without the ability to see the drill steel, the operators could not tell the amount of bow. This again was a potential safety hazard.

B. Redesigned Collapsible Drill Steel Enclosure

To address the problems outlined above, a new design of the CDSE was developed. It was necessary to find a more durable, yet flexible, material. It was also desirable for the bellows to ride close to the drill steel so that any bowing could be seen. Additionally, a slimmer device would take up less space in the confined area where roof bolting takes place.

After investigating various barrier materials and methods to connect to the RBM, a new design was developed by an OMSHR technician. Figure 1b shows the device installed on a RBM inside of the OMSHR hemi-anechoic chamber. Figure 2 shows the disassembled components of the redesigned CDSE. The bellows (Figure 2a) is made from a tube of pure elastomer formed into a flexible hollow tube. This durable material is manufactured from neoprene, buna, butyl, viton, silicone, and Goralon® and is water-resistant. The inside diameter of the bellows is 2.54 cm (1 inch) which allows for 0.315-cm (1/8-inch) clearance around the drill steel when using a 1inch drill bit/steel combination, enabling it to easily move up and down and allowing the operator to see any bowing in the drill steel. The material can be manufactured to any desired length to fit various applications. The bellows used for this evaluation was 122 cm (48 inches) fully expanded and can compress to 27.3 cm (11 inches).

The CDSE top and bottom sections that slide over the drill steel are constructed of aluminum. Spring-loaded ball bearings are threaded into both the top and bottom pieces 60 degrees apart to hold the device in place while allowing it to slide down the drill steel as the hole is drilled. The top section (Figure 2b) of the CDSE consists of a round body with a flange to attach to the bellows and a permanently lubricated bearing that is pressed into the housing. It also consists of a cone-shaped piece with a flange that is pressed into the bearing which allows the cone to contact the roof and remain stationary while the bearing housing, bellows, and the bottom section rotate with the drill steel. Figure 2e shows the disassembled pieces of the top section with the inner bearing (indicated by black arrow) displayed. The bottom section (Figure 2c) is a simple round disc with a flange to hold the bellows, also incorporating spring-loaded ball bearings to couple the bottom of the enclosure to the drill steel. Figure 2d shows the ball bearings inserted into the bottom section (indicated with black arrows) as well as a loose, of-the-shelf ball bearing for illustration purposes. These spring-loaded ball bearings allow easy insertion of the CDSE onto the drill steel and, when stacked steels are used, allow it to transition from one drill steel to another. After a hole is drilled, the top section is manually pushed back to the top of the drill steel ready for the next hole.

The redesigned CDSE addresses the three main constraints of the prototype model. It is smaller and takes up less space when not in use, the material is less likely to become damaged from normal use, and it allows the operator to see any bowing of the drill steel while drilling. An additional benefit due to the redesign is that the CDSE can remain on the drill steel when the drill steel is removed from the machine. Rather than inserting the drill steel into the CDSE connected to the RBM before drilling each hole, the redesigned CDSE remains on the drill steel for the entire process. It is not used when the bolt is installed, so it can be used regardless of bolting method. This factor eliminated the connection hinge and improves storage of the CDSE when a hole is not actively being drilled or when the bolt is being installed. More importantly, it eliminates the extra step required to use the prototype version, further simplifying the correct implementation and increasing the likelihood of acceptance of the redesigned CDSE by the machine operator.

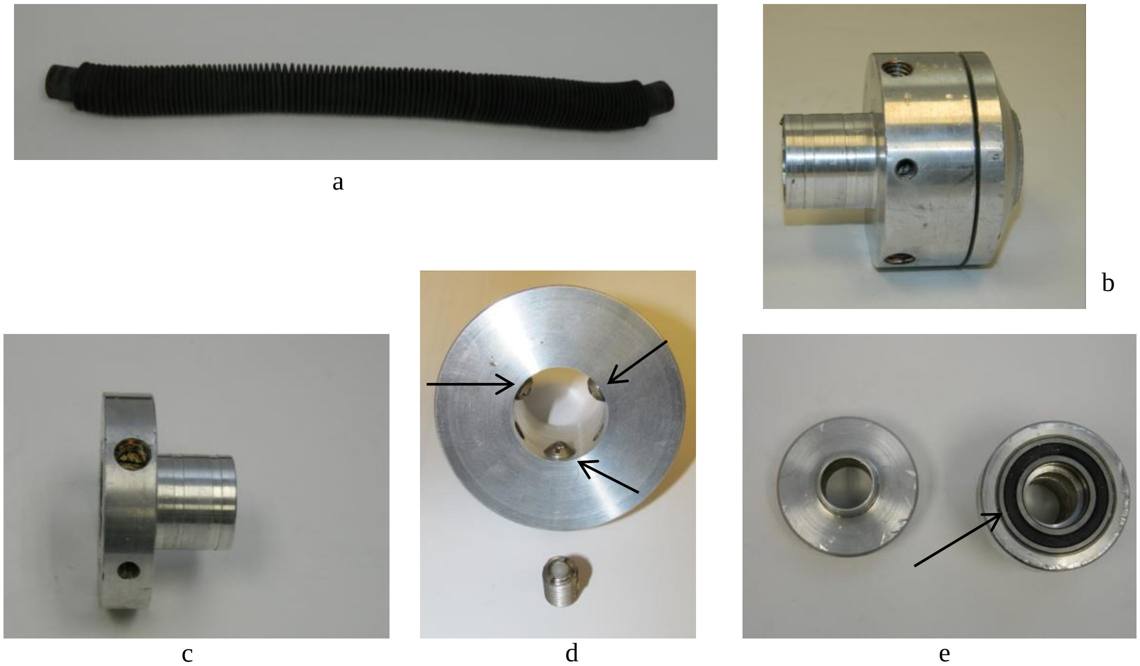

Figure 2: Disassembled redesigned collapsible drill steel enclosure a) Extended bellows. b) Top section that contacts mine roof. c) Bottom section which couples the CDSE to the drill steel. d) Spring loaded ball bearings inserted in bottom section. e) Disassembled top section revealing bearing which allows for rotation.

3. LABORATORY MEASUREMENTS

Laboratory testing of the redesigned CDSE design was conducted in the OMSHR hemi-anechoic chamber. This chamber has interior dimensions of 16.8 m x 10.1 m x 6.4 m, and has a cutoff frequency of 200 Hz. Noise source identification was conducted with a 2.5-meter-diameter acoustic array provided with 84 microphones. The data was then processed using a conventional frequency domain beamforming algorithm. One-third octave band sound pressure level data was acquired using a Larson Davis LxT sound level meter located at the position of the operator's ear.

Testing was conducted using a Fletcher DR S/N 2013317 roof bolting machine. The measurements were taken while drilling into a granite block held in place by a custom-built steel support apparatus. Granite was used as the drilling media to represent a hard roof and consistent compressive strength (24,000 psi). The rotation was set to 325 RPM and thrust set to 3,500 lbs. A new drill bit was used for each hole to further reduce potential test-to-test variability from worn, dull drill bits. Hexagonal drill steels 22 mm (0.87 inch) in diameter were used to drill with 25-mm (1-inch) bits. The drill steels were 122 cm (four feet) in length, and were almost entirely enclosed within the CDSE when it was fully extended. Three 30-second sound level measurements were taken and averaged for drilling with the various configurations representing the potential ways the device may be installed: baseline, CDSE fully extended, CDSE half-extended at the bottom, and CDSE half-extended at the top as shown in Figure 3. The half-extended conditions were tested to assess the difference in performance with a partially covered drill steel vs. a fully enclosed drill steel for potential use in specific mining conditions.

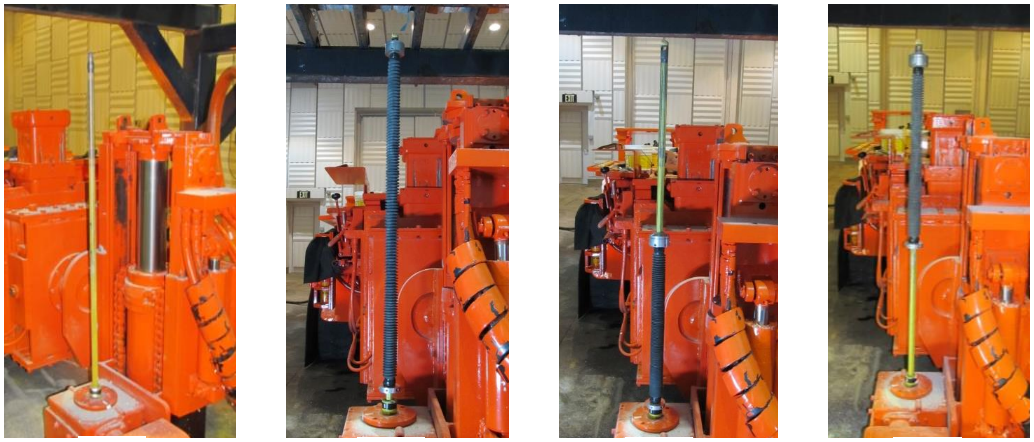

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Figure 3: CDSE installed on a roof bolting machine in the OMSHR hemi-anechoic chamber. Four configurations are displayed: a: baseline (no CDSE), b: fully extended, c: half-extended at the bottom, d: half-extended at the top.

4. RESULTS

The A-weighted sound pressure level at the operator's ear position for baseline drilling in granite was 99.5 dB(A). Drilling with the CDSE installed reduced the A-weighted sound level by 2-4 dB dependent on configuration which included fully extended, partially extended top from the top and partially extended from the bottom. The CDSE fully extended yielded the greatest noise reduction, from 99.5 to 95.4 (a 4.1dB reduction). With the CDSE half-extended at the top, the sound level was 97.7 dB(A), and with the CDSE half-extended at the bottom, the sound level was 95.8 dB(A)—reductions of 1.8 and 3.8 dB from baseline, respectively.

Figure 4 shows the one-third octave band spectrum for each of the four configurations while drilling in granite. From this figure, it can be seen that the frequency content of the radiated noise is dominated by the 3150 Hz through 5000 Hz bands.

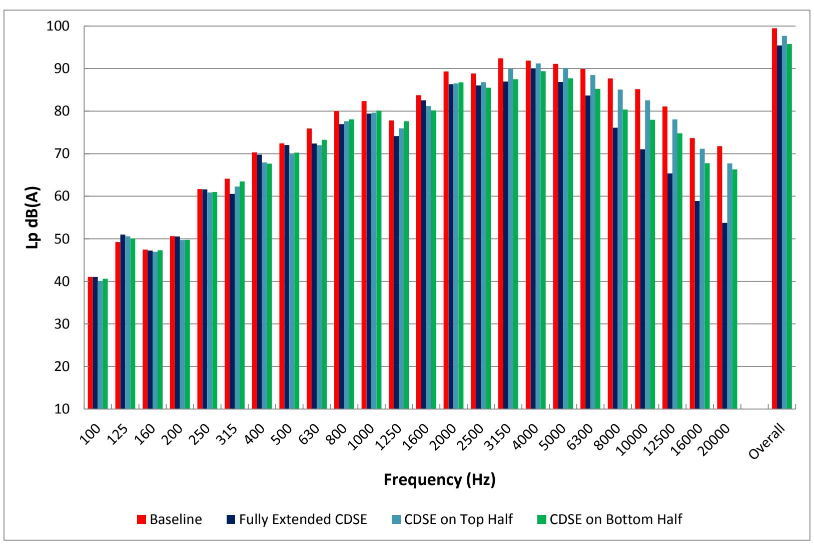

Figure 4: One-third octave band data for baseline and three configurations of the CDSE.

Beamforming results were obtained in the form of one-third octave band acoustic maps for the various tested configurations. Figure 5 shows the acoustic maps for the 3150 Hz, 4000 Hz, and 5000 Hz one-third octave frequency bands. Note that all the maps in this figure have a 6-dB range and are shown with the same color scale. For this reason, the first and third figures of column B should not be interpreted as being noise-free; instead, the noise source in these figures is more than 6 dB below the peak level measured from the baseline configuration. Comparison of the various columns—i.e., configurations—of Figure 5 shows that the fully extended CDSE (Column B) provides the best noise reduction, followed by the half-extended CDSE at the bottom (Column D). These observations agree with the data shown in Figure 5.

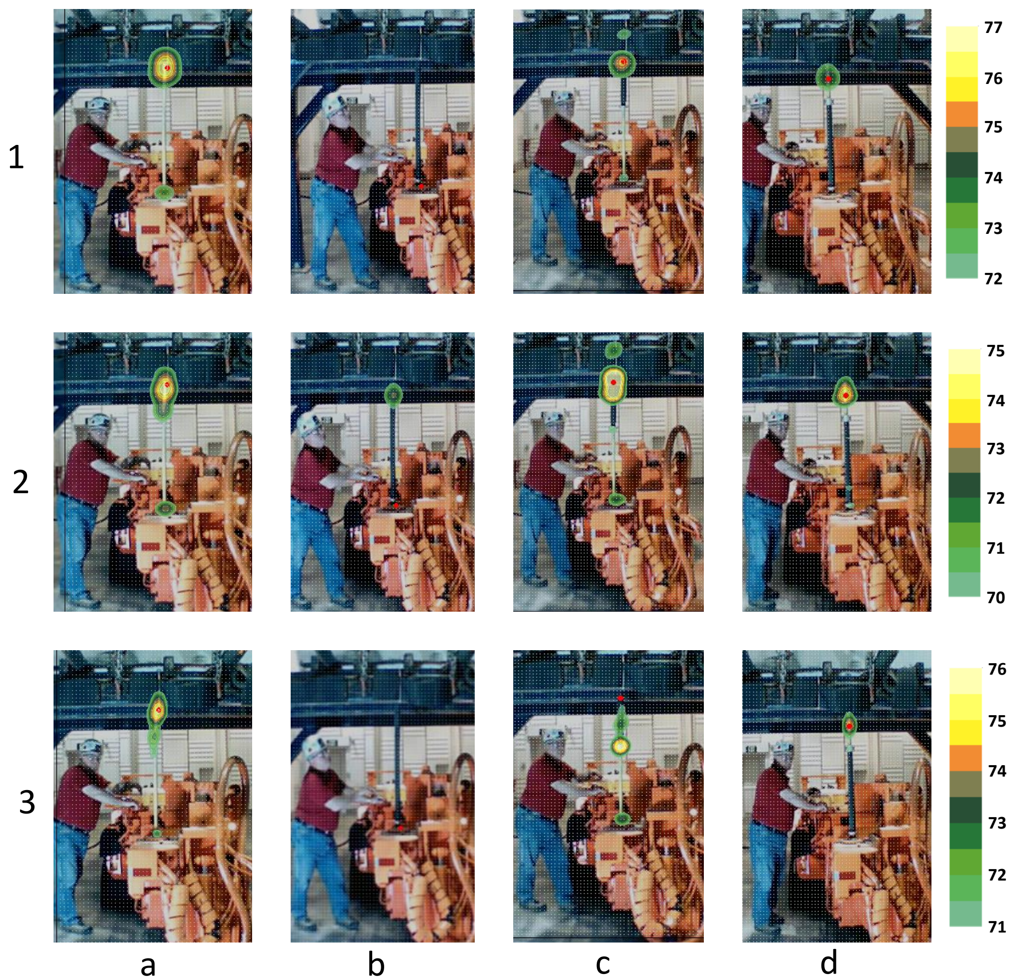

Figure 5: Beamforming results for the redesigned CDSE by one-third octave band and CDSE configuration. Row 1: 3150 Hz, row 2: 4000 Hz, row 3: 5000 Hz. column a: baseline, column b: fully extended, column c: on top half, column d: on bottom half.

5. DISCUSSION

Putting these results into context with earlier research, it is important to note that the prototype version of the CDSE achieved a greater noise reduction than the redesigned version. Laboratory evaluations found a maximum of 5-7 dB reduction for the prototype version[8] versus 3-4 dB noise reduction for the redesigned version. Despite the lesser amount of noise reduction, similar beamforming results were found. Also, the improved usability of the redesigned CDSE allows for simple, continued use of the device which was not possible with the prototype CDSE.

It is also very promising that similar results were obtained with the CDSE fully extended and with it only half-extended at the bottom of the drill steel. The noise reduction with the redesigned CDSE has a positive relationship with the amount of drill steel covered while actively drilling the hole. When the CDSE is located at the top of the drill steel and thus near the bit, as the drill steel advances into the hole the CDSE collapses and covers less of the drill steel. Conversely, when the CDSE is at the bottom of the drill steel and thus near the chuck, as the drill steel further advances into the hole more of the steel is covered by the CDSE—therefore a greater noise reduction can be achieved

There are two potential reasons for the discrepancy in noise reduction results between the CDSE designs. First, the data for the redesigned CDSE was acquired on a different roof bolting machine than the prototype CDSE. Some unknown variable between the machines may have led to differences in noise emission and subsequent noise reduction. However, this is unlikely because only the absolute noise reduction across machines was compared; individual untreated and treated conditions between machines were not compared.

A second reason why slightly poorer noise reduction was obtained with the new CDSE design is the material from which the CDSE was constructed. The prototype device was constructed from material that had specific acoustic properties; however the redesigned CDSE was constructed from an off-the-shelf material chosen for its size and flexibility. While the current material should prove to be more durable and usable to the operator, it may not yield the same noise reduction.

A final consideration regarding these results is that the typical media in an underground coal mine roof strata would be shale, rather than granite which was used during our laboratory testing. Because shale is a softer material than granite, it is feasible that slightly lower noise reductions may be obtained. This highlights the necessity for field testing of the redesigned CDSE to further assess its field usability.

6. CONCLUSIONS

As demonstrated by the results when the CDSE was only half-extended at the bottom of the drill steel, a significant noise reduction can be achieved without completely covering the steel. Because of the design of the CDSE, it can only compress to 27 cm (11 inches). Therefore, to drill a 122 cm (4-foot) hole with the CDSE installed, the drill steel length must be increased by 27 cm to accommodate the un-useable area covered by the fully compressed CDSE. This study shows that a slightly shorter CDSE could be used—not necessarily covering the entire drill steel—and a very similar noise reduction would result. This would reduce the additional drill steel length needed for drilling a specific depth hole, which, in turn, would be more acceptable, especially in low coal mines.

Another potential benefit of the redesigned CDSE as compared to the prototype version is that it can remain on the drill steel during the entire bolt hole drilling and bolt insertion process, if only one drill steel is being used. If multiple stacked drill steels are used, it is simple to manually move the redesigned CDSE from one drill steel to the next. When the CDSE is not in use, it can remain on the drill steel taking up minimal additional space. This provides an overall simpler operation for the RBM operator, increasing the likelihood of acceptance of the CDSE.

The redesigned collapsible drill steel enclosure shows significantly improved usability features as compared to the previous prototype. Because of the durable rubber material, the device will withstand multiple shifts in harsh underground coal mining conditions. Also, due to the slimmer design, it will take up less space when not in use. When the CDSE is installed, the operator will be able to see any significant bow in the drill steel which will improve safety and increase acceptance of the noise control by the mining community. Additionally, it can remain installed on the drill steel during the entire bolt hole drilling and installing process, further increasing the usability of the device. Despite the slightly lower noise reduction obtained with the redesigned CDSE as compared to the prototype version, laboratory tests have shown it to be a promising noise control for the RBM. The next steps are to evaluate the redesigned CDSE in underground mining conditions and seek potential manufacturing partners for modifying the design to be a commercially viable product.

For the redesigned CDSE to progress, a manufacturing partner responsible for device fabrication and/or sales would want to address the material versus acoustic function factor. There will likely be a tradeoff between material and noise reduction properties. There are many materials from which the device could be constructed—from various durometers of rubber and urethane to synthetic fabrics and various plasticized materials. Ultimately the manufacturer of a commercially available CDSE would determine the acceptable middle ground, where miners are protected from noise overexposure and the CDSE maintains its improved usability.

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