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THE EVOLUTION OF DRILL BIT AND CHUCK ISOLATORS TO REDUCE ROOF BOLTING MACHINE DRILLING NOISE

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ABSTRACT

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 underground coal-mining equipment, an example of which is a roof bolting machine. Field studies show that, on average, drilling noise is the loudest noise that a roof bolting machine operator would be exposed to and it contributes significantly to the operators' noise exposure. NIOSH has determined that the drill steel and chuck radiate a significant amount of noise during drilling. NIOSH and the Corry Rubber Corporation have developed a bit isolator that breaks the steel-to-steel link between the drill bit and drill steel and a chuck isolator that breaks the mechanical connection between the drill steel and the chuck. This effectively reduces the noise radiated by the drill steel and chuck and reduces the noise exposure of the roof bolter operator. The paper documents the evolution of the bit isolator and chuck isolator. Laboratory testing confirms that production bit and chuck isolators reduce the A-weighted sound level generated during drilling by 3.7 to 6.6 dB

INTRODUCTION

Hearing loss prevention is one of 21 Priority Research Areas listed in the NIOSH National Occupational Research Agenda [1]. Further, the Department of Labor Mine Safety and Health administration (MSHA) collects noise sample data that assists NIOSH in selecting equipment whose operators are most likely to be overexposed to noise [2]. Such 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) (Table 1). Of these machines, the roof bolting machine (RBM) operator was the second most likely to be overexposed among operators of all equipment used in underground coal.

Table 1. Percentage of noise over-exposures by machine.

Machine	%
Continuous mining machine	35
Bull dozer	24
Roof bolting machine	17
Front end loader	8
Shuttle car	6
Auger miner	5
Truck	5

To develop effective noise controls, it was important to determine the tasks and noise levels associated with significant noise exposure for roof bolting machine operators. The objective was to reduce an operators' noise exposure to a time-weighted average (TWA) of 90 dB(A) or less for an eight-hour shift. This would correspond to a noise dose of 100%, the maximum allowed per the MSHA PEL. Thus, NIOSH performed noise dosimetry and time-motion studies to determine the noise doses and sound levels associated with the typical tasks required of a RBM operator, and the time spent conducting these tasks. Post-processing of this data revealed the tasks the operator devoted the most time to, the noise dose accumulated during each task, and, of course, the tasks which are the primary contributors to the operators' noise dose exposure. This information helped NIOSH to determine where noise control development should be focused.

Tables 2 and 3 summarize data collected during a time-motion study of a dual-boom J.H. Fletcher roof bolting machine [3]. The tasks shown are those for which the operator was engaged at least 1% of his shift. The 'other' category of Tables 2 and 3 includes time spent riding the elevator, when the operators were bolting alone, or both drilling, or both bolting, and other times where the activity could not be documented. Table 2 shows that the operators spent a significant amount of time drilling and bolting simultaneously, roughly 3 ½ hours of the shift. Shown in Table 3, Operator 1 accumulated 52% PEL dose during this time, two-thirds of his daily noise exposure, 78% PEL dose. Operator 2 accumulated 68% PEL dose during this time, greater than half of his full-shift exposure of 127%. Further analysis showed that drilling sound levels far exceeded those associated with the bolting portion of the duty cycle (Table 4).

Table 2. Time spent by task, minutes.

Task	Operator 1	Operator 2
Both drilling & bolting	218	218
Drilling alone	7	10
Riding mantrip	28	28
Tramming	63	63
Lunch	54	54
Prep time	108	108
Other	241	239

Table 3. PEL Dose by task, %.

Task	Operator 1	Operator 2
Both drilling & bolting	52	68
Drilling alone	2	4
Riding mantrip	8	21
Tramming	11	18
Lunch	0	2
Prep time	5	9
Other	0	7
Total	78	127

Table 4. Equivalent TWA sound level, dB(A).

Task	Operator 1	Operator 2
Drilling	90	131
Bolting	70	86

With typical drilling times and proportionately short bolting times for resin-type roof bolts, the operators spent significantly more time drilling than bolting. These observations confirmed the initial expectation that for the RBM, the drilling portion of the operators' duty

cycle exposed the operator to the highest noise levels and was the most significant contributor to the operators' noise dose. Thus, if noise controls were to be effective at reducing RBM operator noise exposures, then drilling noise must be reduced.

In percussive rock drilling, one notable source of noise generation is drill steel vibration [4,5]. There are three fundamental ways to reduce these vibrations, and thus noise: reduce the cause of the vibration, attenuate the vibration, or attenuate the noise. NIOSH sought to quantify the vibration levels of the components associated with drilling on the roof bolting machine. These included the drill head, slinger plate, drill guide, drill steel, and the drill media.

Figure 1 shows a slip ring assembly to interface drill steel acceleration signals with data acquisition equipment. Figure 2 shows acceleration levels measured on a hexagonal drill steel and a 35-mm-diameter bit during a 5-second sample (rotation speed of 200 rpm and thrust of 9.4 kN). NIOSH used granite as the drill media to represent high compressive strength roof and for the fact that this compressive strength should remain consistent throughout the drilling, which helps ensure test repeatability. Levels peaked at more than 500 g's, confirming there is significant vibration in the drill steel during drilling.

Figure 1. Drill steel accelerometers and slip-ring assembly.

NIOSH used a 42-microphone Bruel and Kjaer beamforming array and associated data acquisition system and analysis software to locate noise sources near the drill steel area and a supplemental microphone placed near the RBM operators head to measure operator ear sound levels. Granite served as the drill media for the aforementioned reasons.

A jaw-type shaft coupling with a 58 shore D durometer spider served as a simple device to test the premise that reducing the mechanical coupling between the drill steel and the chuck would reduce sound levels at the operator's ear position (Figure 3). Using the jaw-type coupling reduced the operators sound from a baseline of 100 dB(A) to 96 dB(A) for 9.4 kN of thrust and from 104 dB(A) to 100 dB(A) for 22 kN of thrust.
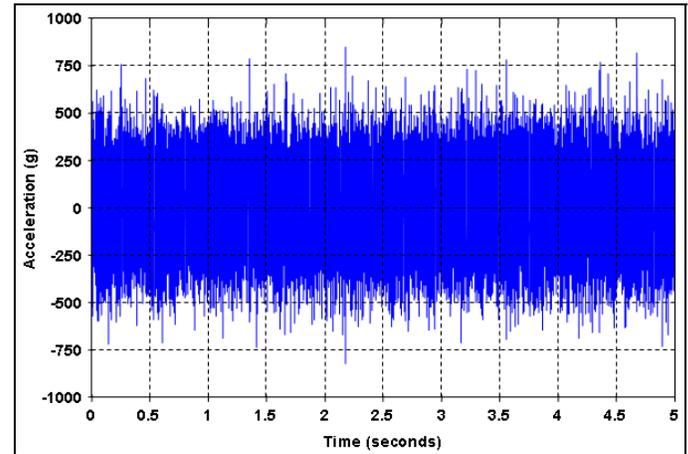

Figure 2. Typical drill steel acceleration, hexagonal drill steel, 35-mm-diameter bit, granite drill media.

Figure 3. Jaw-type coupling with 58 Shore D urethane spider.

Additional testing using the beamforming array showed that the steel radiates a significant amount of noise during drilling. Figure 4 shows baseline data collected using a thrust of 9.4 kN. The noise sources are centered roughly 100 to 200 mm (4 to 8 inches) below the drill steel-media interface and above the chuck. As the drill steel advances during drilling, the lower noise source advances with the chuck, while the upper source essentially remains just below the media. Figure 5 shows beamforming results with the inclusion of the jaw-type coupling with the same operating conditions. For the figures, light colors indicate areas of high noise radiation while dark colors indicate areas of lower noise radiation. Given these results, NIOSH deemed vibration isolation as a viable option to reduce noise generation during RBM drilling.

Further development of an isolation noise control concept required the aid of a collaborating partner proficient in the design and production of vibration isolators. Therefore, NIOSH began working with Corry Rubber Corporation on bit and chuck isolators.
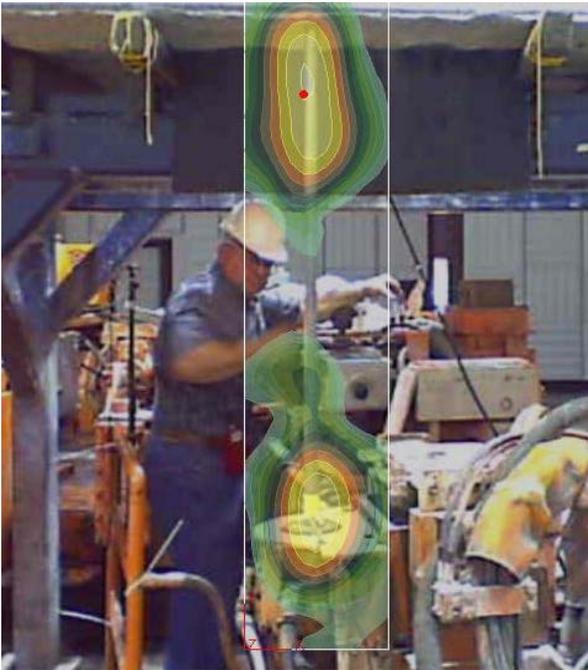

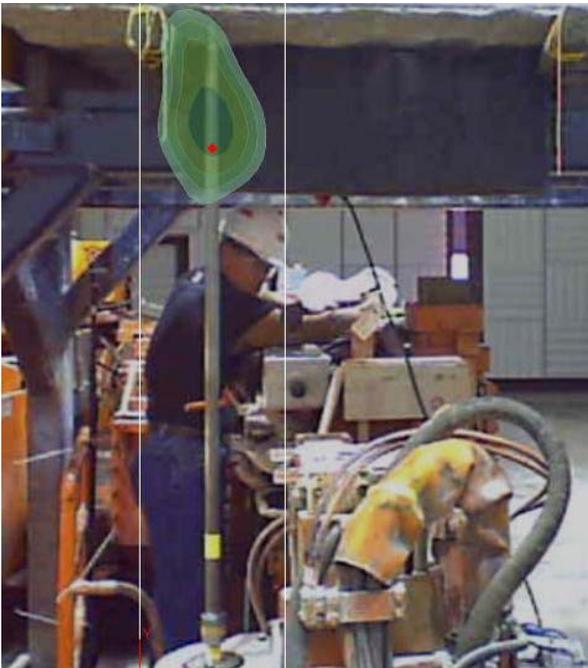**Figure 4.** Beamforming of baseline drilling, 100 dB(A) at the operators' position.

Figure 5. Beamforming of drilling with the jaw-type coupling, 96 dB(A) at the operators' position.

DESIGN OVERVIEW

The final isolator designs are shown in Figure 6. These designs evolved from several prototype designs that were evaluated for noise attenuation and durability. There are three main parts to each: the inner steel member, the outer steel member, and the elastomer. The elastomer, which is between the inner and outer steel members, is the part that provides the vibration isolation. Some of the earlier designs

consisted of a bonded joint (elastomer bonded to an inner member) which was subsequently assembled into an outer member. These "pre-compressed, bonded joint designs" utilize a post-vulcanization (PV) bond between the outer surface of the elastomer and the inner surface of the outer steel member to react cutting forces. Advantages of pre-compressed bonded joint designs include improved elastomer durability (after assembly, the elastomer is in compression) and ease of manufacture since the mold has to accommodate only one metal and, therefore, one bond.
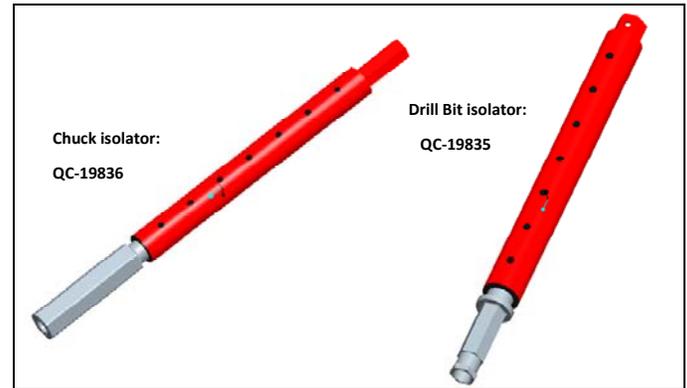

Figure 6. Final production designs of isolators for use with 35-mm-diameter drill bits.

While these designs offered sufficient noise attenuation, they did not meet the load carrying requirements due to the bond strength and variability associated with PV bonds. The current production designs are fully bonded designs which means the elastomer is bonded to the metal components during the molding operation thus eliminating the need for a PV bond. Based on lab testing, the production designs provide outstanding noise attenuation while meeting all load requirements.

A typical cross section of the production isolator design is shown in Figure 7. The outer and inner members are machined out of 4130/4140 steel and heat treated to 350 BHN. Various elastomers were evaluated for noise attenuation as part of a design of experiments, but the production elastomer will more than likely be a 50 to 55 durometer (Shore A) natural rubber (NR) blend. The bonded length of 254 mm is consistent across all designs and necessary to safely withstand cutting forces entirely through the elastomer section. An 11.4-mm gap protects the isolator from overload since the outer member will bottom out against the inner member shoulder at roughly 45 kN. Any load above 45 kN will then be reacted by the metal components instead of the elastomer. 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
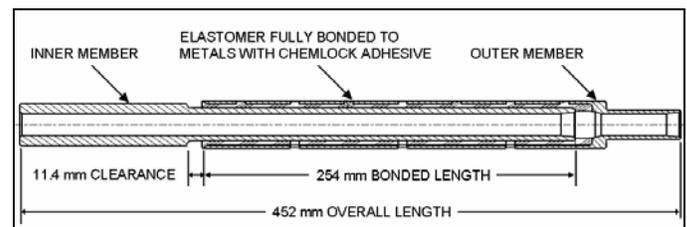6. Estimated torsional static stiffness (for noise attenuation): 6.8 to 20.3 N-m/deg.

Figure 7. Cross-section of production design chuck isolator.

The stiffness requirements were based on sound level measurements using prototype isolators. The sound level at the operator's ear was measured during "normal" drilling and also with several prototype isolator parts with varying stiffness. The production designs meet the requirements listed above. Extensive lab testing and analysis was performed on the production design to verify these requirements.

ELASTOMER COMPOUND EVALUATION

Several isolators were made with various elastomer compounds (Figure 8). These elastomers were selected to provide a broad range of dynamic and static properties for sound level evaluation while still satisfying the requirements outlined above. A description of each elastomer compound evaluated is shown in Table 5.

Figure 8. Isolators bonded with elastomers from Table 5.

Table 5. Evaluated elastomer compounds listed by CRC compound number and description.

100 Modulus (MPa)	Elongation (%)	Tensile (MPa)	Durometer (Shore A)	Damping Loss factor[A]
M-350-40 : 45 durometer NR				
1.6	569	22.4	45.3	0.09
M-460-2 : 58 durometer NR				
2.7	438	20.8	59.2	0.10
M-370-35 : 68 durometer NR				
4.1	360	25.8	67.7	0.17
M-660-1 : 50 durometer butyl rubber				
1.1	807	16.8	48.3	0.44
[A] (tandel), 10 Hz / ± 20% strain				

The natural rubber compounds have a range of tensile modulus varying from 1.6 MPa (45 durometer compound) to 4.1 MPa (68 durometer compound). The butyl compound was developed to provide approximately the same static stiffness as the 45 durometer natural rubber with 4 times more damping. Furthermore, the 58 durometer and 45 durometer natural rubber compounds have nearly the same damping but different stiffness. The idea here is to explore the effects damping and stiffness have on noise attenuation.

LAB TESTING

Isolators bonded with the elastomers detailed in Table 5 were tested in the lab both in the torsion and axial directions. The test machines used for this testing are shown in Figures 9 and 10. The purpose of this testing was to verify that stiffness and load requirements were met.

A summary of all the testing completed with results follows.

1. Axial static stiffness – record load up to 7.6 mm deflection. See Figure 11.
2. Axial static stiffness test – loaded in the axial direction to 18 kN.
3. Dynamic stiffness at 5 +/- 0.5 mm – perform frequency sweep from 1 Hz to 30 Hz in 3 Hz increments. Record dynamic stiffness, K', damping stiffness, K", and loss factor (tan del). See Figure 12 for dynamic stiffness, K', versus frequency.
4. Torsion test to approximately 410 N-m (the design torque requirement) and record torque versus angular deflection curve. See Figure 13.
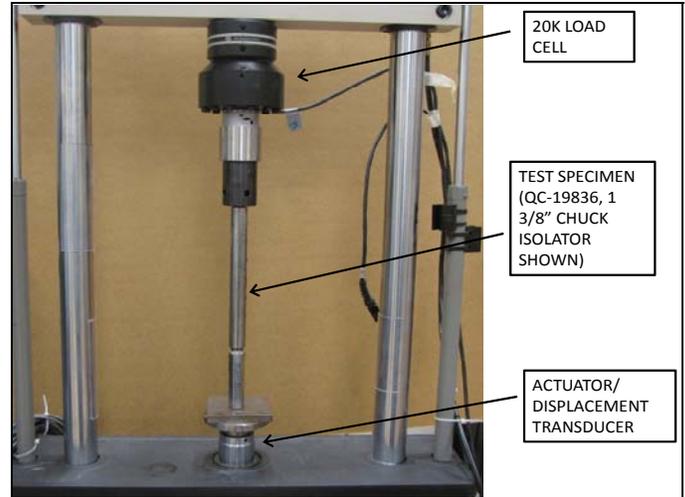5. Torsion test one sample to failure to determine failure torque.

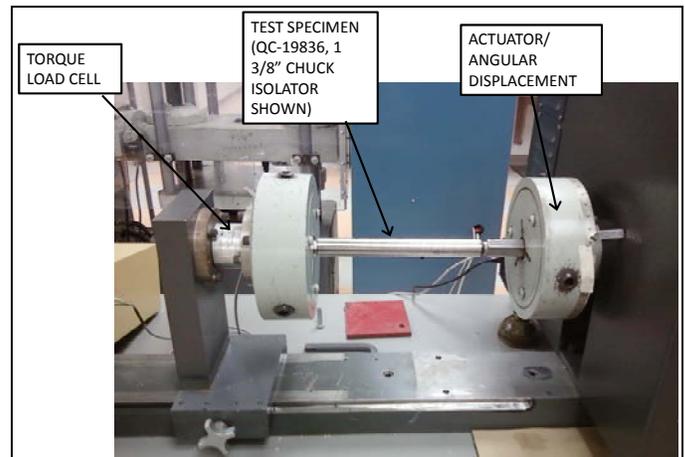**Figure 9.** MTS810 test system used to measure axial load capacity and static and dynamic stiffness.

Figure 10. Apparatus used for testing torsional load capacity and static torsion stiffness.
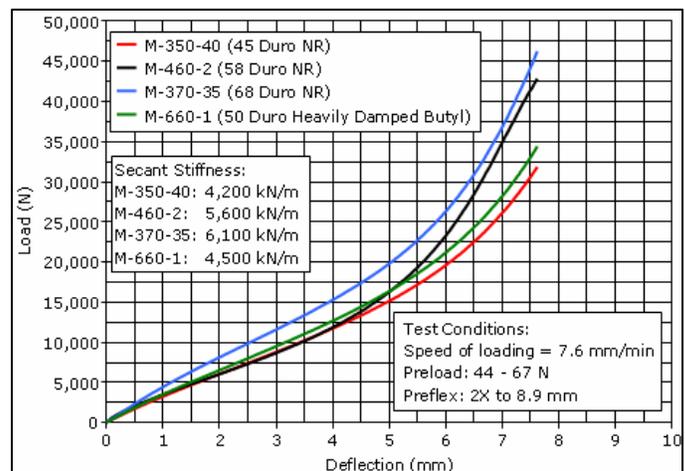

Figure 11. Axial static load-deflection curves.

SUMMARY TABLE AND DISCUSSION OF RESULTS

Axial static and dynamic stiffness and torsional stiffness for all the isolators tested is summarized in Table 6. Some general observations can be made:

1. Measured stiffness (both axial and torsional) is consistent with the durometers specified in Table 1 for each compound. In other

words, the 68 durometer NR has the highest torsional and axial stiffness followed by the 58 durometer and then the 45 durometer compounds.

2. All stiffness measured meet design requirements and were verified with FEA and hand calculations.

3. The 50 durometer heavily damped butyl is shown to be highly frequency sensitive (see Figure 12). While the static stiffness is nearly the same as the 45 durometer natural rubber, the dynamic stiffness, K', at 30 Hz is more than twice as high. This sort of behavior (frequency sensitivity) is typical of heavily damped elastomer compounds. The noise and vibration benefits from high damping may be offset by the higher dynamic stiffness at higher frequencies.

4. Load requirements of 45 kN axial and 410 N-m torsion were safely met by all isolators. Metal components showed no evidence of yielding and elastomer showed no evidence of tensile failure or bond failure at these loads. Additionally, two isolators were loaded to failure on the torsion machine with failure torques of 730 N-m and 760 N-m which is nearly twice the torque requirement.

Table 6. Stiffness results summary. Elastomers listed by compound number (CRC designation) and description.

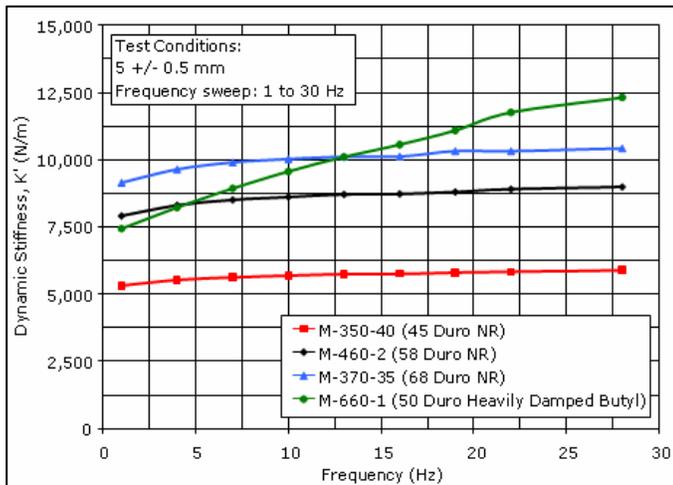| Axial static (secant) stiffness at 7.6 mm (kN/m)	Axial static (secant) stiffness at 18 kN (kN/m)	Axial dynamic stiffness 10 Hz, ± 0.5 mm (kN/m)	Torsional (secant) stiffness at 410 N-m (N-m/deg)
M-350-40 : 45 durometer NR			
4,200	3,100	5,600	9.5
M-460-2 : 58 durometer NR			
5,600	3,400	8,600	10.2
M-370-35 : 68 durometer NR			
6,100	4,000	10,200	11.9
M-660-1 : 50 durometer butyl rubber			
4,500	3,300	9,600	TBD

Figure 12. Dynamic axial stiffness, K', vs. frequency.

TEST SETUP FOR SOUND LEVEL MEASUREMENTS

A computer-controlled drilling apparatus (see Figure 14) was used to test the bit and chuck isolators made with the natural rubber compounds. Problems with the vacuum system on the test apparatus prevented testing of the butyl rubber parts. An optical tachometer was used to check the rotational speed for each test. A Bruel & Kjaer Type 4188 microphone was positioned roughly 1 meter from the drill steel at a height of about 1.5 meters.

For all testing, 35-mm-diameter drill bits were used with hexagonal drill steels. A 1.4-meter-long drill steel was used for baseline measurements. When the bit and chuck isolators were tested, shorter drill steels were used to maintain a total length of 1.4 meters.

Measurements with either a bit isolator or a chuck isolator were performed using a 1.0-meter-long drill steel while measurements with both a bit isolator and a chuck isolator were completed with a 0.7-meter-long drill steel.
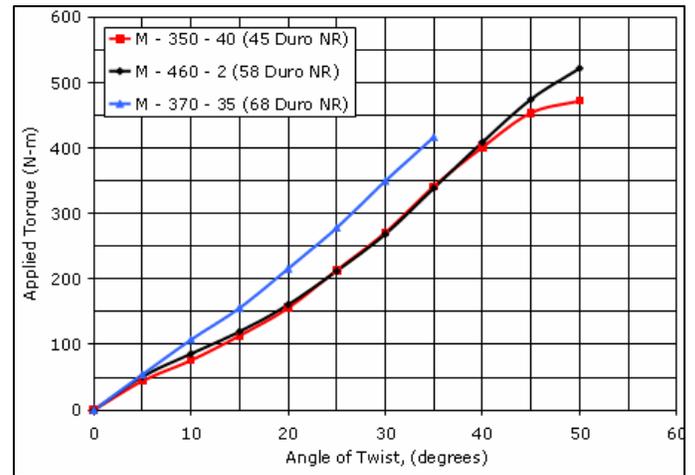

Figure 13. Static torque vs. angle of twist.

Figure 14. Test setup for sound level measurements at the operator's ear.

All tests were performed with a rotational speed of 270 RPM, a penetration rate of 28 mm/sec, and a maximum thrust of 22 kN. An LMS Pimento portable data acquisition system was used to record the sound pressure using 24-bit resolution at 20,000 samples/second. The microphone data were post-processed to calculate the A-weighted 1/3-octave-band sound pressure levels according to ANSI standards [6]. Table 7 shows the tests performed without and with drilling.

Table 7. Test configurations for sound level measurements.

Test	Bit Isolator	Chuck Isolator
BG	not applicable	not applicable
HYD/VAC	not applicable	not applicable
BASE	not applicable	not applicable
T1	45 durometer NR	None
T2	45 durometer NR	45 durometer NR
T3	58 durometer NR	None
T4	None	58 durometer NR
T5	58 durometer NR	58 durometer NR
T6	68 durometer NR	None
T7	68 durometer NR	68 durometer NR

Prior to performing measurements with drilling, the sound pressure was measured with only the hydraulic and vacuum systems operating. Figure 15 shows the A-weighted sound levels in 1/3-octave bands with the hydraulics and vacuum systems and for drilling with a 1.4-meter-long hex drill steel. The figure clearly shows that noise from

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the hydraulics and vacuum are insignificant compared to drilling noise. The figure shows that the levels in the 400 Hz through 10 kHz 1/3-octave-bands increase by 10 dB or more with drilling. In addition, the levels at and below 315 Hz do not change much which suggests the noise at these frequencies is due to the hydraulics and vacuum instead of drilling. The figure also shows that the highest in-band levels are in the 2500, 3150, and 4000 Hz 1/3-octave bands. The remaining figures will focus on the levels above 250 Hz because drilling noise does not have significant low frequency content.
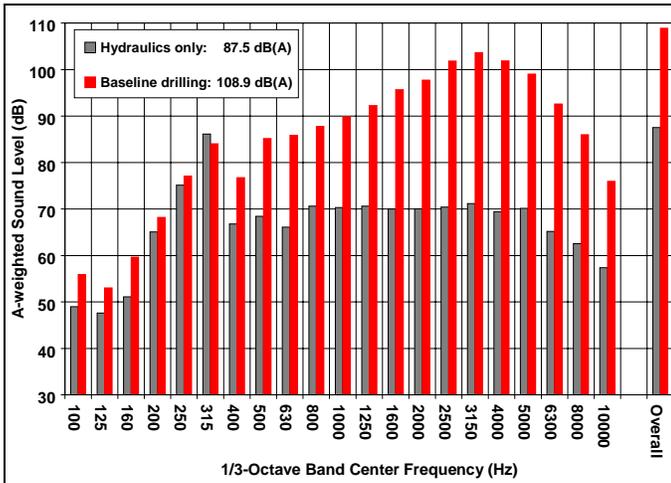

Figure 15. A-wtd SPL in 1/3-octave bands for hydraulics and baseline drilling conditions.

Figure 16 shows the results for the tests with bit isolators compared to the baseline. The figure shows that each of the bit isolators significantly reduced drilling noise above 1600 Hz. The 45 durometer bit isolator achieved the highest reductions while the 68 durometer bit isolator yielded the least reductions. The 45, 58, and 68 durometer bit isolators reduced the overall A-weighted sound level by 6.6, 5.9, and 3.9 dB, respectively. Since the stiffness of a rubber component decreases as durometer decreases, the data suggest that decreasing the stiffness of the bit isolator could further reduce the sound level. However, reducing the durometer can have a negative impact on the life of the part.
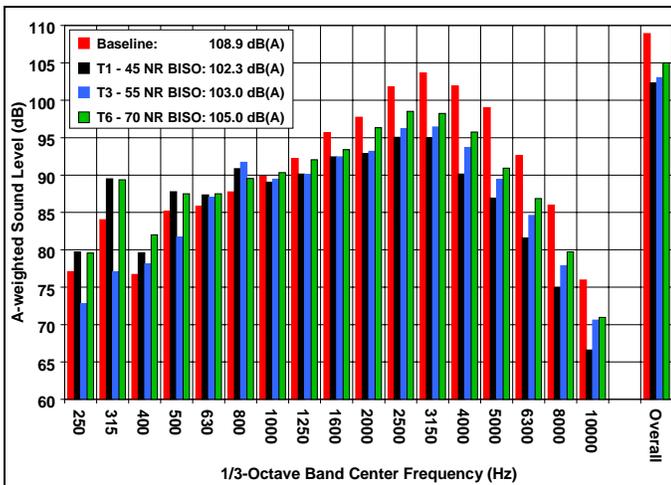

Figure 16. A-wtd SPL in 1/3-octave bands for baseline and with bit isolators.

A single test was conducted with a chuck isolator only. Figure 17 shows the resulting spectra for the baseline compared to the test with a 58 durometer chuck isolator. The figure shows that the chuck isolator substantially reduced the levels above 1600 Hz and reduced the overall A-weighted sound level by 3.7 dB.
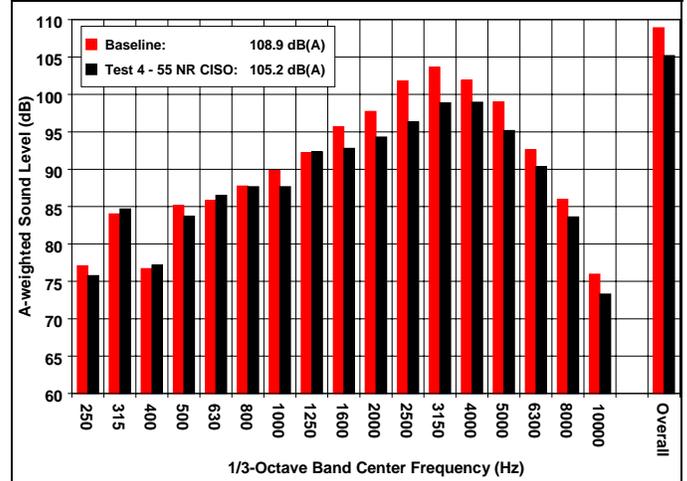

Figure 17. A-wtd SPL in 1/3-octave bands for baseline and with only a chuck isolator.

Figure 18 shows the resulting 1/3-octave band spectra for drilling with a 58 durometer bit isolator and with both a 58 durometer bit isolator and chuck isolator. The figure shows a marginal additional reduction of the in-band levels for some frequencies. However, the changes are so small this could be simply test-to-test variation.
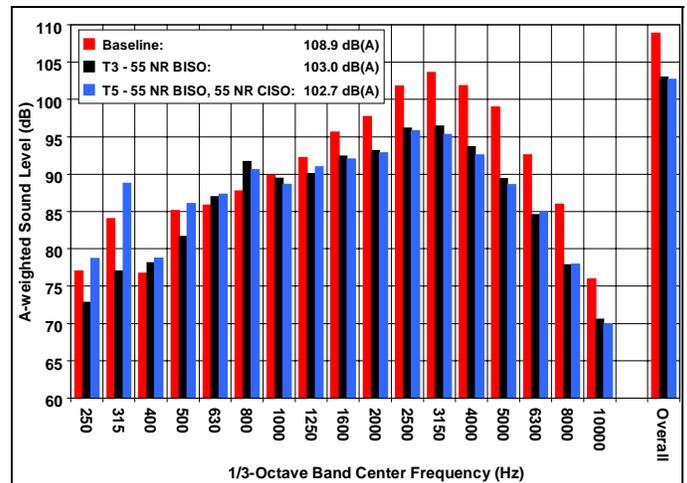

Figure 18. A-wtd SPL in 1/3-octave bands: baseline; 58 duro NR BISO; and 58 duro NR BISO with 58 duro NR CISO.

Combinations of bit and chuck isolators of the same durometer were tested to explore their effect on the noise generated by drilling. Figure 19 shows the results for these combinations along with the results for baseline conditions. The figure shows that the levels with the 58 durometer isolators are lower than those with either the 45 or 68 durometer isolators. This is somewhat surprising since isolation usually improves as stiffness is reduced. However, the figure shows the combination of the least stiff isolators – the 45 durometer parts – resulted in higher levels. This could be a result of the lower stiffness chuck isolator allowing the drill steel to drill an out-of-round hole. This would tend to cause the sides of the drill steel to rub against the drill medium which would in turn increase noise. Future testing should explore using a soft bit isolator in combination with a wide range of chuck isolators to fully examine this phenomenon.

Figure 20 shows the results for the best three tests with isolators along with the baseline results. The figure shows that using a 45 durometer bit isolator resulted in the greatest reductions. However, Figure 20 shows each of these tests resulted in substantial sound level reductions in the 1/3-octave bands at and above 1600 Hz.
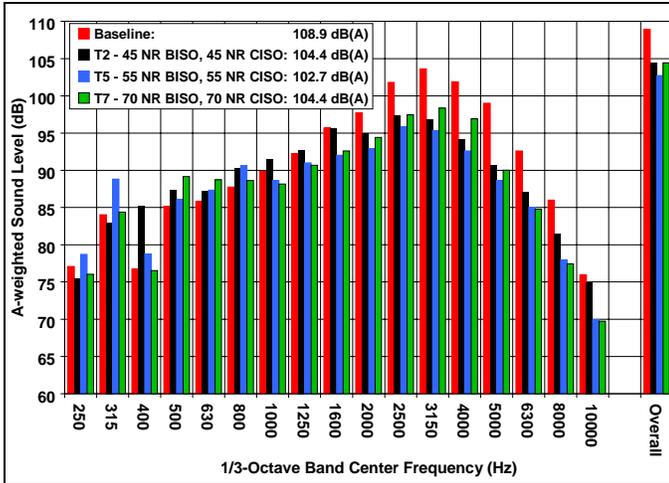
Figure 19. A-wtd SPL in 1/3-octave bands for baseline; 45 duro NR BISO and CISO; 58 duro NR BISO and CISO; and 68 duro NR BISO and CISO.
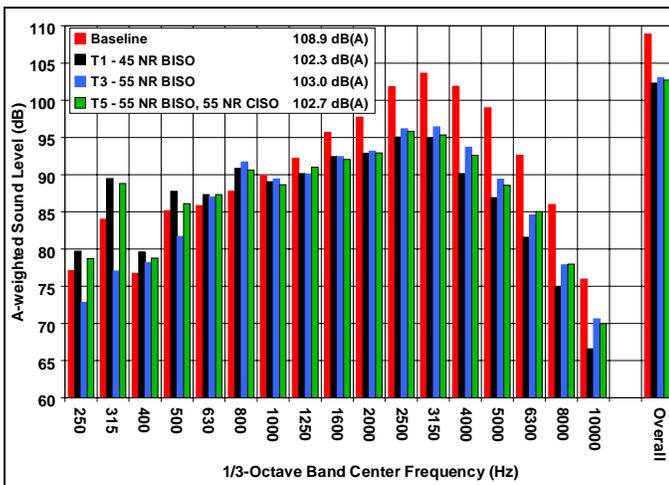

Figure 20. A-wtd SPL in 1/3-octave bands for baseline and best three tests: 45 duro NR BISO, 58 duro NR BISO, and 58 duro NR BISO with 58 duro NR CISO.

CONCLUSIONS

The current designs of production bit and chuck isolators evolved from relatively simple isolation devices that were only suitable for laboratory testing. The production designs were verified to meet design targets for spring rate, torque and load capacity, and sound level reduction. Testing with an automated drilling apparatus proved that bit and chuck isolators with natural rubber elastomers reduced the sound level near the drill steel. While all the tested isolators reduced the A-weighted sound level whether used singly or in combination, the 45 durometer natural rubber bit isolator achieved the highest reduction, 6.6 dB, while the 58 durometer natural rubber bit isolator yielded a reduction of 5.9 dB. Measurements with a combination of a bit isolator and chuck isolator revealed that the sound level could increase compared to isolator-only values if the stiffness of the chuck isolator is low. This suggests there is an optimal stiffness for the chuck isolator.

REFERENCES

1. National Institute for Occupational Safety and Health, 1996. National Occupational Agenda, Department of Health and Human Services Publication No. 96-115.

2. Title 30 CFR Part 62, 2000-2005, U.S. Department of Labor, Mine Safety and Health Administration, Information Resource Center, Denver, Co.

3. Jeffrey Shawn Peterson and Lynn Alcorn, "Results of noise measurements from underground testing of a roof bolting machine duty cycle," Noise-Con 2007.

4. I. Hawkes and J. A. Burks, "Investigation of Noise and Vibration in Percussive Drill Rods", Int. J. Rock, Mech, Min. Sci. & Geomech, Abstr, 16, pp 363-376 (1979).

5. I. Carlvik, "The Generation of Bending Vibrations in Drill Rods", Int. J. Rock, Mech, Min. Sci. & Geomech, Abstr, Vol 18, pp 167-172 (1981).

6. ANSI/ASA S1.11-2004 (R2009). Octave-Band and Fractional-Octave-Band Analog and Digital Filters. Melville, NY: Acoustical Society of America.