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The Effect of Hearing Protection on Kurtosis

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ABSTRACT

Hearing loss in the construction and mining sectors has about a 25% prevalence rate based upon published NIOSH research. Dunn et al. demonstrated that impact noise was more hazardous to the hearing of chinchillas than an equal level (Leq) continuous noise [1]. Zhao et al. demonstrated that human workers exposed to high kurtosis (4th standardized moment) noise accumulated hearing loss at faster rates than those workers exposed to lower kurtosis values [2]. Operation of machinery can be particularly hazardous when that noise contains significant peaks of high levels exceeding the average levels. Jackhammer noise is one example of a noise exposure that has both a high exposure level (107 dB SPL) and a high kurtosis (15 to 17). This study evaluated six hearing protection devices fitted on an acoustic test fixture. The average reductions of jackhammer noise level for the HPDs was between 21 and 42 dB. For traditional passive HPDs (muffs and plugs), the kurtosis values were reduced to between 3 and 12. For a filter-style earplug in the open condition, the kurtosis value was reduced from 16 to 12. For the earmuff, the kurtosis value was reduced from 15 to 3.

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1. INTRODUCTION

In road construction, jackhammers are commonly used to remove material in preparation for laying new road surface. The peak, impulse-noise levels of a jackhammer can exceed 120 dB SPL at the operator's ears or 100 dB SPL a few meters in front of the operator. Depending upon position where noise is sampled, the equivalent A-weighted levels can range from 90 to 110 dB(A) SPL. The permissible exposure times for such high levels would be 2 hours to less than 2 minutes based upon an 85-dB(A) limit for 8 hours and a 3-dB exchange rate [3].

In the ANSI S3.44 standard for estimating occupational noise exposure, a 5-dB allowance can added to exposures that are primarily impulsive [4]. Dunn et al. found that

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chinchillas exposed to equivalent levels of continuous and impulsive noise exhibited greater hearing loss for impulsive exposures [1]. Zhao et al. found a similar increased risk for impulsive noise exposures among Chinese workers [2]. Exposure to high-level impulsive noise present a greater potential to produce hearing loss among workers.

In 2010, researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted measurements of several models of jackhammers to identify noise sources and to evaluate the performance of possible noise controls. Five hearing protection devices (HPDs) were tested with an acoustic test fixture (ATF) to evaluate performance in high-level impulsive noise. Methods from the ANSI S12.42 standard [5] were applied to estimate the insertion loss of the HPDs and determine allowable exposure times when protection is worn. Recordings of the occluded and unoccluded ATF were used to estimate the kurtosis in both conditions and the potential change in the allowable exposure times.

2. METHODS

2.1 Jackhammer Loaded Testing

Measurements of a Makita model HM1810 jackhammer with a Bosch model HS2163 narrow chisel were conducted at the NIOSH Pittsburgh Mining Research Division's large hemi-anechoic chamber in January 2011. The jackhammer was operated fully loaded on a test stand constructed from 20x26x6 inch thick concrete blocks having a compressive strength of 5000 psi (Quality Concrete, Pittsburgh, PA). The concrete had a nominal curing time of 28 days. The concrete blocks were stacked in a 3 by 3 grid as shown in Figure 1. The concrete test stand was built over a grid of rubber acoustic ballistic tiles to protect the floor and damp vibrations (New Century Northwest LLC, Eugene, OR). The 24x24x1.5 inch rubber tiles weighed about 29 lbs each and had a stiffness of 70 Shore A. During testing, the jackhammer operator stood on top of the test stand and chipped through the concrete of the first layer of concrete blocks. The operator was instructed to allow the weight of the jackhammer to do most of the downward work and to apply only downward force on the jackhammer to control the tool [6].

2.2 Hearing Protector Testing

Five models of hearing protection devices (Bilsom 707 Impact II® earmuff, Etymotic Research Inc. Electronic BlastPLG® EB1 earplug, 3M™ Combat Arms™ single tip earplug, 3M™ E-A-R™ Express™ Pod Plugs™, and 3M™ E-A-R™ Classic™ foam earplug) were evaluated with the jackhammer using an ATF. The Bilsom 707 earmuff and EB1 earplug have been discontinued. The ATF was built by the French-German Research Institute of Saint Louis and had a single GRAS 60711 coupler fitted with a ¼" Brüel and Kjær 4135 pressure microphone with Head Acoustics HMS II pinna and 10 mm ear canal. Each hearing protection device was fitted on the fixture. A pair of occluded and unoccluded measurements were made with the jackhammer in nominally the same location to yield approximately the same levels. One transit of the jackhammer through the concrete blocks was made. The hearing protection was removed, the jackhammer moved to the side and another transit was made. Recordings were made with a National Instruments PXI-4462 card, ±42V range, and 24-bit resolution for 5 seconds. The first 2.5 seconds of the recordings were used in the analysis because not every transit of the jackhammer lasted the entire 5 seconds.

Figure 1. Concrete blocks, chisel close-up, and jackhammer operator.

2.3 Impulse Spectral Insertion Loss

The ANSI S12.42-2010 standard specifies that an impulse source be used to estimate the complex acoustic transfer function for the unoccluded condition between the field probe microphone and the acoustic test fixture [5]. The source is assumed to remain in a fixed location relative to the microphones. With the jackhammer, the complex, transfer function changes slightly whenever the source is moved, thus precluding the strict application of this method. Instead, a spectral transfer function is determined for the unoccluded condition and is used to estimate the unoccluded ear spectral levels of the ATF when it is occluded.

Fackler et al. [7] proposed a modification of IPIL that maintained the spectral information included in the complex transfer function and permitted a comparison to real ear attenuation at threshold (REAT) measurements of HPDs. However, the complex transfer function used to estimate IPIL and impulse spectral insertion loss (ISIL) is a function of the distance from the source to the receivers. For each transit of the jackhammer, the impulse source is moved in all three directions (right/left, front/back and up/down). Although the spatial distances are small and likely inconsequential, the complex transfer function does not remain constant. The ISIL is determined with a transfer function computed with the output levels of one-third octave band filters from the field probe and the unoccluded ear of the ATF,

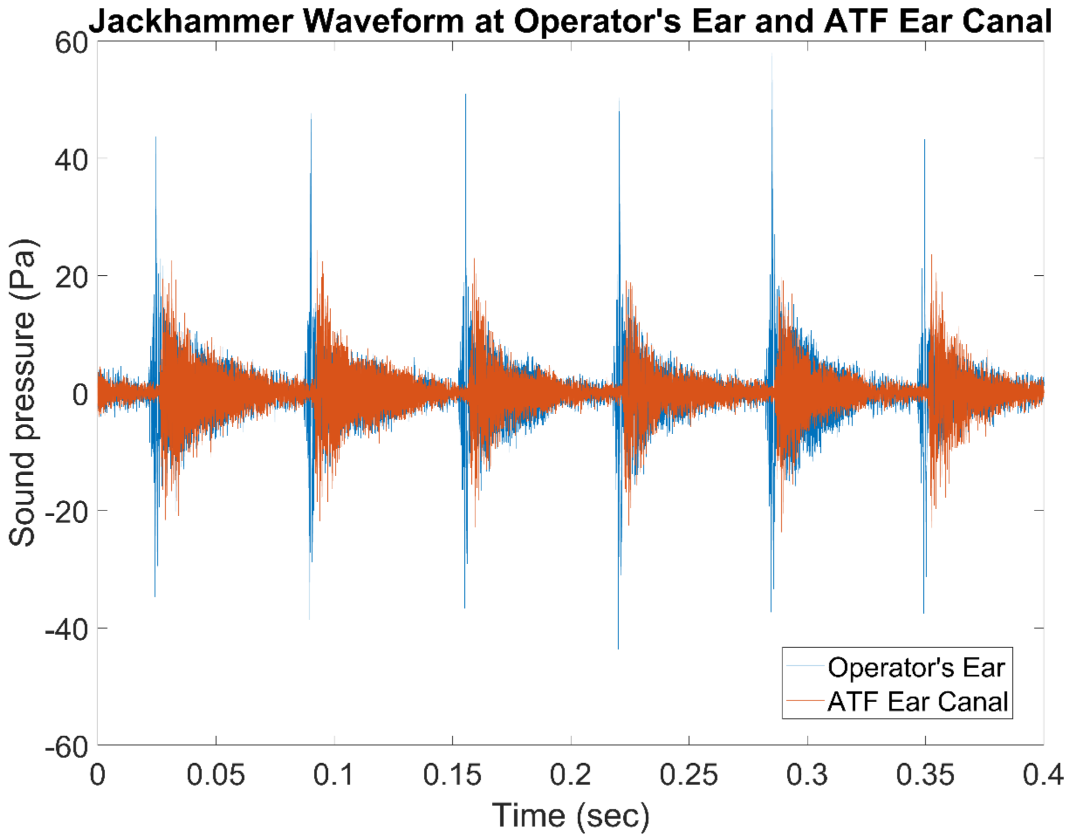
$H_{\mathrm{FF,ATF},f} = H_{\mathrm{TOB},f}\left(p_{\mathrm{FF}}(t)\right) - H_{\mathrm{TOB},f}\left(p_{\mathrm{ATF,open}}(t)\right)$, where $H_{\mathrm{TOB},f}$ is the third octave band filter for the center frequency, f, and $H_{\mathrm{FF,ATF},f}$ is the transfer function between the field probe microphone and the unoccluded ear of the ATF [8]. The phase of the transfer function is not used.

2.4 Kurtosis analysis

Lei et al. [9] proposed using kurtosis, $\beta = \left[\frac{E[(x-\mu)^4]}{(E[(x-\mu)^2])^2}\right]$, to characterize the impulsive character of a noise exposure amplitude. In evaluating workers' noise exposures, Zhao et al. [2] used cumulative noise exposure to reconcile impulsive and non-impulsive exposures, CNE $= L_{\mathrm{Aeq,8h}} + \mathrm{K}[\log\ T/\log 2]$, where T is the exposure duration in years, $\mathrm{K} = \ln(\beta) + 1.9$, and β is the kurtosis. This form worked well when the exposures were long term, but it is time dependent and may not be particularly useful when analyzing exposure recordings that last only seconds. Goley et al. [10] proposed a kurtosis correction to the equivalent noise level that was not dependent upon the length of a person's exposure time, $L'_{\mathrm{eq}} = L_{\mathrm{eq}} + \lambda \log_{10}\frac{\beta}{\beta_G}$, where λ is 4.02, β is the kurtosis of the noise sample, and $\beta_G = 3$ is the kurtosis of a normal distribution. This correction was calculated on the first 2.5 seconds of the jackhammer recordings and applied to the equivalent A-weighted levels, L_{Aeq}.

3. RESULTS

Impulses from the jackhammer are shown in Figure 1. The blue trace shows the microphone at the operator's ear and the orange trace is the ear canal microphone of the ATF. The operator levels in this short sample range from about 125 to 130 dB peak SPL. The ATF levels range from about 120 to 123 dB. The signal level at the ATF change as the jackhammer moves over the concrete blocks, closer and further away. The cycle rate of the jackhammer is about 15 strikes per second and the ring of the jackhammer impact decays significantly within each cycle.



The overall A-weighted noise levels calculated from the one-third octave band data from 100 to 10000 Hz are reported in Table *1*. The levels at field probe microphone, 17 cm from the ATF right ear, were between 105 and 108 dBA. The occluded levels varied from 66 dB for the Express Pod earplug to 85 dB for the Combat Arms earplug in the open filter condition. The kurtosis values for the unoccluded ATF conditions ranged between 14.8 and 17.2. When the hearing protector is applied, the kurtosis is reduced significantly. The A-weighted attenuations ranged between 21 and 42 dB for the open filter Combat Arms earplug and the Express Pod Plugs, respectively. The other protectors yielded between 34 and 38 dB attenuation.

Table 1. The average L_{Aeq} levels, kurtosis values, and A-weighted Attenuation for the six hearing protector unoccluded and occluded conditions.

Hearing Protector	Unoccluded Condition		Occluded Condition		Attenuation A-weight (dB)
	L_{Aeq} (dB)	Kurtosis, β	L_{Aeq} (dB)	Kurtosis, β	
Impact 707	107.5 ± 3.0	15.0 ± 3.4	74.0 ± 3.8	2.6 ± 0.6	33.5 ± 4.6
EB-1	107.8 ± 2.4	14.8 ± 2.1	73.8 ± 3.0	6.2 ± 1.4	34.0 ± 1.1
CAE Closed	108.3 ± 4.4	15.4 ± 2.8	73.2 ± 2.4	7.1 ± 3.0	35.1 ± 3.6
CAE Open	105.8 ± 4.0	15.5 ± 2.9	84.8 ± 2.6	12.1 ± 3.5	21.0 ± 1.6
Pod	108.5 ± 4.3	17.2 ± 7.1	66.8 ± 4.1	6.6 ± 3.4	41.7 ± 5.5
Classic	108.9 ± 2.6	17.0 ± 4.6	70.7 ± 5.7	10.6 ± 6.6	38.2 ± 4.7

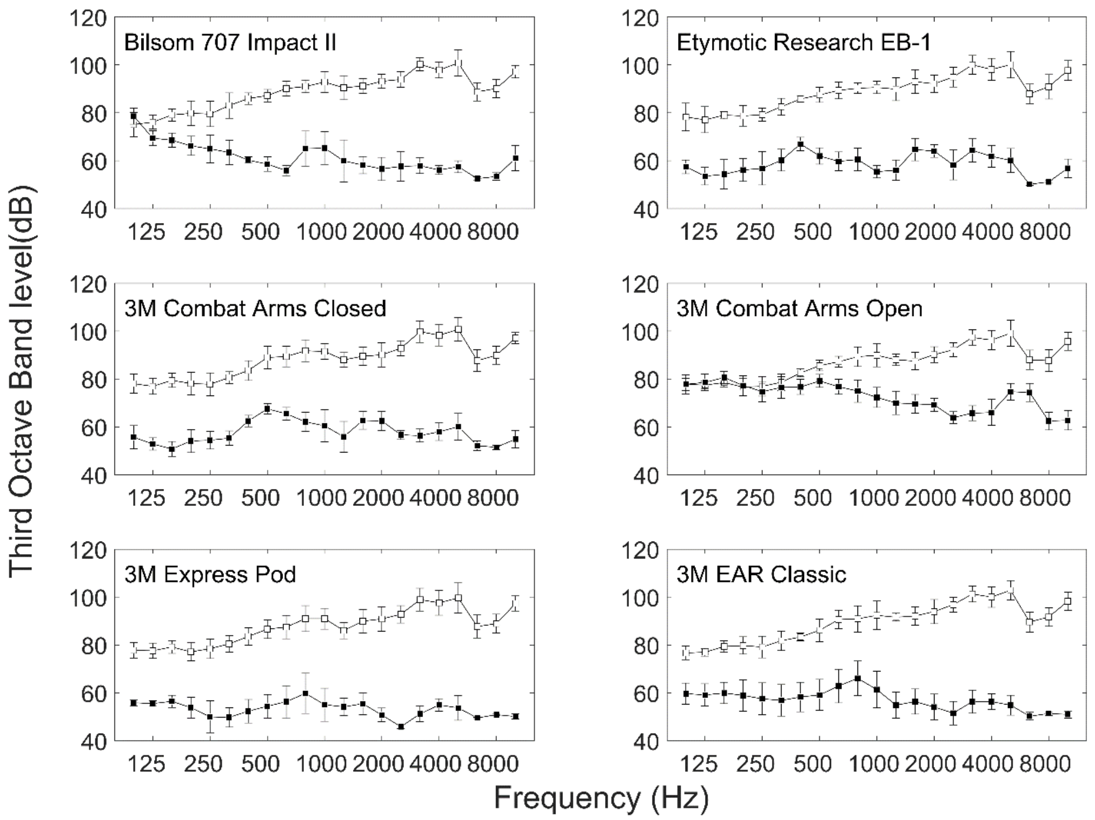


Figure 2. The spectra of the unoccluded and occluded recordings of the ATF with different hearing protectors. The unoccluded levels are shown as open symbols. The occluded levels are shown as solid black symbols. The error bars represent one standard deviation.

In Figure 2, the one-third octave band spectrum levels are presented for the unoccluded (open symbols) and occluded (closed symbols) conditions. The dominant region of the jackhammer noise is in the 3000 to 6000 Hz region. For the Bilsom 707 Impact II earmuff, the attenuation is nearly zero at the lowest frequencies. Similarly, the 3M Combat Arms earplug in the open filter condition has little attenuation for frequencies below 500 Hz. The Etymotic Research EB1 and the 3M Combat Arms closed filter condition have nearly the same occluded spectrum. This finding is not surprising considering that the design of the three flanges is nearly identical between the two products. The Express Pod and Classic earplugs also have similar occluded levels. The Express Pod earplugs fit completely within the ear canals of the fixture while about 60% of the Classic earplugs could be inserted into the ear canal of the fixture.

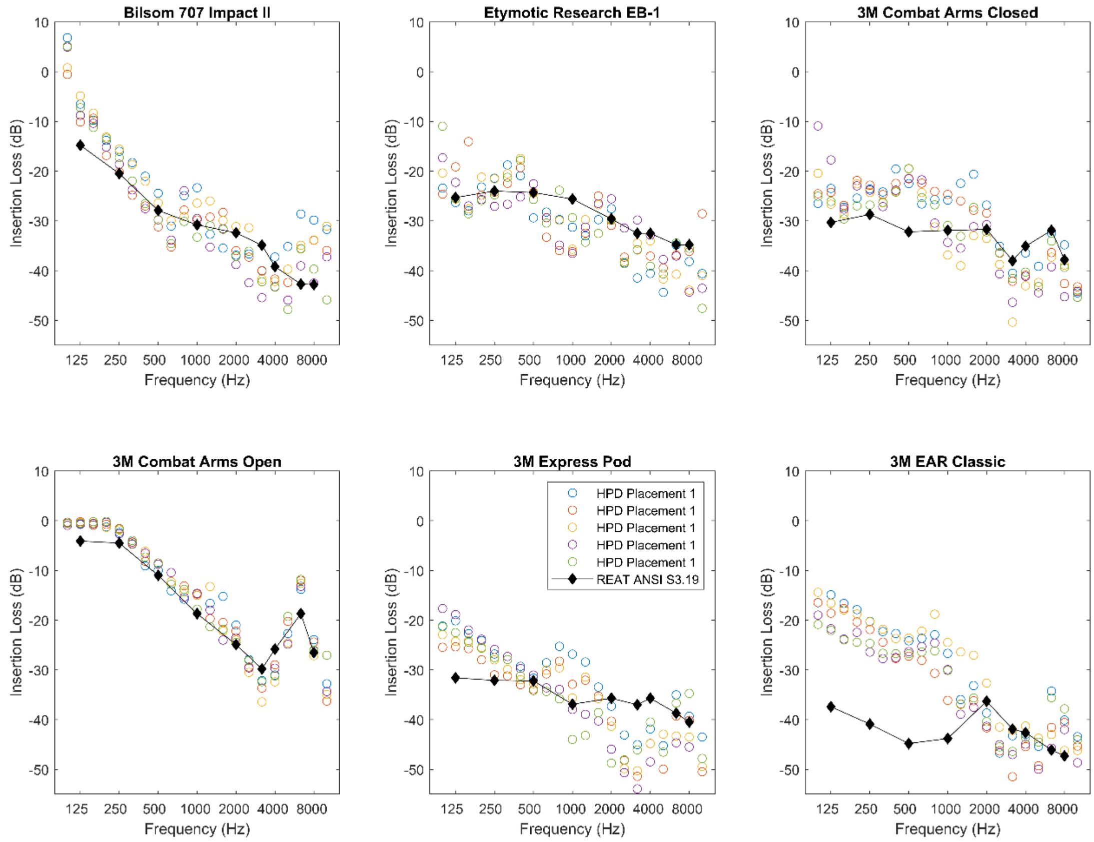


Figure 3. Comparison of ISIL results for each protector model and sample fitting with the Manufacturer's experimenter-fit REAT data.

In Figure 3, the ISIL results are compared to the manufacturers' published REAT data. The five fittings of the HPDs on the ATF are indicated with different colored circle symbols and the REAT are displayed as black diamonds connected with a solid line. The agreement of the ISIL with REAT is good except for the Express Pod and Classic earplugs. The results between 2 and 6 kHz on the ATF overestimate the REAT data for the Express Pod earplug. The REAT data from 125 to 1000 Hz overestimate the ATF data for the Classic earplug. Two competing factors might explain these differences for the Express Pod and Classic earplugs. Both plugs create the seal to the canal of the ATF with a foam material. The entire Express Pod plug fits into the canal and may provide greater attenuation than is observed in real persons due to the bone conduction that affects 2 to 4 kHz REAT data. The Classic plug is affected by the short ear canal of the ATF and fails to provide significant attenuation below 1000 Hz.

3.1 Effects of Kurtosis on Exposure Time

Kurtosis correction was calculated for all of the protected and unprotected conditions as shown in Table 2. The kurtosis adjustment, $\Delta L_\beta = \lambda \log_{10}\left(\frac{\beta}{\beta_G}\right)$, for the unoccluded condition was nominally a 3-dB increase. The occluded kurtosis corrections ranged from ΔL_β = -0.3 to 2.3 dB. The earmuff had the least kurtosis correction, -0.3 dB, and the open-filter Combat Arms earplug had largest correction, 2.3 dB. The other hearing protectors had about a 1 to 2 dB increase in the adjusted exposure level. The relative exposure time can be calculated, $T_{L,\beta}/T_L = 2^{\Delta L_\beta/3}$, where 3 is the exchange rate, $T_{L,\beta}$ and T_L are the exposure times for the kurtosis-adjusted and unadjusted exposure levels. For the Combat Arms earplug, the allowable exposure time would be reduced by about 60% when kurtosis is included.

Table 2. The average unprotected and protected L_{Aeq} levels, kurtosis correction levels and combined levels for the six hearing protector conditions.

Hearing Protector	Occluded Conditions			Unoccluded Conditions		
	L_{Aeq} (dB)	β- Adjusted Level (dB)	Combined Level (dB)	L_{Aeq} (dB)	β- Adjusted Level (dB)	Combined Level (dB)
Impact 707	74.0	-0.3	73.7	107.5	2.8	110.3
EB1 (Off)	73.8	1.2	75.0	107.8	2.8	110.6
CAE Closed	73.2	1.4	74.5	108.3	2.8	111.1
CAE Open	84.8	2.3	87.1	105.8	2.8	108.7
Pod	66.8	1.2	68.0	108.5	2.9	111.4
Classic	70.7	2.2	73.0	108.9	3.3	112.3

4. DISCUSSION

The kurtosis adjustment was dependent upon the protector more strongly than was expected. Before this investigation, the author would have suggested that the protector with the greatest attenuation ought to have the greatest effect on kurtosis. However in this case, the earmuff yielded the greatest reduction in the kurtosis adjustment. This effect may be explained by the greater attenuation of the high frequency noise relative to the low frequency noise provided by the earmuff. Impact and impulse noises tend to have sharp transitions from low amplitudes to high amplitudes (e.g. a gunshot, a hammer strike). Preferential filtering of high frequency noises by earmuffs should smooth out the transients more so than a flat attenuation spectrum that will uniformly attenuate all of the frequency content.

A second consideration for hearing loss prevention is not so much the added effect on the exposure levels caused by kurtosis, but rather the effectiveness of correct use of hearing protection. Without the kurtosis adjustment, all of the protectors reduced the jackhammer noise to below 85 dBA, the NIOSH REL. The Express Pod earplug had the lowest occluded exposure level as measured on the ATF. The Classic earplug provided the next lowest occluded exposure level. The additional length of the ear canal provided greater contact surface allowing the entire body of the foam earplug to be in contact with the ear canal walls in subsequent versions of the ISL acoustic test fixture and the GRAS 45 CB test fixture [11, 12, 13]. Related to hearing loss prevention, the proper fitting of an earplug in a worker's ear canal will have a far more significant reduction of the hazardous noise than worrying about whether the kurtosis is better reduced by one type of protector or another.

The Combat Arms open filter condition earplug might not be recommended for this particular noise exposure. Berger and Hamery [14] examined the response of the Combat Arms earplug in response to a range of impulse noise levels, 110 to 190 dB peak SPL. At the lowest level, the attenuation of the filter is minimally effective. The filter relies upon the pressure differential on either side of the filter (unoccluded to occluded) to change the viscous boundary layer in a nonlinear manner. At the jackhammer levels of about 110 dB SPL, the attenuation would be expected to be minimal. Thus, the open filter condition is an application of the wrong hearing protection device for the exposure. Murphy et al [15] tested an advanced hearing protection device with a group of workers at a metal fabrication stamping plant. This product also used a filter inserted into the sound bore of a semi-custom earplug. Many workers returned the semicustom earplugs and reverted to the foam earplugs that they had been accustomed to because the stamping noise transmitted by the semi-custom earplugs was much louder than they were used to experiencing. They preferred the earplugs that gave higher levels of attenuation.

5. CONCLUSIONS

The protection afforded by a properly fit HPD was between 20 and 42 dB. For all of the protectors, the occluded levels before adjusting for kurtosis were below the 85 dB(A) NIOSH permissible exposure level. The Combat Arms earplug with the filter open was close to the 85 dB(A) PEL, and when kurtosis was accounted for, the adjusted level was 87 dB(A). For the other HPDs, the protected levels were at or below 75 dB(A) with and without kurtosis adjustment. The kurtosis adjustment increased the exposure levels slightly, which translated to a reduced exposure time. Hearing protection provided a far greater reduction in exposure time. As always, proper fitting and consistent use of hearing protection when in hazardous noise should be emphasized.

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