The Effect of Selected Theoretical Distributions of Sound Levels on the Calculated Noise Dose

by

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ABSTRACT

The determination of a noise dose during a work shift is affected by, among other factors, the distribution of sound levels. Sound levels can be assumed to follow different theoretical distributions. The two most commonly used distributions for evaluating occupational exposures to contaminants are the normal and lognormal. Noise exposure has been shown to follow either distribution.

This report discusses the effects of normal, lognormal, and weibull distributions on the noise dose. Each chosen distribution is selected to have the same arithmetic mean and standard deviation. Three conditions are investigated: the mean equal to the threshold (the sound level above which noise contributes to the noise exposure), the mean 10 dB greater than the threshold, and 10 dB below the threshold. Each of the selected theoretical distributions has a different effect on the calculated noise dose.

A comparison is made between the noise dose, as calculated, simply using the average sound level and that calculated considering the sound level distribution. The former is associated with sound level measurements and the latter with personal noise

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dosimeter measurements. As expected, the resulting differences between the two methodologies are influenced by the assumed means and standard deviations of sound level distributions. It appears that the lognormal distribution exerts the greatest influence, which can be substantial for large standard deviations. The 3 dB exchange rate exacerbates the effect compared to the 5 dB exchange rate.

The implication of the influence of the assumed distribution of sound levels is that workers may be included in a hearing conservation program (HCP) where this is not necessary. However, worse is the possible exclusion of a worker who should be enrolled in an HCP.

INTRODUCTION

A sound level meter (SLM) or a personal noise dosimeter is often used to assess a worker's daily or long-term noise exposure. Both instruments have been widely utilized in determining occupational noise exposure. The main attraction of the personal noise dosimeter is its ease of use and its ability to integrate fluctuating sound fields continuously. In addition, a personal noise dosimeter can provide a histogram for hearing protector effectiveness evaluations, identify dominant noise sources for noise control purposes, and survey job functions for which SLMs are not practical. Further, by using multiple personal noise dosimeters, an industrial hygienist can determine the individual noise exposure of several workers simultaneously. The SLM, on the other hand, is labor intensive requiring the presence of the industrial hygienist and the continuous interpretation of the noise reading. It also requires tedious calculations for determining the noise dose. However, some feel that it is advantageous to have the expertise of the industrial hygienist, or other specialist, there, on-site, during the noise measurement as contrasted to the automated measurement of the personal noise dosimeter. On the contrary, having a professional observer on-site at even a very small fraction of the U.S. work sites is not practical. Therefore, the personal noise dosimeter will be the instrument of primary choice if accurate U.S. worker noise exposure histories are to be established.

If the exposure is confined to a single steady-state (non-varying) sound level, then computing the noise dose would be easy. However, workers are not generally exposed to such an idealistic noise environment. Typically the sound levels vary continuously throughout the work shift. These variations of sound levels make it cumbersome to compute the noise exposure using an SLM measurement sampling methodology. Furthermore, assigning a sound level and the time period to fluctuating SLM needle movements for most real world environments is difficult, if not impossible.

While an integrating SLM is capable of continuously integrating fluctuating noise automatically, the measuring technician must be able to hold the integrating SLM in the hearing zone of the worker without endangering either the technician or the worker. According to Royster[1], the technician would have to obtain several samples over the work shift in order to approximate the accuracy of the data obtained using a personal noise dosimeter. In addition, the International Standards Organization[2] and the American National Standards Institute[3] in their standards for measuring occupational noise exposure state that the time for SLM measurements must be of sufficient duration to characterize the exposure. This implies that several measurements will be necessary.

The noise dose, as calculated from SLM readings and time intervals, is generally computed using the estimated mean sound level during the time interval of interest. For this method the standard deviation, associated with the mean sound level of the fluctuating meter needle, is usually not taken into account. In contrast, the personal noise dosimeter continuously integrates fluctuating noise automatically taking into account the distribution of sound levels along with the mean sound level. Therefore, the noise exposure as measured with this type of instrument should correspond closely to the true noise dose.

It will be shown that the noise dose as measured with an SLM can differ substantially from that measured with a personal noise dosimeter especially for widely fluctuating sound fields. The difference is a function of the mean sound level and the standard deviation of the sound level distribution. The effect is most pronounced near the threshold. The threshold is the sound level at which the SLM or personal noise dosimeter begins to integrate the measured sound levels into the noise exposure. In order to estimate the expected differences that result in ignoring the standard deviation of the distribution of sound levels, the following procedures is used.

PROCEDURE

In order to simplify the calculations, variations in sound level are assumed to occur over a total exposure time of 480 minutes. Figure 1 shows a typical variation of sound levels with respect to time. For this study, it is assumed that the temporal variations in sound level can be represented by any one of the sound level distributions (normal, lognormal, or weibull) shown in Figure 2. As can be seen, each is unimodal having a different characteristic shape. Mathematical descriptions of the three distributions, along with defined means and standard deviations, are given in Appendix I.

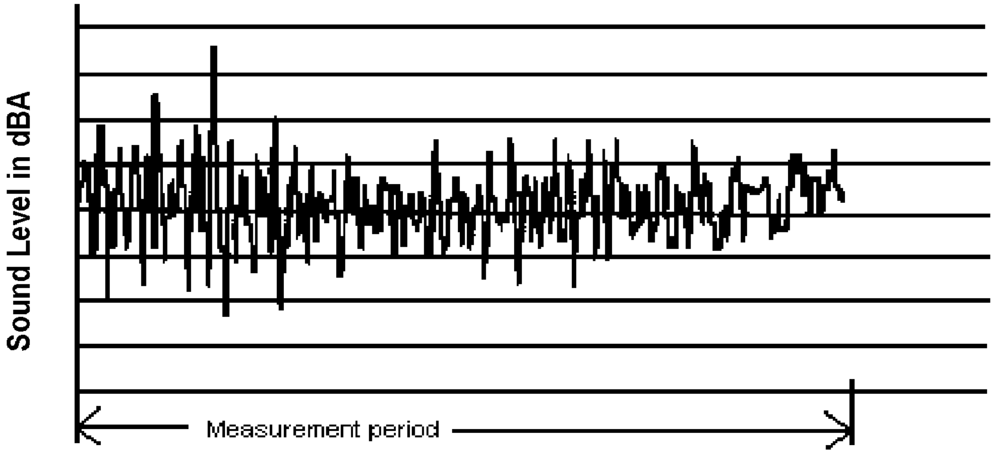

Figure 1. Time History of the Noise

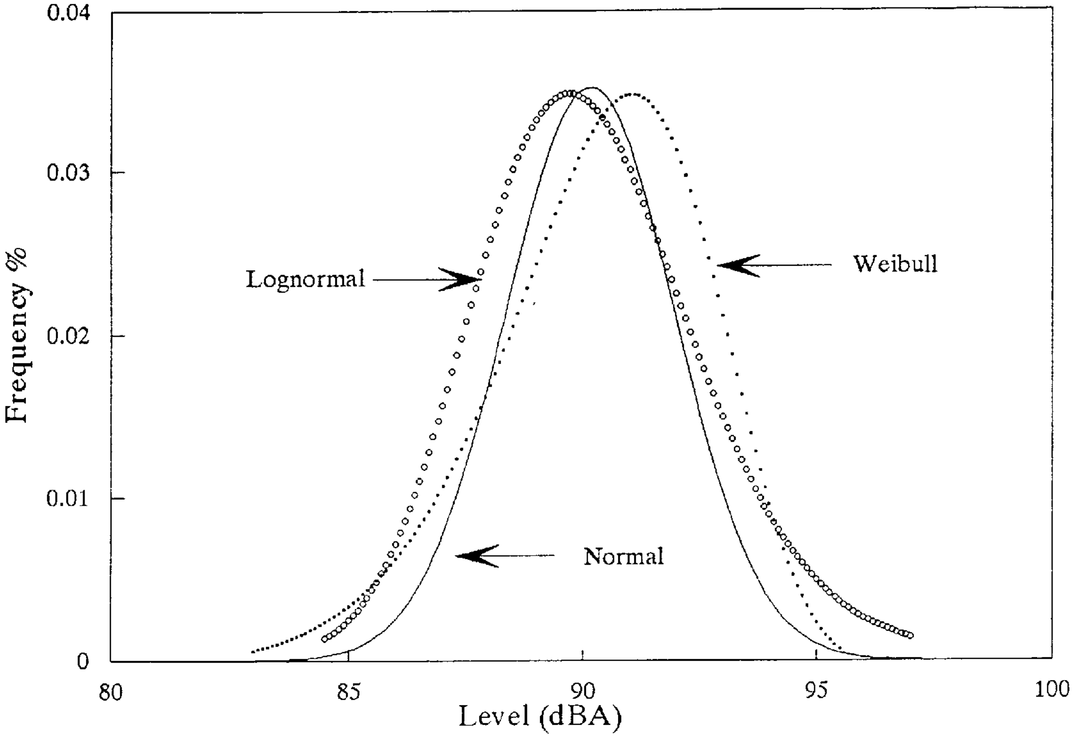

FIGURE 2. Graphical Description of the Three Sound Level Distributions Used

Many researchers have used the normal distribution to describe biological phenomena. Its bell-shaped curve which is symmetrical at both tails is one of the most recognized functions. According to Lancaster[4], the distribution of single shift noise exposures approximately follows a bell-shaped curve.

The lognormal distribution is another widely recognized function. It has often been used to describe the day-to-day exposure to occupational contaminants[5]. Also, the size distribution of aerosol particles has been described as following a lognormal distribution[6]. This distribution is skewed as its right tail is longer than its left tail. Valoski[7] has shown that the day-to-day distribution of noise exposures of underground coal miners follows the lognormal distribution better than the normal distribution.

The weibull distribution was originally developed by Weibull[8] for studies in statistical reliability of the lifetimes of components and systems. This distribution is chosen for this study because it is asymmetric, having a longer left tail than right tail. The intent of its inclusion is to represent those worker noise exposures having a preponderance of lower sound levels as contrasted with the lognormal distribution, which has a preponderance of higher sound levels.

CALCULATIONS

To estimate the noise dose obtained from SLM readings the following equation is used:

$$D_{SLM} = 100\frac{C}{T} \qquad \textbf{(1)}$$

Where:

D_{SLM} = Percent noise dose as calculated from the L_{AVG} sound level,

C = Exposure time at the L_{AVG} sound level (480 minutes),

T = Allowable exposure time for the L_{AVG} sound level.

To estimate the noise dose, as obtained from the personal noise dosimeter, the apportionment of sound levels is constructed for the selected distributions with intervals of 0.02 dBA. These small intervals allow the calculation of noise doses in increments that closely approximate a continuous distribution. To keep the mathematics simple, a 480-minute exposure to a single sound field containing one distribution of fluctuating levels was assumed. The analysis for this simple situation can be extended to complex noise exposures where the worker is subjected to multiple sound fields.

The mean sound levels are chosen to represent a range of sound levels from substantially below the threshold to substantially above the threshold. Moreover, the standard deviations are chosen to encompass the range of standard deviations typically encountered in the mining industry based upon the authors' experience[9].

Each mean sound level and its associated standard deviations are inserted into the proper distribution equation to determine the probability density for that noise distribution. The exposure time at each sound level is determined by multiplying the probability of being at that level by 480 minutes. Once the time at each sound level is determined, the noise dose is calculated using the following equation.

$$D_{DOS} = 100\sum\frac{C_i}{T_i} \tag{2}$$

Where:

D_{DOS} = Percent noise dose as calculated from the appropriate distribution,

C_i = Exposure time at the ith sound level (minutes),

T_i = Allowable exposure time at the ith sound level (minutes).

The allowable exposure times are based upon a 90-dBA criterion level ($L_{Criterion}$) and either a 90-dBA or 80-dBA threshold ($L_{Threshold}$). The effect of a 5 dB and a 3 dB exchange rate is also examined. If the sound level is below the threshold then the allowable duration is infinity. This results in a noise dose of 0% for those sound levels regardless of exposure duration.

RESULTS AND DISCUSSION

Three selected conditions are thought to cover most situations. The mean sound level was varied from 10 dBA below threshold to 10 dBA above threshold. Besides varying the mean sound level, the standard deviations were also varied.

The findings for the condition where the mean sound level is 10 dBA above the threshold are shown in Figures 3 and 4 for the 5 dB and 3 dB exchange rates, respectively. The dose that would be computed using a sound level meter and time-level study is shown on the Figures as D_{SLM}. In the Figures, the standard deviation in dBA is along the horizontal axis and the dose in percent is along the vertical axis.

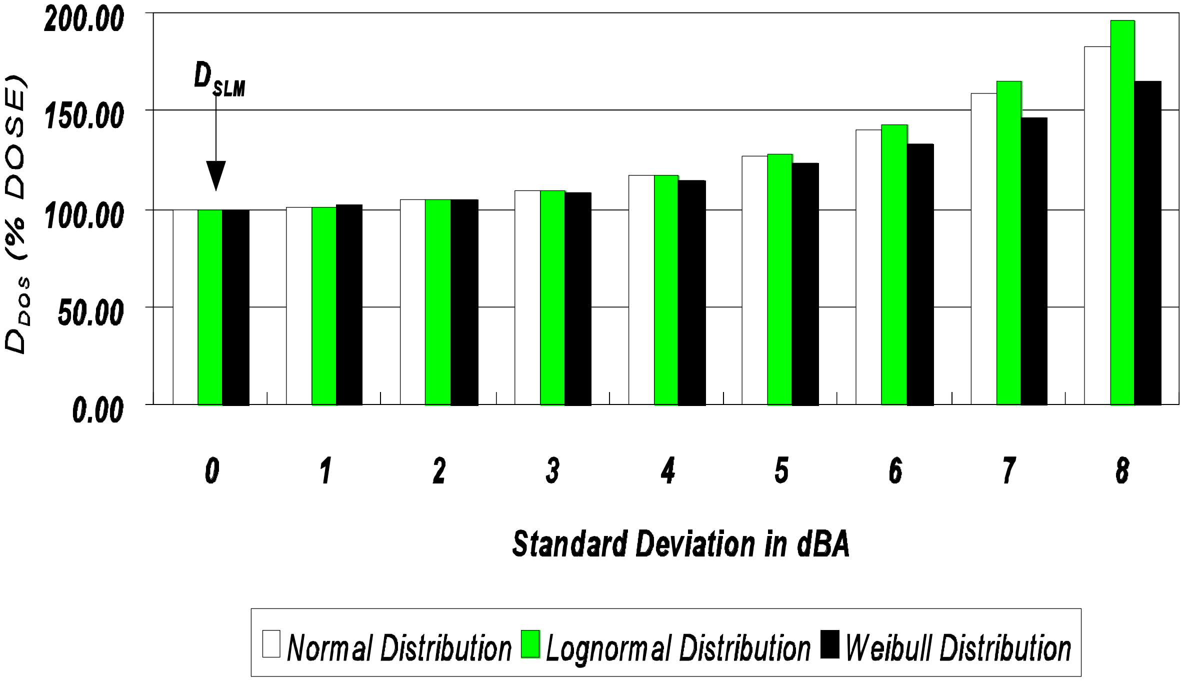

Figure 3 Comparison of D_{DOS} and D_{SLM} for L_{AVG} 10 dBA above $L_{Threshold}$ and a 5 dB Exchange Rate (L_{AVG} = 90 dBA, $L_{Threshold}$ = 80 dBA, $L_{Criterion}$ = 90 dBA)

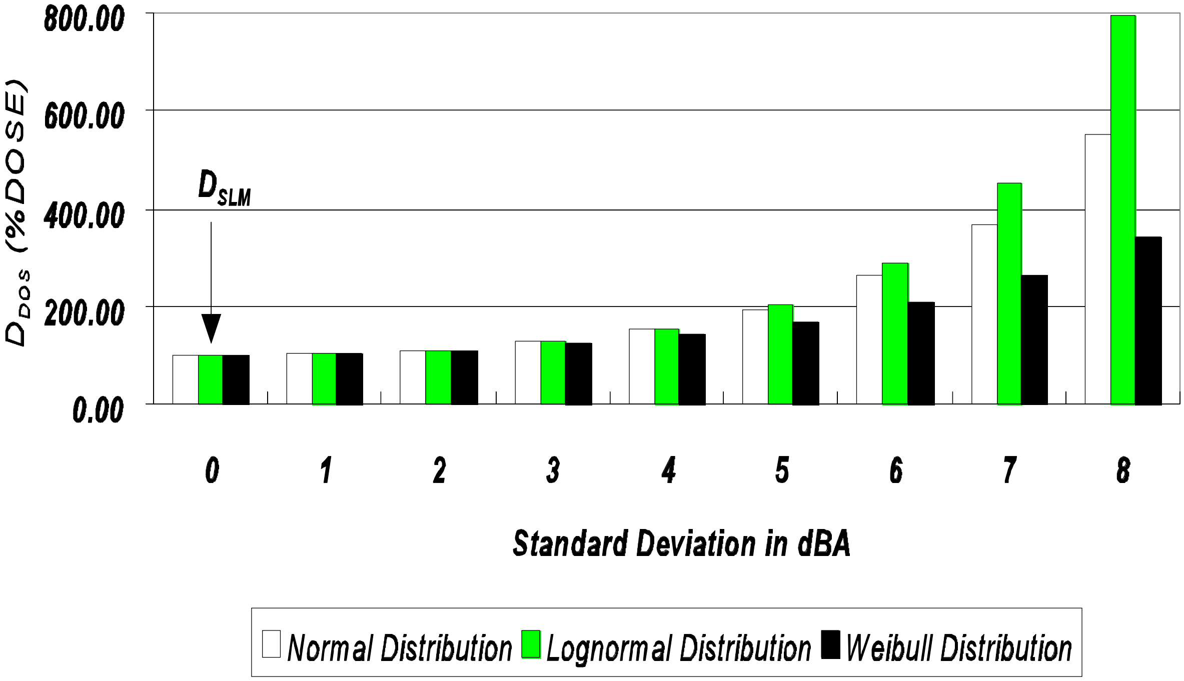

Figure 4 Comparison of D_{DOS} and D_{SLM} for L_{AVG} 10 dBA above $L_{Threshold}$ and a 3 dB Exchange Rate (L_{AVG} = 90 dBA, $L_{Threshold}$ = 80 dBA, $L_{Criterion}$ = 90 dBA)

As can be seen in Figures 3 and 4, the standard deviation affects the noise dose as obtained with the personal noise dosimeter, D_{DOS}, differently for each distribution. D_{DOS} is at least equal to the noise dose as obtained with the SLM, D_{SLM}. As the standard deviation increases, D_{DOS} also increases. Once the standard deviation exceeds one, the weibull distribution has the smallest D_{DOS} and the lognormal distribution the largest. In fact, at large standard deviations, regardless of assumed distribution, D_{DOS} is more than double D_{SLM}. The same pattern is true for the 3 dB exchange rate; however, the differences between the distributions are more dramatic. This effect of the 3 dB versus 5 dB exchange rate is consistent with the finding of Christensen[10]. Christensen found that there were large differences in the doses determined with a 5 dB and a 3 dB exchange rates for widely fluctuating noises.

The condition where the mean sound level equals the threshold is presented in Figures 5 and 6 for the 5 dB and the 3 dB exchange rates, respectively. Here, for small standard deviations, D_{DOS} is clearly less than D_{SLM}. For large standard deviations, D_{DOS} exceeds D_{SLM}. At small standard deviations, the weibull distribution has the largest D_{DOS}. However, at large standard deviations, the lognormal distribution has the greatest D_{DOS}. At larger standard deviations, regardless of assumed distribution, D_{DOS} is more than double D_{SLM} for the 3 dB Exchange Rate and nearly double for the 5 dB Exchange Rate. Like the other conditions, the 3 dB exchange rate exacerbates the situation.

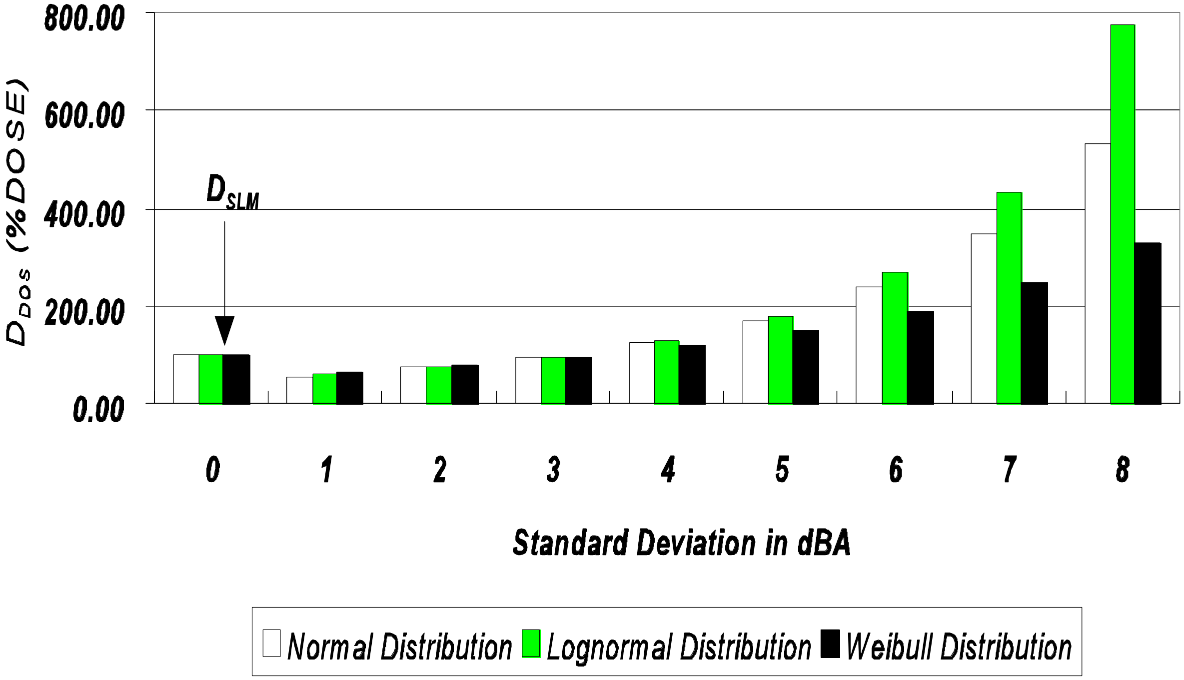

Figure 5 Comparison of D_{DOS} and D_{SLM} for L_{AVG} equal to $L_{Threshold}$ and a 3 dB Exchange Rate (L_{AVG} = 90 dBA, $L_{Threshold}$ = 90 dBA, $L_{Criterion}$ = 90 dBA)

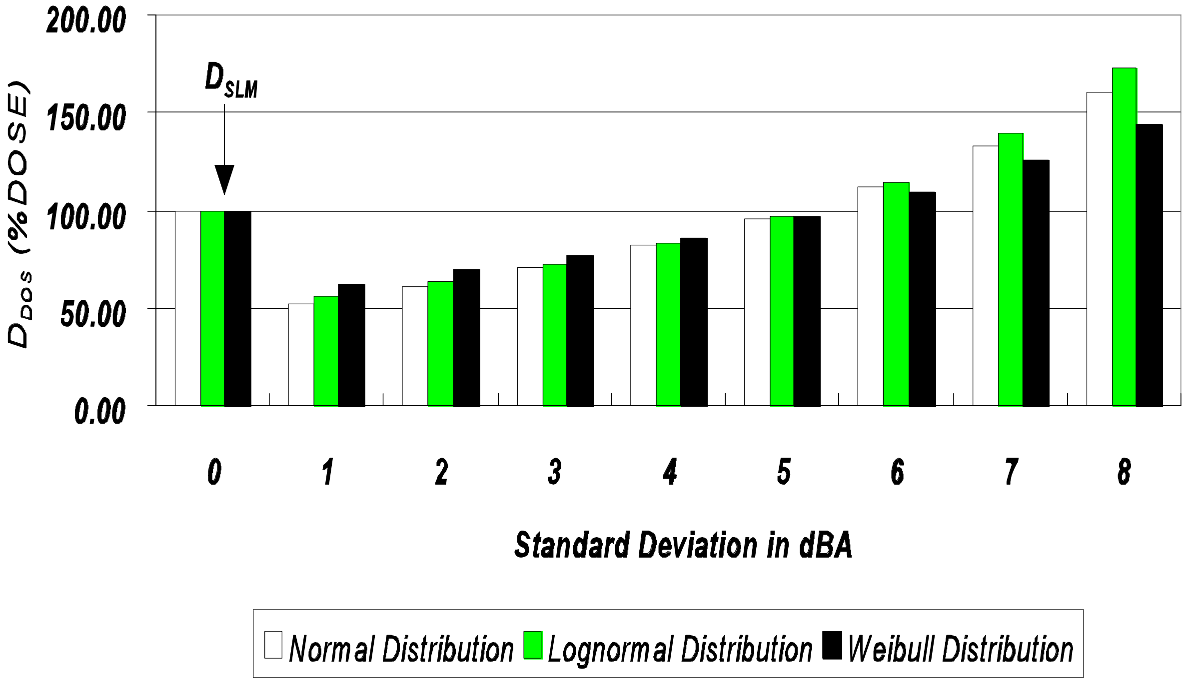

Figure 6 Comparison of D_{DOS} and D_{SLM} for L_{AVG} equal to $L_{Threshold}$ and a 5 dB Exchange Rate (L_{AVG} = 90 dBA, $L_{Threshold}$ = 90 dBA, $L_{Criterion}$ = 90 dBA)

Figures 7 and 8 present the condition where the mean sound level is 10 dBA below the threshold for the 5 dB and 3 dB exchange rates, respectively. Like the condition discussed above, the weibull distribution yields the smallest D_{DOS} and the lognormal distribution the largest. Not until the standard deviation reaches 4 dB does the calculations yield a noise exposure. The 3 dB exchange rate exacerbates the situation.

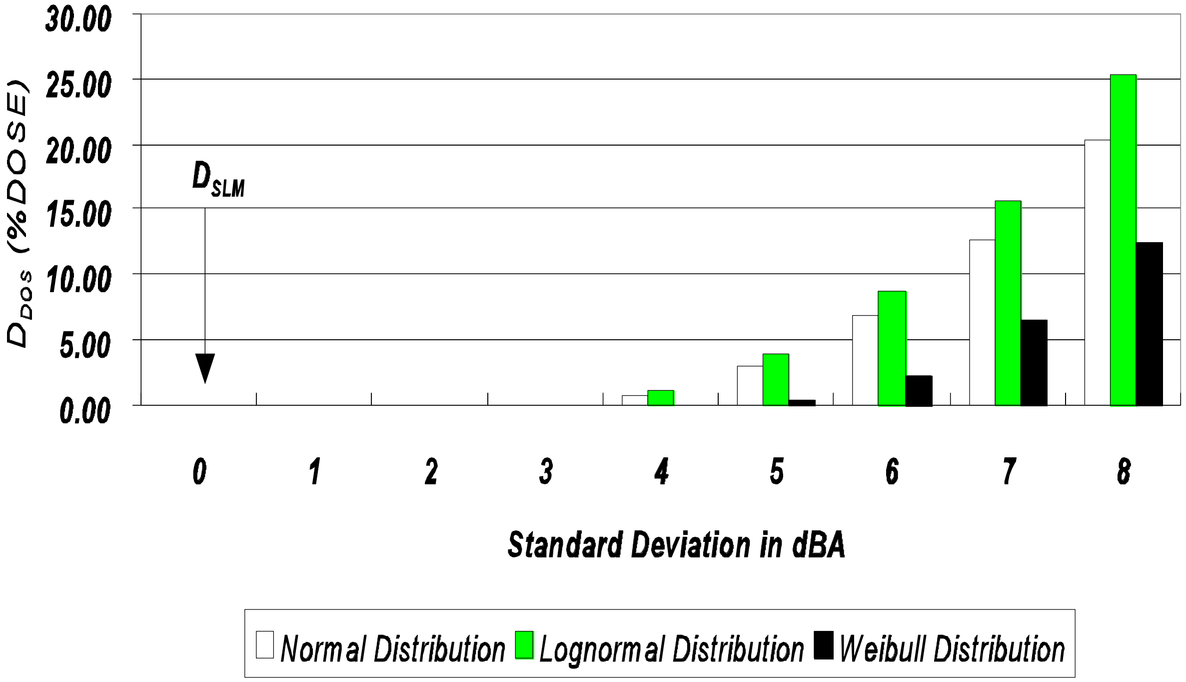

Figure 7 Comparison of D_{DOS} and D_{SLM} for L_{AVG} 10 dBA below $L_{Threshold}$ and a 5 dB Exchange Rate (L_{AVG} = 80 dBA, $L_{Threshold}$ = 90 dBA, $L_{Criterion}$ = 90 dBA)

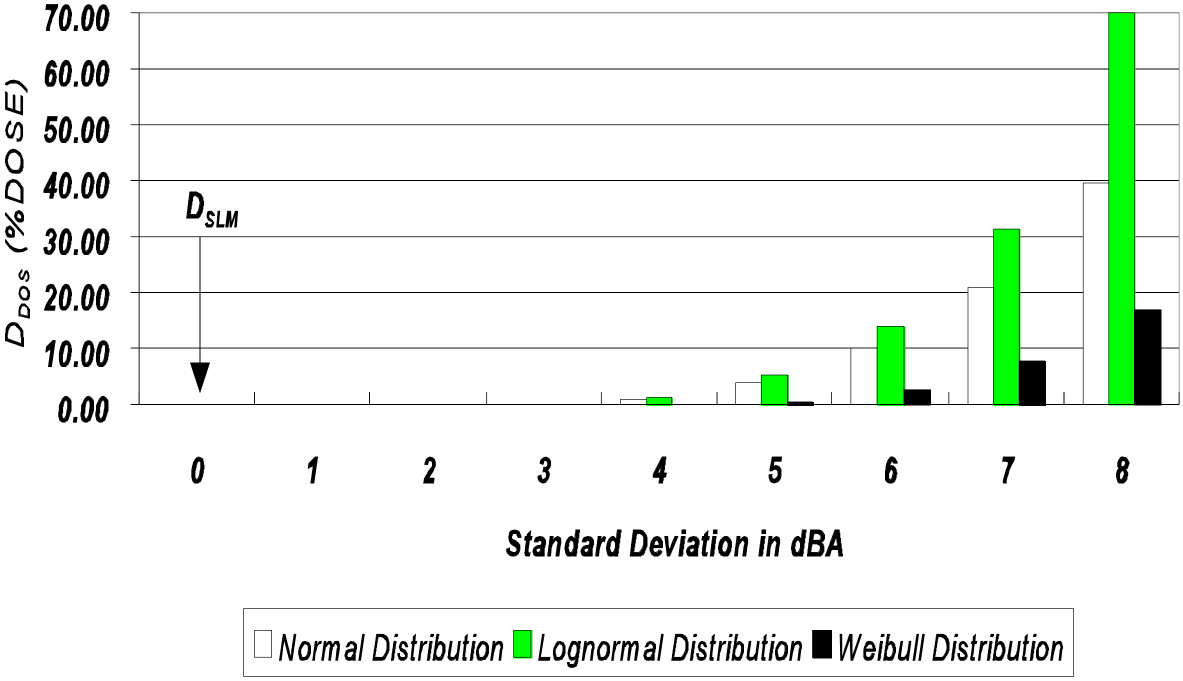

Figure 8 Comparison of D_{DOS} and D_{SLM} for L_{AVG} 10 dBA below $L_{Threshold}$ and a 3 dB Exchange Rate (L_{AVG} = 80 dBA, $L_{Threshold}$ = 90 dBA, $L_{Criterion}$ = 90 dBA)

CONCLUSIONS

The computed noise dose using the mean sound level can differ dramatically from the calculated noise dose using an assumed distribution of sound levels. Generally, the larger standard deviations magnify the effect. At large standard deviations, the calculated noise dose, using the distribution, D_{DOS}, can greatly exceed the noise dose calculated by simply using the mean sound level, D_{SLM}. The exception is where the mean sound level is significantly below the threshold. The effect of standard deviations is most pronounced where the mean sound level is equal to the threshold. As the personal noise dosimeter continually integrates all the fluctuations into the noise exposure, it provides a better measure of noise exposure in varying sound fields. Further, the effect of the distribution of sound levels is exacerbated by using a 3 dB exchange rate.

Calculation of exposure based solely on the mean sound level could result in the worker erroneously enrolled in or, worst yet, not enrolled in a hearing conservation program.

The assumption of the type of distribution that the sound levels follow can greatly affect the calculated noise dose. Generally, the lognormal distribution has the largest noise doses and the weibull has the smallest.

One possible solution for overcoming the effect of large standard deviations on calculation of the noise exposure based upon mean sound level meter measurements is to determine the noise exposure using a personal noise dosimeter. When using this type of instrument, the technician is removed from dangerous situations. While the integrating SLM, like the personal noise dosimeter, continually integrates all the fluctuations into the noise exposure, this instrument has the disadvantage of having the technician hold the instrument in the hearing zone of the worker. Holding the integrating SLM in the hearing zone of the worker may endanger the technician or the worker. Furthermore, in order to approximate the accuracy of a personal noise dosimeter measurement, several integrating SLM measurements over the work shift would be necessary.

Appendix I. Mathematical Description of the Distributions Used

The mean and standard deviation of the samples collected are calculated using:

$$L_{avg} = \sum_{i=1}^{n} \frac{L_i}{n} \qquad \textbf{(3)}$$

$$S_L = \sum_{i=1}^{n} \frac{(L_i - L_{avg})^2}{n-1} \qquad \textbf{(4)}$$

Where:

L_i = ith sound level sample collected

n = number of sound level samples collected

If a **<u>normal distribution</u>** is assumed the probability density function can be written as:

$$F(L) = \frac{1}{\delta\sqrt{2\pi}} e^{-\frac{(L-\mu)_2}{2\delta^2}} \qquad \textbf{(5)}$$

Where:

μ = mean of the normal distribution

σ = standard deviation of the normal distribution

When the normal distribution is used in conjunction with the collected sound level samples then:

$$\mu = L_{avg}$$

If a **lognormal distribution** is assumed the probability density function can be written as:

$$F(L) = \frac{1}{L\sigma\sqrt{2\pi}} e^{-\frac{[\ln(L)-\mu]^2}{2\sigma^2}} \tag{6}$$

$$mean_{lognormal} = e^{\frac{(2\mu - \sigma^2)}{2}} \tag{7}$$

$$SD_{lognormal} = \sqrt{e^{2\mu + \sigma^2}\,(e^{\sigma^2} - 1)} \tag{8}$$

When the lognormal distribution is used in conjunction with the collected sound level samples then μ and σ are chosen so that:

$$mean_{lognormal} = L_{avg}$$

$$SD_{lognormal} = S_L$$

When the **weibull distribution** is assumed the probability density function can be written as:

$$F(L) = \alpha\beta^{-\alpha} L^{\alpha - 1} e^{-\left(\frac{L}{\beta}\right)^{\alpha}} \tag{9}$$

Where the mean and standard deviation of the weibull distribution are:

$$mean_{weibull} = \frac{\beta}{\alpha}\,\Gamma\left(\frac{1}{\alpha}\right) \qquad \textbf{(10)}$$

$$SD_{weibull} = \sqrt{\frac{\beta^2}{\alpha}\left\{2\Gamma\left(\frac{2}{\alpha}\right) - \frac{1}{\alpha}\Gamma\left(\frac{1}{\alpha}\right)^2\right\}} \qquad \textbf{(11)}$$

When the weibull distribution is used in conjunction with the collected sound level samples then α and β are chosen so that:

$$mean_{weibull} = L_{avg}$$

$$SD_{weibull} = S_L$$

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