A New Method for Rating Hazard from Intense Sounds: Implications for Hearing Protection, Speech Intelligibility, and Situation Awareness

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IMPLICATIONS OF A NEW METHOD FOR RATING HAZARD FROM INTENSE SOUNDS

The auditory hazard assessment algorithm for the human (AHAAH), developed by the US Army Research Laboratory, is theoretically based and has been demonstrated to rate hazard from intense sounds much more accurately than existing methods. The AHAAH model operates in a PC level computer and analyses hazard in the time domain. In addition to reproducing the conductive path from air to the cochlea accurately it includes a non-linear stapes (clips large displacements) and an active middle ear muscle system. It is being written into a new US Army MIL-STD-1474(e) and is used by the Society of Automotive Engineers for the analysis of airbag noise hazard. The model shows that low-frequency energy at high levels can act to reduce the flow of energy into the inner ear, reducing the hazard. Traditional analyses tend to overrate the hazard from large calibre weapons impulses. The model also shows that impulses with little low-frequency energy, e.g. rifles, may be underrated in hazard by traditional methods. Hearing protective devices (HPDs), in order to be effective for gunfire type impulses, were shown to need most attenuation in the mid-range and less at lower frequencies, much like the attenuation curve for the non-linear combat arms plug. At the same time, speech intelligibility with such an attenuator could be much better than for an HPD with good low-frequency attenuation. Future developments of the model will include expansion to cover a wider range of intensities and an adaptive middle ear muscle system.

1.0 INTRODUCTION

Intense noise fields around weapon systems pose a variety of critical problems in which the requirements for protection, communication and effective weapon systems intertwine in complex ways. With the continuing emphasis on high performance and light weight, the noise fields in and of themselves have become a hazard from which the ear and even the body may need to be protected. Recent statistics from the battlefield suggest that even with considerable emphasis on hearing conservation, hearing loss nevertheless ranks fourth in the list of casualty-producers. This fact makes two points. First, protecting the ear through improved equipment design and adequate hearing protection are not options, but are requirements in the modern military. And second, the fact that hearing loss is a casualty-producer demonstrates that the sense of hearing is now understood to be essential to adequate soldier performance in the military. It is needed both for the purpose of communication as well as for providing situation awareness. Thus the sense of hearing must be protected and maintained in as near a normal state of acuity as possible.

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However, when we protect the ear, we often inadvertently create an auditory deficit by reducing sensitivity to sound as well as by interfering with the auditory system's ability to localize noise sources. In this case the cure is remarkably similar to the disease!

If, on the other hand, we seek to reduce the noise at the source, then a second set of dilemmas present themselves. Hazard reduction at the source is the ideal answer; however, it typically involves reducing the energy in the source or providing shielding from it. The first alternative may make the system less powerful (and therefore exposes troops to greater risk) while shielding may add unacceptable weight.

Dealing effectively with these problems requires a good theoretical grasp of the parameters involved so that intelligent compromises can be made that will optimise system performance. In this talk we will focus on the new perspective brought to these issues by a new method of rating hazard from intense sounds that has been developed by the US Army Research Laboratory. The Auditory Hazard Assessment Algorithm for the Human (AHAAH) is essentially an electro-acoustic analog of the ear written as a computer program. It is presently being written into what will become MIL-STD-1474 (e) and has already been accepted by the Society of Automotive Engineers as the procedure for calculating the hazard from airbag noise exposures (SAE, 2003). The program and its supporting documents are available for download at www.arl.army.mil/ARL-Directorates/HRED/AHAAH/.

Central to dealing with the optimisation of system performance in the military is the ability to evaluate the hazard associated with intense sounds and the protection provided by HPDs. This presentation will introduce the AHAAH model, describe its validation and explore some of its implications.

In his keynote address at this meeting, Dr. Dancer has already pointed out that noise issues limit weapon design. Overestimation of hazard, often done on the pretext that it is "conservative", nevertheless leads to inferior weapon design, which in turn results in casualties and jeopardizes mission accomplishment Present criteria tend to err in this direction. Likewise, underestimation of hazard leads to hearing loss in troops, which also creates casualties and jeopardizes mission accomplishment. The goal in predicting hazard must be accuracy – errors in either direction must be avoided.

2.0 THE AHAAH MODEL

2.1 The Interpretive Challenge

Currently, the world's standards rate hazard based on some measure of pressure and duration or alternatively by measuring the A-weighted energy in the exposure. Today there is general agreement that these standards for intense noise exposures (140 dBP and above) work very poorly. In addition to being inaccurate, they lack a theoretical base, relying on correlations between various noise measures and incipient hearing loss in human subjects. Therefore, without a solid theoretical understanding, when impulses with unusual pressure histories arise, there is little certainty that the existing methods of analysis will fit. This situation has produced paradoxical data. Consider that a rifle impulse at the firer's ear contains a little over 1 J/m^2 of A-weighted energy. Data from soldiers firing the FNC rifle (Brinkmann, 2000) suggest that an unprotected exposure of 5 rounds fired from one's own weapon would be just on the verge of producing permanent hearing loss in the 95%ile ear. This agrees well with the French use of A-weighted energy, which would allow an 8.7 J/m^2 exposure (Dancer, 2000). At the same time, data from the US Army's Albuquerque studies (Johnson, 1998; 1994) have demonstrated that an exposure to 2000-3000 J/m^2 from a simulated cannon impulse, (also A-weighted) at the ear canal entrance, produced no hearing loss. Thus, on the basis of A-weighted energy somewhere between 5 and 3000 rifle shots would be tolerable. It is clear that at these levels A-weighted energy rates hazard very poorly.

Or consider the interpretive problem associated with the alternative schemes used in Germany (Pfander, 1975), The Netherlands (Smoorenburg, 1980), the UK (Ministry of Defence, 1982) and the US (MIL-STD-1474(d), 1997). In these criteria differing measures of peak pressure and duration are used to enter a hazard analysis diagram. The data discussed in the previous paragraph appear in Fig. 1 where we see pressure histories of the two impulses. The rifle impulse was recorded in the free field at the firer's ear location and the simulated cannon impulse was recorded at the ear canal entrance under an earmuff. In all the criteria, higher pressures and longer durations are rated as more hazardous. The problem is that 6 of the rifle impulses are hazardous and 100 of the simulated cannon impulses are in fact safe. It is difficult to see how any method of rating hazard that depends on a measure of peak pressure and duration could possibly hope to reconcile these data.

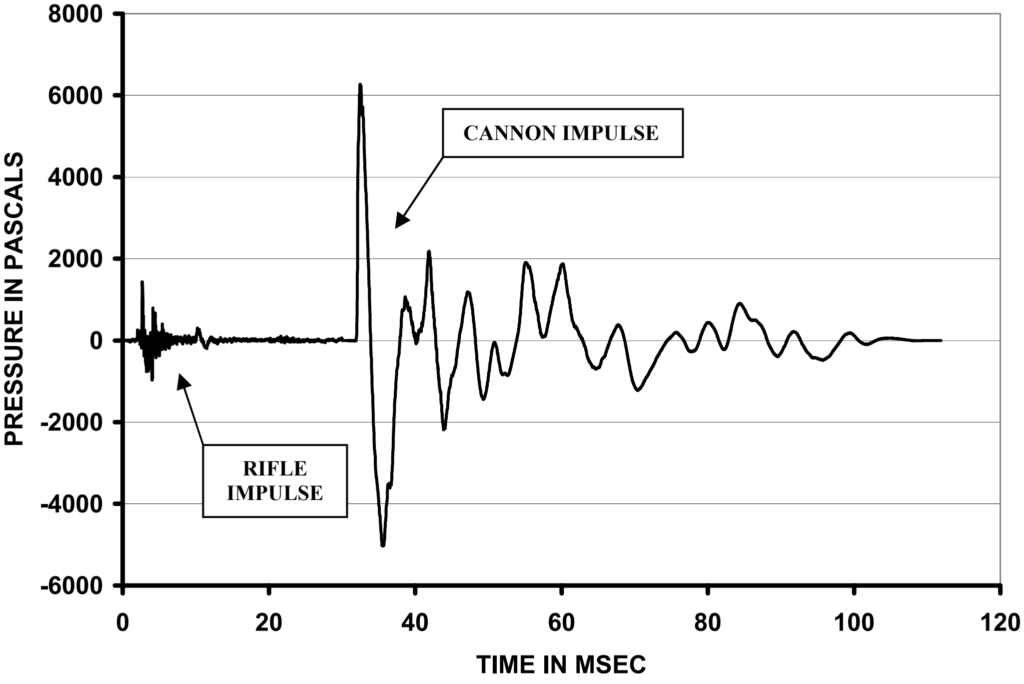

Figure 1. Pressure history of a rifle impulse followed by a cannon impulse.

2.2 Approach to Solving the Problem

Rather than seek yet another acoustic metric that might correlate with hearing loss, we approached the problem by trying to establish a theoretically based understanding of how the ear operates at high intensities. Once those processes were understood, then the appropriate metric(s) became apparent. In the end, the basis for hearing loss at high intensities can be understood initially to be mechanical disruption of the tip links within the hair cells in the organ of Corti, as illustrated in Fig. 2. If the amplitudes continue to rise, the extent of the mechanical disruption can, of course, rise to the destruction of the organ of Corti itself. At the level of the hair cell, the basic loss process is taken to be mechanical stress modelled as a fatigue of materials, i.e. we keep track of the number of flexes of the basilar membrane and their amplitudes (in microns, upward flexes only), square them, and accumulate the sum at 23 locations within the cochlea (roughly 1/3 octave intervals). The result of this calculation is called the Auditory Risk Unit (ARU). The model does not actually calculate the hair cell movements; but takes the simpler option of calculating basilar membrane displacements, which are the forcing function for the hair cell displacements.

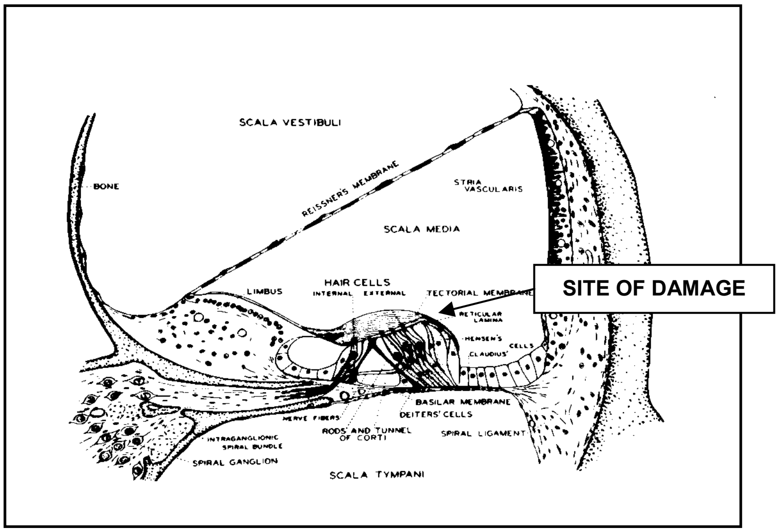

Figure 2. Cross section of the organ of Corti showing likely site of initial damage

The real complexity for predictive purposes lies in the multiple non-linearities that are part of the ear's basic physiology. It is well known that the ear is differentially sensitive to frequency, conducting sound best in the mid-range of frequencies, cutting off at the low frequencies because it is too stiff and at the high frequencies because it is too massive. The ear is also equipped with middle ear muscles that contract and stiffen the middle ear, changing its conductivity up to 20 dB or more, depending on frequency. Their behavior adds a non- linearity that changes with time (as a result of the dynamics of the muscle contraction) and differentially as a function of frequency (low frequencies are affected more than the higher frequencies). And lastly, at very high levels the middle ear itself becomes non-linear in that it is incapable of transmitting displacements larger than 20 microns or so due to the constraint imposed by the annular ligament of the stapes. This element is extremely important in explaining the ear's ability to withstand very high-energy exposures. In essence, at high levels the middle ear becomes a powerful peak-clipping device.

2.3 Creation of the AHAAH Model

Keeping track of the interactions of the various non-linearities is a task ideally suited for a mathematical model of the ear. Various elements of the ear's structure had been modelled by different researchers in the past; but the elements lacked the integrative "glue" that would enable a pressure in the free field to be propagated via head-related transfer functions, through the external and middle ears, into the cochlea and down the basilar membrane. The non-linear dynamics of the middle ear also needed to be included in the model as well as the damage model in the inner ear. We opted to do an electro-acoustic model of the ear, maintaining conformality with the structure of the ear. The model could be simpler; but one of the functions of modelling is insight, and keeping the model's structure like that of the ear promotes engineering insight. The result was first a model specific to the cat ear that reproduced the existing data for the conductive path from the free field to the cochlea. This model was then tested with damaging stimulation in biological ears. In the end the correlation between the model's output and the average hearing loss measured for 12 differing exposures was 0.94, which meant that it was predicting very successfully. Once that model was validated, it was turned into the human version by adjusting the electro-acoustic elements to match human dimensions and values. The variables were then fine-tuned to assure that the model reproduced the transfer function data that had been reported for the human ear. Thus the AHAAH model for the human ear was developed essentially without reference to human hearing loss data. At the time (1996) it was assumed that it would be challenged with data and adjusted as necessary to achieve a fit. So far no adjustment has been made. The process of the development of the model took place during the tenure of two NATO RSGs (RSG-6 and RSG-29) on impulse noise. The details of the development and the codes were shared with these groups.

2.4 The Model's Features

Operationally, the model is user-friendly. It runs in near real-time on a PC level computer and uses WINDOWS conventions. The software allows for the importation, editing, and analysis of waveforms. It also includes an analytical feature in the form of a movie that shows basilar membrane displacements during the analytic epoch and indicates what portion of the waveform produced them.

The movie has proven to be an essential element of the model. Given that the damage mechanism is mechanical stress within the cochlea, it follows that the process needs to be followed in the time domain, i.e. specific timing of individual oscillations in the pressure waveform make a difference in the transmission through the middle ear (the stapes limits large displacements) and the resulting damaging effect within the cochlea. This point is discussed in section 3.2 of this paper. The argument that the ear needs to be evaluated in the time domain is a theoretical position that differs from the arguments for the use of a frequency domain measure, e.g. A-weighted energy. Such a statistic simply ignores the pattern in which simulation arrives, taking the position that only the total energy in the analytic epoch need be accounted for.

In order to be useful as a DRC, it was necessary to find some method of including susceptibility of the ear in the calculation of hazard. In order to do this as simply as possible, we accepted the idea that a susceptible ear is like a normal ear being driven harder. If we assume that susceptibility is normally distributed, like many auditory values, with a standard deviation of 6 dB, then it follows from simple statistical considerations that to simulate the 95%ile ear, the sound pressure level should be raised 10 dB (1.64 SDs). The same logic allows the calculation of hazard for any other level of susceptibility.

2.5 Prediction of Hazard with the AHAAH Model

The model calculates hazard in Auditory Risk Units (ARUs), defined earlier, which have been related to hearing loss in the cat model. The formula relating ARUs to threshold shift is:

$$\text{CTS} = 26.6 \times \text{LN}(\text{ARU}) - 140.1$$

Where: CTS is Compound Threshold Shift measured within ½ hour

Thus an exposure totalling 500 ARUs would be expected to produce a CTS of 25 dB. One of the determinations of the Albuquerque studies (and the general agreement the NATO RSG 029, [2003]) was that a 25 dB threshold shift at (any frequency) should be considered the limit of tolerable exposure; hence, 500 ARUs could also be considered a just tolerable exposure.

The ultimate test of the model is whether or not it predicts hearing loss for the human ear. In order for an exposure to be interpretable by the model, a digitised waveform for the exposure must be available and there should be measures of hearing sensitivity before and after the exposure. With those requirements there are somewhat more than 70 experiments with interpretable human data, the largest body of which is the US Army's Albuquerque studies. In those tests, groups of 60 subjects wearing hearing protection were exposed to explosive impulses intended to mimic the free field response of Army weapons (Johnson, 1994; 1998). The model's prediction was calculated from the waveform measured in front of the ear canal entrance. To establish the validity of the model's response, the question was asked regarding whether or not the model's prediction could be rejected as inaccurate, i.e. if the model said the exposure were safe and 6 Ss showed unacceptable threshold shifts, then the model's prediction was considered inaccurate. Or if the model said the exposure was hazardous and no subject showed a 25 dB threshold shift, then the model's prediction would be rated as inaccurate for that condition. For comparison purposes, the Albuquerque data were also evaluated in the same manner with the US Army's MIL-STD-1474(D) and the A-weighted energy measure (Price, 2003).

The evaluation diagram used appears in Table 1 which shows the evaluation of the Albuquerque data based on MIL-STD-1474(D). In this diagram the cells contain codes that identify the specific exposures. Entries in the upper left and lower right quadrants represent accurate calls, while entries in the lower left and upper right quadrants represent either over – or under-estimation of hazard respectively. In the case of MIL-STD-1474(d) it is apparent that for these impulses it tends to err in the direction of over-predicting hazard, and in no case did it identify an exposure as safe that was in fact hazardous. Its prediction was correct in 19 of the 53 experiments (36% correct).

In Table 2 we see the result for the evaluation using the A-weighted energy criterion, i.e. exposure to L_{AEQ8} > 85 dB is considered hazardous. It is apparent that A-weighted energy, even more than MIL-STD 1474(D) tends to over-predict hazard for these impulses. It was correct on 13 of the 53 cases (25% correct).

In Table 3 we see the evaluation as done by the AHAAH model. It is apparent that it has been largely successful in rating the hazard. In no case was a hazardous impulse called safe and it erred in over-estimating the hazard in three instances. Overall, the model was correct in 50 of the 53 cases (94% accuracy).

Approximately 20 other exposures to small arms, spark gap discharges, shoulder-fired rockets, etc. could be evaluated with the model. They were gleaned from the literature of the last 40 years and while it was not possible to be as rigorous in the application of the analyses, they nevertheless provided interesting tests and an additional "reality check" on the efficacy of the model in dealing with a wide range of conditions. In all those cases the model's prediction was correct, giving it an over-all accuracy for both protected and unprotected exposures of better than 95%.

EVALUATION BY MIL STD-1474			
		OUTCOME	
		SAFE	HAZARDOUS
PREDICTION	SAFE	01 T1 T2 F1 F2 F3 G1 G2 G3 R1 R2	
	HAZARDOUS	O2 O3 O4 O5 O5 O7 O8 T3 T4 T5 T6 T7 T8 F4 F5 F6 F7 F8 F9 G4 G5 G6 G7 G8 G9 GF GH R3 R4 R5 R6 R7 R8 R9	O9 OF OH T9 TF TH FF FH

Table 1. Evaluation of the Albuquerque dataset with MIL-STD-1474(d).

EVALUATION BASED ON A-WEIGHTED ENERGY

		OUTCOME	
		SAFE	HAZARDOUS
PREDICTION	SAFE	G1 G2 G3 R1	
	HAZARDOUS	O1 O2 O3 O4 O5 O6 O7 O8 T1 T2 T3 T4 T5 T6 T7 T8 F1 F2 F3 F4 F5 F6 F7 F8 R2 R3 R4 R5 R6 R7 R8 R9 G4 G5 G6 G7 G8 G9 GF GH	O9 OF OF T9 TF TH FF FH F9

Table 2. Evaluation of the Albuquerque dataset with the A-weighted energy criterion

EVALUATION BY AHAAH

		OUTCOME	
		SAFE	HAZARDOUS
PREDICTION	SAFE	O1 O2 O3 O4 O5 O6 O7 O8 T1 T2 T3 T4 T5 T6 T7 T8 F1 F2 F3 F4 F5 F6 F7 F8 G1 G2 G3 G4 G5 G6 G7 G8 G9 R1 R2 R3 R4 R5 R6 R7 R8	
	HAZARDOUS	GF GH R9	O9 OF OH T9 TF TH F9 FF FH

Table 3. Evaluation of the Albuquerque dataset with the AHAAH model

2.6 Acceptance and Adoption of the Model.

The AHAAH model is gaining acceptance as a method of rating hazard. It has been successfully peer reviewed by the American Institute of Biological Sciences (2001), is being used by the Society of Automotive Engineers as the basis for rating hazard from airbags (SAE, 2003), is in a draft technical report of the American National Standards Institute (ANSI, 2005), is being proposed as the basis for rating hazard in the US Army's MIL-STD-1474(e), and is being proposed to the US Army's Surgeon General as the basis for a damage-risk criterion for the Army.

3.0 IMPLICATIONS OF THE AHAAH MODEL

3.1 Range of Applicability of the AHAAH Model

The model was designed to address virtually <u>any</u> intense sound, regardless of its origin or its physical characteristics. It is true that the specific focus during validation studies was on gunfire level sounds (140 dBP and higher) where the loss mechanism within the cochlea is clearly mechanical stress. The human exposure data used in validation have ranged from about 155 dBP to 185 dBP. For those levels at least, we have seen that the model fits the data very well. However, there is still a question as to how far downward in level the method will work. In that regard, it is interesting to note that at lower levels pressure specifications are typically in rms values. Waveforms with rms pressures in the 125-130 dB region might easily have peak pressures over 140 dB. Such pressures (and higher) can be found near jet engines on carrier decks or in maintenance settings where they are being test-run.

3.2 New Analytic Insights from Time-Domain Analysis.

It is often the case in modern science that technical insights are linked to the development of analytical tools that provide new ways to examine phenomena. The AHAAH model provides such an opportunity. It keeps track of displacements in the middle and inner ear, arguing that in order to understand damage at the level of the hair cell, the exact pattern of instantaneous displacements must be known. In other words, it operates in the time domain. It also makes a movie of the analysis interval that shows displacements within the ear and the hazard attributable to them. Measures such as A-weighted energy lose track of instantaneous displacements and follow only the total energy in the epoch being analysed distributed across frequencies, i.e. it operates in the frequency domain. For some purposes the two methods can provide similar answers; but in other cases they do not. Consider the case of the pressure history from an airbag deployment shown in Fig. 3. The AHAAH model calculates 1342 ARUs (clearly hazardous) with 94 J/m^2 of A-weighted energy (also considered a hazardous exposure). On the other hand, the AHAAH model shows through its movie feature that most of the calculated hazard occurs at the moment pointed to by the black arrow (about 10 msec into the waveform). If that dip in the pressure history were eliminated, the hazard would drop to 435 ARUs (safe exposure); but the A-weighted energy would still be 74 J/m^2, which would still be rated as hazardous. The dip in pressure is a function of a bounce the bag makes as it deploys. Were some damping mechanism designed into the bag to prevent the rebounding bounce, then the deployment would be safe. The answer to this noise hazard would be an engineering change unrelated to the sound of the bag filling. Not every noise problem lends itself to this innovative kind of resolution. However, we can now observe that a new analytical tool, the AHAAH model, is now available for use.

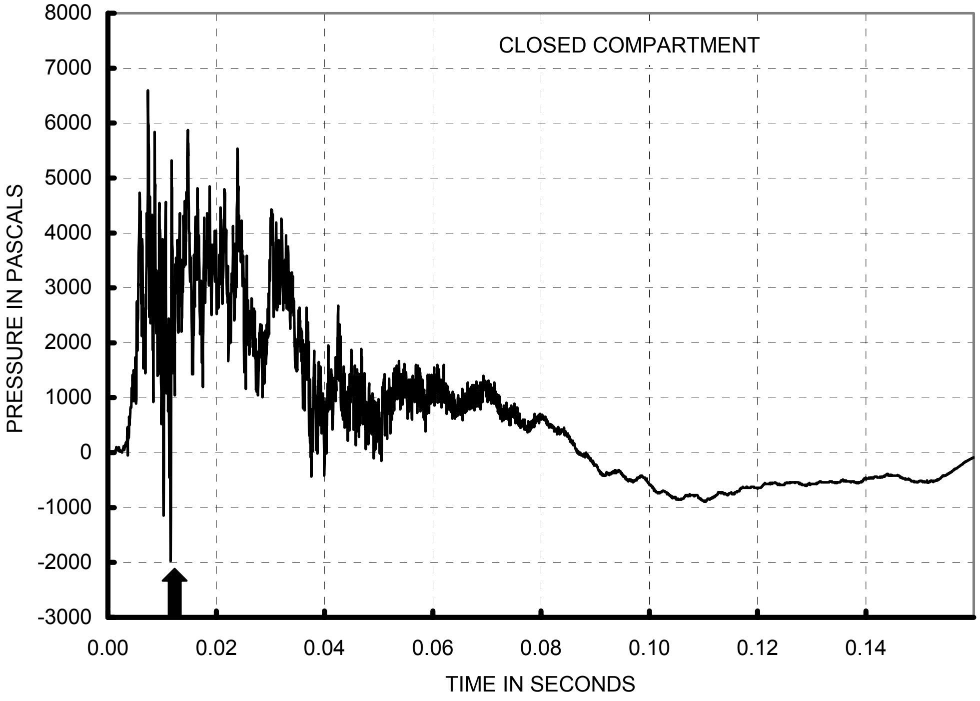

Figure 3. Pressure history of airbag waveform at the driver's left ear in a closed compartment

3.3 A New View of the Influence of Low-Frequency Energy

3.3.1 Impulses with a Lot of Low-Frequency Energy

It would be fair to say that today A-weighted energy is generally regarded in the hearing conservation world as the measure of choice for rating hazard, at least for SPLs below 160 dB. It reflects the transfer function of the ear based on the (psychological) loudness of a sound at 40 dB. It also has the additional advantage that, now that meters have been built to include its characteristics, it is easily measured. However, for many years, there has been the suspicion that for high-level noises it may include too much low-frequency energy and other weighting systems have been proposed (Buck, Dancer and Parmentier, 2003). In Fig. 4 we see the transfer function for the ear for free-field pressure to stapes volume velocity as calculated by the AHAAH model. One curve depicts the transmission in a normal ear and the second curve depicts transmission with the middle ear muscles contracted. For comparative purposes the A-weighting curve has also been plotted. It is apparent that the A-weighting curve does indeed cut off slower than the transmission curve, especially if the middle ear muscles are contracted. On this basis it might be expected that the AHAAH model will rate lower frequencies as less hazardous than an A-weighted measure, consistent with the transmission of the human ear.

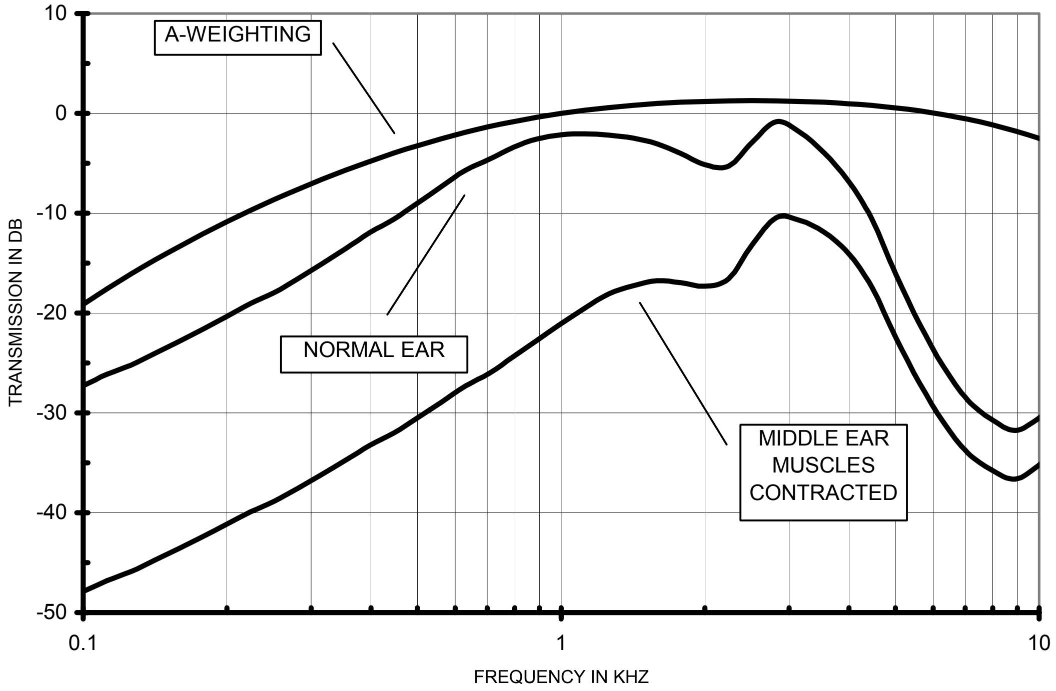

Figure 4. Transmission of the human ear with no muscle contraction and with a middle ear muscle contraction compared with the A-weighting function

If the only problem with A-weighting were that its low-frequency cut-off slope needed to be changed, then the answer to the problem would be simple. However, like many processes that take place at high intensities, the problem is that other things are happening simultaneously. Namely, the middle ear, which has an absolutely remarkable linear range (better than 120 dB), becomes non-linear at very high levels. Displacements of the stapes are constrained by the annular ligament so that it can't move more than 20 microns or so. And this means that waveforms at high levels are severely peak clipped as they enter the cochlea, which is where the basic damage takes place. This effect can be seen in Fig. 5 for an impulse from a 105 mm Howitzer. In the figure, taken from a display in the AHAAH program, the upper panel is the calculated stapes displacement for the pressure history in the lower panel. In this illustration, a "warned" exposure has been assumed (middle ear muscles are contracted). It is apparent that the stapes displacement resembles the pressure history; but with an important difference. Because of the compression by the stapes, the initial peaks in the pressure history are relatively much higher than the same peaks in the stapes displacement and conversely, the smaller oscillations in the latter part of the pressure history form a much larger part of the waveform entering the cochlea. By using the movie feature of the model, we can determine that ½ of the hazard has accrued by 17.5 msec into the waveform. That portion of the waveform represents 86% of the A-weighted energy in the impulse. It follows that 14% of the energy (the latter portion of the wave) also contains ½ of the hazard. These effects are largely the result of the peak-clipping action of the middle ear. It can only be seen as ironic that the portion of the waveform we have traditionally focused on in rating hazard, the initial high peak pressure, contained 54% of the A-weighted energy but was responsible for only 3% of the hazard. Put another way, if the initial peak (3 msec of the waveform) were totally eliminated, the hazard in the remainder of the waveform would have changed only from 673 to 651 ARUs for the warned ear. If the ear were unwarned we get the surprising result that the hazard would have risen 16% from 2093 to 2422 ARUs because of the delay in starting a middle ear muscle contraction.

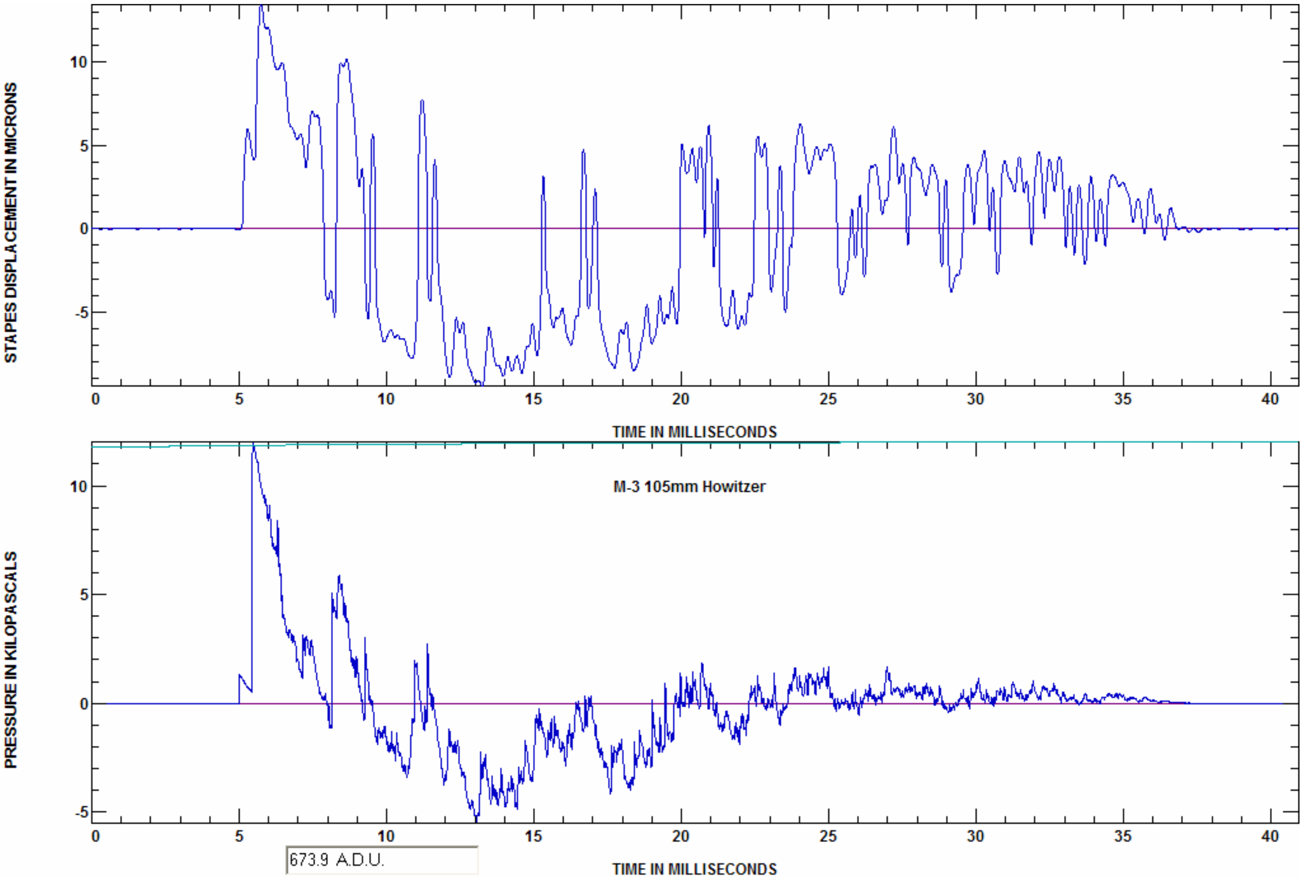

Figure 5. AHAAH model's calculation of the stapes displacement (upper panel) in response to the free field pressure from a 105 mm Howitzer. Middle ear muscles are contracted during the episode.

Furthermore, the presence of such a non-linearity means that proper evaluation of its effect must be made in the time domain, rather than the frequency domain, i.e. just exactly when peaks and dips occur in the waveform matters. Oscillations that occur during periods of high displacement (during clipping) are not transmitted and oscillations that occur during moments when the stapes displacements are in their linear range are transmitted. Thus, lower frequency energy has the power to modulate the flow of higher frequency energy. This is the best explanation of why the AHAAH model was successful in predicting hazard for the Albuquerque data and the other methods were not.

3.3.2 Impulse with Less Low-Frequency Energy

It might appear at this point that the AHAAH model supports the idea that gunfire impulses are simply much less hazardous than we thought and that MIL-STD-1474(d) and an A-weighted energy measure are grossly over-conservative. That would be a serious misapprehension. Where there is less low-frequency energy, as in small arms fire, the picture is essentially reversed. At the levels typical for small arms, the middle ear is only moderately non-linear, in which case the assessment of hazard reverses. Consider the case for an unprotected exposure to a hypothetical rifle impulse portrayed in Fig. 6. At the highest peak pressure, 168 dB, AHAAH allows one round, A-weighted energy none. However at lower pressures, as the ear becomes more linear, the two measures separate by about 10 dB with A-weighted energy allowing much more exposure. At 158 dB, where experiments with human Ss have been done (Brinkmann, 2000) these tests have been done and 3 or 6 rounds is essentially in the right region. But at lower pressures, there are simply not any data on human exposure, so this comment can only be precautionary. If the AHAAH model is correct at 140 or 150 dBP, then A-weighted energy is grossly under-conservative and serious hearing loss could result from exposures predicted to be safe. If AHAAH fails to predict correctly at these intensities, then the error will be one of over-conservatism. Interestingly enough, the A-weighting prediction and the AHAAH prediction would be essentially identical at the lower pressures if the AHAAH model were predicting hazard for the 50%ile ear.

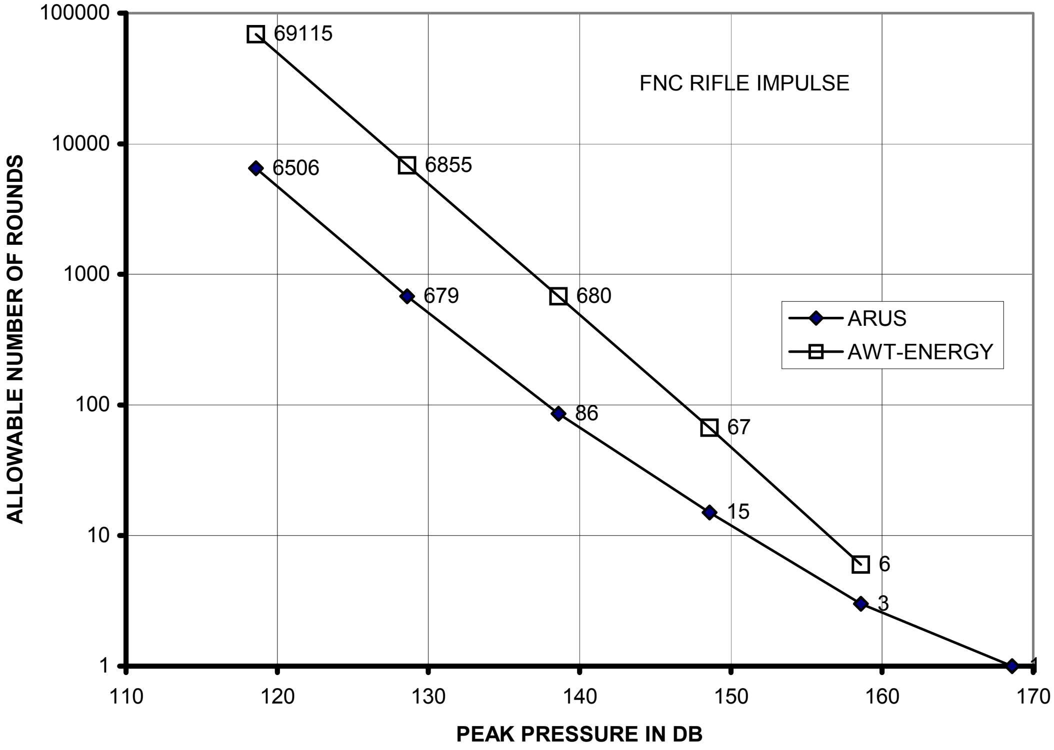

Figure 6. Allowable number of rounds for a rifle impulse, unprotected exposure as rated by the AHAAH model and A-weighted energy

MIL-STD-1474(d) only allows exposures with protected hearing at levels above 140 dB. If we calculate the exposure allowed for a rifle impulse using that standard, we typically arrive at an allowable number of rounds between 100,000 and 1,000,000 for single hearing protection. If we calculate the effect of an HPD or measure the hazard using a protector on a manikin, the AHAAH model estimates about 600 – 15,000 rounds for the warned ear, depending on the impulse and the protector. Again, there is an immense discrepancy between these two systems. Surely MIL-STD-1474(d) is under-conservative. It allows 15-25 dB more energy than an A-weighted energy criterion would. However, under the protector, peak pressures are in the 125-140 dB region, an area where the AHAAH model is untested. More data would obviously be welcome here.

3.4 IMPLICATIONS FOR LEVEL/NUMBER TRADING RATIO CALCULATIONS

Tradition has the power to focus thinking in familiar patterns. One such persistent idea is that there is a level/number trading ratio for impulses which expresses the change in the acceptable number of impulses for a given change in level (Smoorenburg, 2003). In the case of A-weighted energy, a 10-fold change in number would require a 10 dB reduction in level. The problem is that this concept presumes that the ear is essentially linear. While that is true for an immense dynamic range, it is not true at very high levels. For instance, if we take an impulse and artificially change its level over a wide range we can observe a progression of effect. In Fig. 7 we see the allowable number of impulses for the airbag impulse in Fig. 3, were its peak pressure changed in 10 dB steps from 112 to 182 dB. By way of comparison, the level/number ratio has also been plotted on the right hand ordinate. At the low intensity end, the trading ratio is essentially 10 (an energy relationship – for a 10 dB increase in peak pressure, the number of rounds allowable drops by a factor of 10).

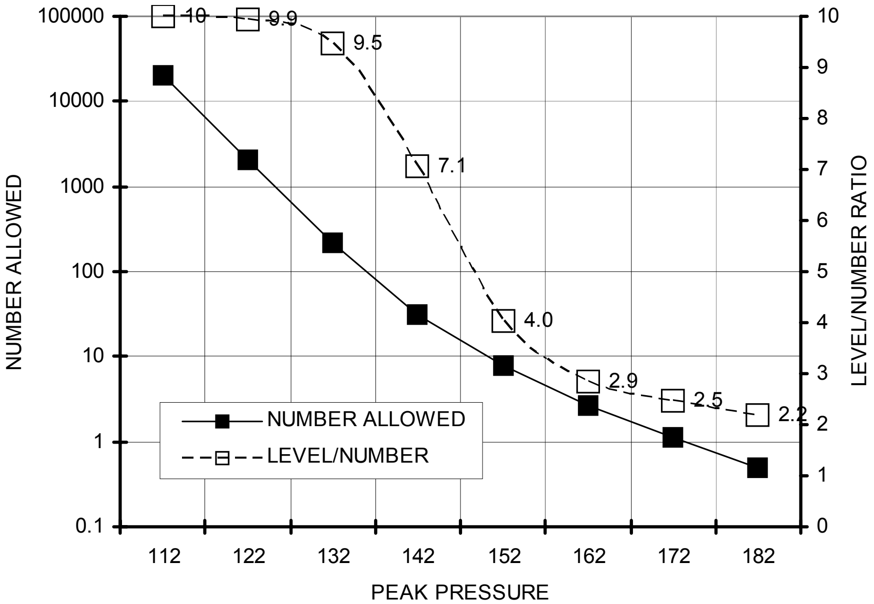

Figure 7. Allowable number of impulses for a warned ear for the waveform in Fig. 3 (left ordinate). Also plotted is the level/trading ratio for each of the levels.

However, as the pressure rises and the clipping of the stapes has its effect, the ratio changes downward to 2.2 at 182 dB. This makes sense, given the non-linear middle ear. This particular impulse is taken as illustrative of the problem in general. It is apparent that it would be irrational to seek a single level/number trading ratio to work for impulses over a wide range of pressures. Smoorenburg has nonetheless tried (2003) to find the level/trading ratio and found numbers for various impulses and experiments that fall in the range plotted in this figure. The AHAAH model is thus consistent with the available data in arguing that no single level/trading ratio for impulses should be expected to exist.

We also note in passing that in his review chapter on impulse noise, Smoorenburg (2003) had credited the AHAAH model as doing essentially the right thing for impulse noise. However, he faulted the model for being "over compressive" i.e. failing the find a proper trading ratio. A close examination of the text indicates that in fact Smoorenburg in one case simply misapplied the model and in a second, made a mathematical error. If these two errors were corrected, his reservations with respect to the model disappear.

3.5 IMPLICATIONS FOR WEAPON DESIGN

For large calibre weapons, which typically produce high peak pressures and contain a great deal of low frequency energy, the AHAAH model represents an important change in thinking. In general, AHAAH suggests, consistent with the data from the Albuquerque studies, that higher peak pressures and longer durations are in fact more tolerable than previously thought. Alternatively, it may mean that for some purposes, double hearing protection will no longer be required. Double hearing protection, without some provision of a talk-through system, has never been viewed as practical in the field. The double protected ear is essentially deaf, and that's simply not acceptable in combat.

The move to a theoretically based hazard rating system means that a new range of design options may become available. Reducing peak pressure may not be the best way to reduce hazard and alternate processes can now be pursued. One the one hand, it may be possible to use the new tools to produce even more powerful weapons that are no more hazardous than the current ones. Alternatively, it may be possible to pursue the design of weapon systems with the capacity of the current weapons; but with exposures that are safe without hearing protection or at least no more hazardous than current systems. Given the uncertainty of HPD use in combat, it would be prudent to pursue a goal of reducing the hazard from weapons so that less protection is needed.

On the other hand, the AHAAH model emphasizes the hazard from small arms, an area that has traditionally been overlooked. Many years ago, a study by Walden, Prosek and Worthington (1967) found that hearing loss in the US Army was prevalent and about equal in magnitude in the various combat arms. In terms of exposure, the artillery would have been considered the worst hazard; but it was not so. It is only a hypothesis; but it may well be that the weapon most likely to produce a hearing loss is the rifle. Surely there are more of them and exposure is more likely, especially in training. Generally, when the AHAAH model is used to estimate hazard with an HPD, it allows a reasonable number of impulses, perhaps a few hundred. However this is typically much less than allowed with MIL-STD-1474(d), which might allow many thousands. Clearly small arms may presently be an under-appreciated hazard.

Currently, there is specific concern for the ability to fire shoulder-fired rockets from within a room or a bunker. Special designs have evolved; but in the end, human safety may well be the determining factor regarding their acceptability. The impulse within a room is indeed intense and prolonged with the result that the existing hazard rating methods severely restrict and/or prohibit firing. The AHAAH model may provide a more accurate assessment and promote safer designs in this arena.

3.5 IMPLICATIONS FOR HPDS

One of the advantages of a model is that it allows one to try different contingencies for their effects. In one such exercise the question was asked regarding what the best possible attenuating characteristic was for an HPD when the stimuli were different types of gunfire in quantities that might be encountered in military operations, e.g. 300 rounds from a rifle or a cannon. To do the test, attenuation characteristics were created, flat across frequencies, for example or a pattern of attenuation shaped like the threshold curve. A digital filter with that characteristic was used to process waveforms from the different weapons and the waveform was run through the model. By processing a series of these trials it was possible to determine how much attenuation would be required to make a 300 round exposure acceptable. A typical outcome for a cannon impulse is plotted in Fig. 7. The rather surprising outcome of this calculation was that the low frequency attenuation did not seem to matter. Below 1 kHz the attenuation declined at 6 dB/oct for the threshold-shaped curve yet the curves reached about 40 dB in the 1-2 kHz region and they were calculated to have the same protective effect. Essentially the same pattern was observed for the other exposures (rifles, rockets, etc.) even though the absolute levels of attenuation varied with the exposure. In general, low frequency attenuation is much less critical than the attenuation in the mid-range of frequencies. Or put conversely, low frequency energy is not necessarily the enemy.

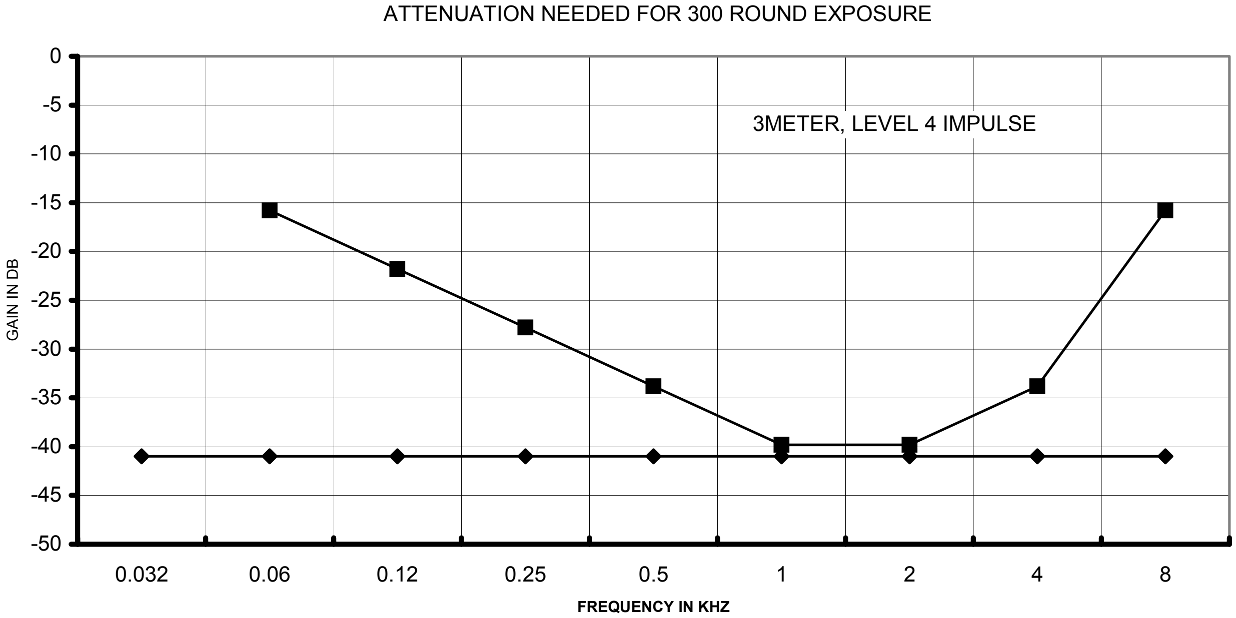

Figure 7. Calculated gain (attenuation) needed in an HPD for a 300 round cannon impulse exposure. The 3m level 4 impulse had a peak pressure of 185 dB in the free field.

The primary reason that low frequency attenuation may not be critical at these levels is, as we have seen, that the middle ear itself has become non-linear and blocks sound transmission. This can be seen in Fig. 8 in which we have plotted the allowable number of simulated cannon impulses (measured under a protector) as a function of the A-weighted energy in the impulse or the hazard as calculated by the AHAAH model. For low

SPLs where the ear is essentially linear (upper left portion of the figure) the two curves are almost parallel. But as the pressure rises, the two curves diverge markedly. The ARU curve bends to the right (allowing more rounds than A-weighting) because the stapes displacement has been limited and the energy has not been transmitted to the inner ear.

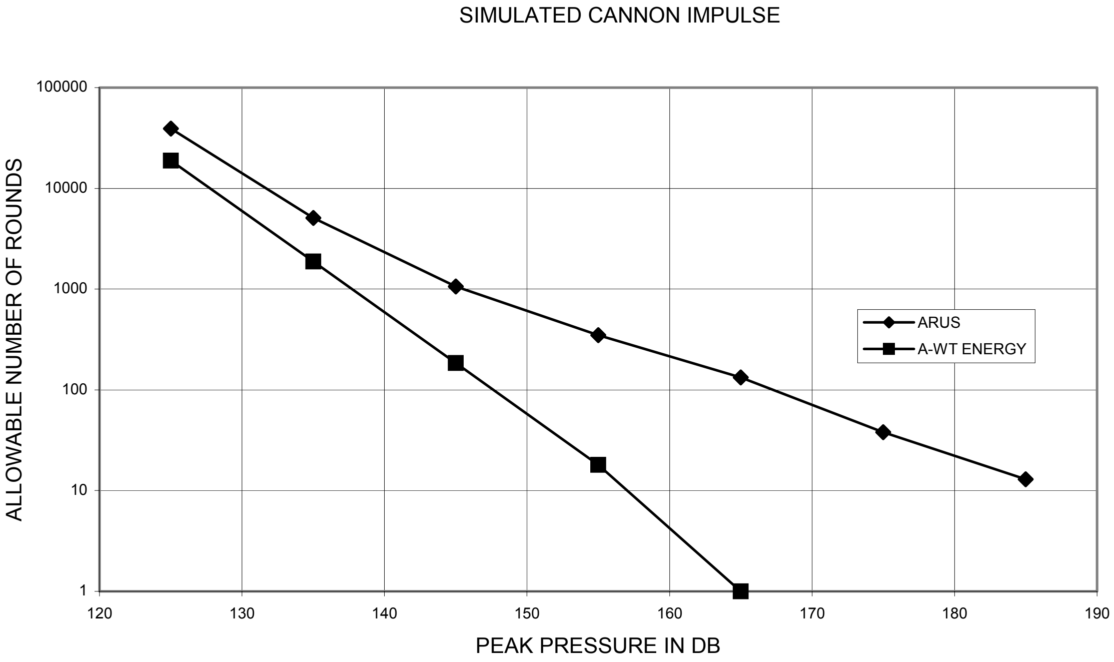

Figure 8. Allowable number of simulated cannon rounds as calculated with the AHAAH model or an A-weighted energy criterion.

So far as HPD design is concerned, then, the message is optimistic. Typically, the low frequencies are hard to attenuate and good attenuations in the mid-range are easier to achieve. Fortunately, that pattern may be acceptable. In fact, the non-linear protector now known as the “Combat Arms Plug” (CAP) in the US Army has an attenuation characteristic very much like the “threshold-shaped” attenuation curve in Fig. 7. The success of the combat arms plug is consistent with the analysis done with the AHAAH model.

There is another aspect to this as well where MIL-STD-1474(d) is concerned. In it, only two corrections are allowed for hearing protection, one for single protection and one for double protection. This is without regard to the specific attenuation of the protector or the variability of its fit in use. Thus there is no reward for better HPD design (or penalty for worse designs either). In the case of the AHAAH model (or an A-weighted energy criterion) better design could be measured, analysed and rewarded.

3.6 IMPLICATIONS FOR SITUATION AWARENESS AND SPEECH INTELLIGIBILITY

One of the strong points in favor of the non-linear CAP is that at low pressures it provides only a small amount of attenuation, which in turn permits the wearer to understand speech while wearing it and to generally stay aware of what is going on in the surroundings. The attenuation of the CAP plug for waveforms at different peak pressures is shown in Fig. 9 along with the threshold shaped attenuation curve from Fig. 7. We see that the low frequency attenuation of the CAP and that of the threshold shaped attenuation curve are very similar. This is consistent with the success of the CAP plug in protecting the ear, in spite of its relatively poor low frequency attenuation.

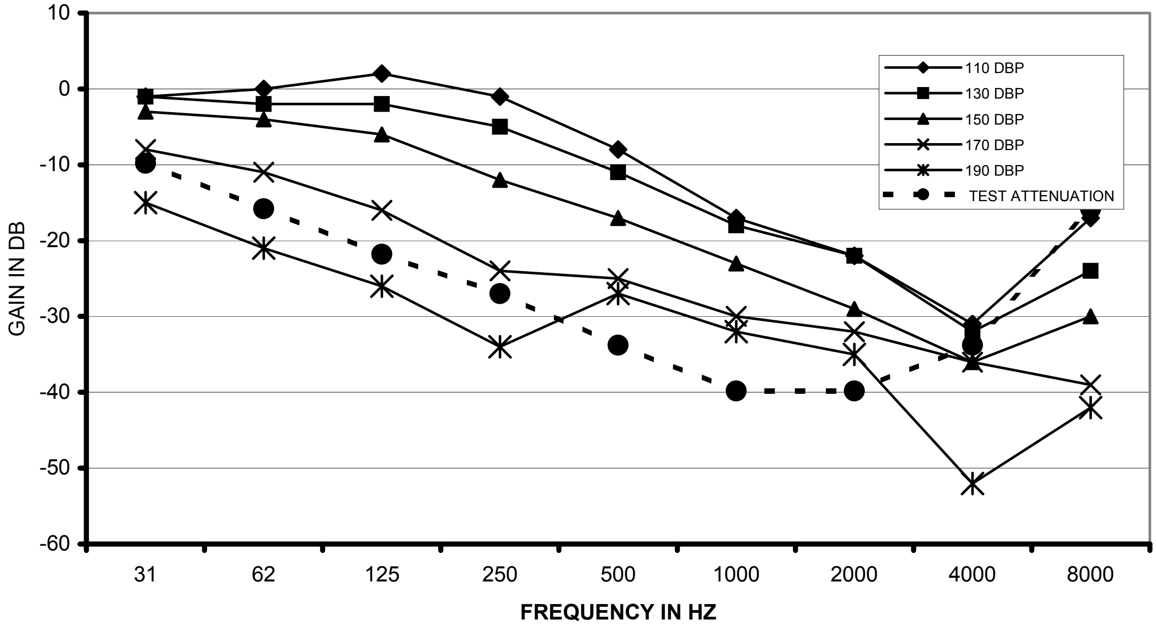

Figure 9. Gain (attenuation) of non-linear earplug as function of peak level of the incident pulse, plus the threshold attenuation curve from Fig. 7 (dashed line).

One of the purported strengths of the CAP is that it helps to maintain both situation awareness and speech intelligibility. By means of a simple calculation we can gain an appreciation of the improvement in speech intelligibility brought about by the use of an HPD with little low-frequency attenuation. The Articulation Index (AI) is an old measure that relates speech intelligibility on a variety of measures through the calculation of weighted signal-to-noise ratios in octave bands important in the perception of speech. We might, for instance ask what the difference in speech intelligibility would be if HPDs such as those in Fig. 7 were worn. If the HPD were limiting the speech signal, as it might in a quiet environment, typical of many combat situations, then we can calculate that the improvement in the AI would be about 0.2 for the plug with less low frequency attenuation. The significance of the 0.2 change in AI would depend on the specific conditions; but if intelligibility were marginal, that much change could be the difference between 20-30% intelligibility and 80-90% intelligibility, an immense difference.

3.6.1 The Effect of Speech Intelligibility on Performance

The effect of speech intelligibility on performance of combat related tasks is surprisingly strong. Peters and Garinther (1990), working at the Army Research Lab ran a series of experiments that systematically varied the speech intelligibility within a communication system and tested its effect on crew performance. The final outcome appears in Fig. 10. In this figure, probability of mission success is plotted as a function of the percent speech intelligibility within the communications system. If the task were very simple, not requiring much communication, then the upper bound of the area fits. Speech intelligibility doesn't make too much difference. On the other hand, when the mission consisted of tank crews attacking one another in an unconstrained situation (in a simulator)(lower curve in the figure), then the effect of speech intelligibility is immense. There is an almost 1:1 correspondence between changes in speech intelligibility and mission success. There is little in the way of materiel improvement that could produce such a dramatic effect on system performance. Good hearing and good speech intelligibility are essential to successful military operations.

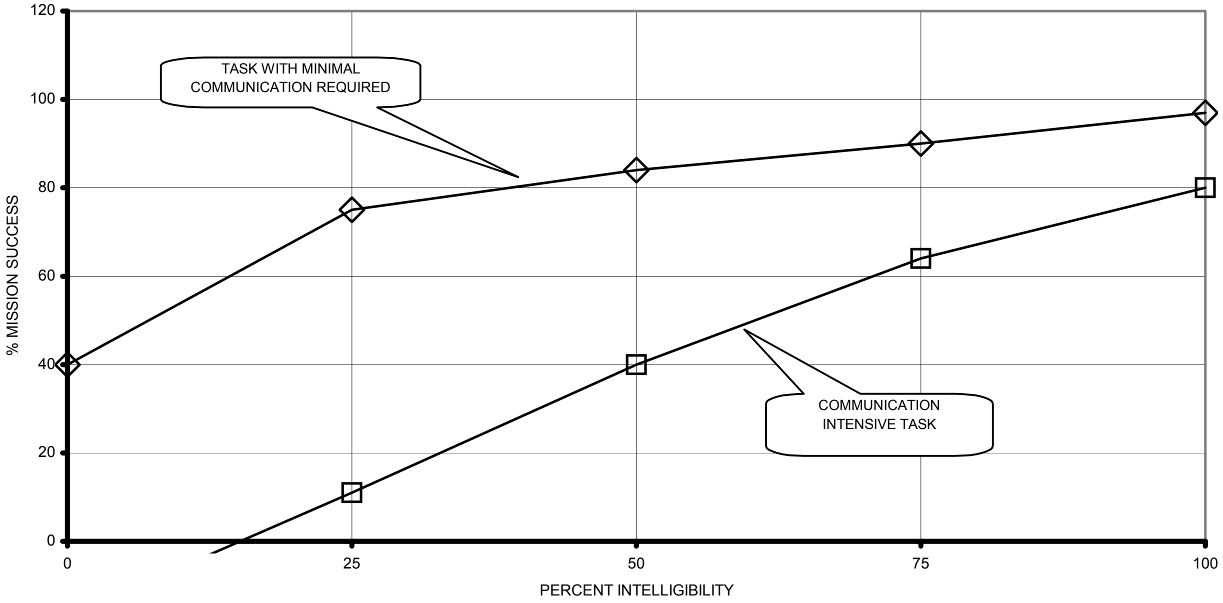

Figure. 10. Probability of mission success as a function of speech intelligibility in the crew communication system

4.0 TECHNICAL ISSUES FOR THE FUTURE

4.1 An Integrated Measure

4.1.1 The AHAAH Model

As of this writing, it appears that the AHAAH model is performing well for impulse noise predictions at high SPLs. However, it would clearly be desirable to have an integrated analysis system that could appropriately analyze, without compromise, all exposures from continuous noises at low levels to impulses at very high levels. As we have noted earlier, there is real question as to the range of intensities for which the AHAAH model as presently configured could serve as an adequate descriptor. The prospect of creating an integrated measurement and analysis system is indeed laudable, technically challenging, and would require some theoretical insight to complete. We are presently working toward this end.

4.1.2 A-Weighted Energy

One of the justifications offered for the use of A-weighted energy as a measure is that it is an integrated measure. In this case the argument the A-weighting allows the combining of lower level continuous and intense impulsive exposures may appear to fit the situation; but it is seriously compromised from a theoretical standpoint. For example, such a measure takes no account of changes in the loss mechanism as intensity rises. An exposure to an 85 dBL_{AEQ8} with a factory noise at about 85 dB means that if the exposure is continued daily for a working lifetime, recovery will occur quickly each day and a very small loss may occur in 20 or 30 years. On the other hand, the same level of exposure to an intense impulse may have so severely stressed the cochlea that it is on the edge of permanent damage, recovery processes would be prolonged and daily exposure would probably be a bad idea. If the exposure were a few dB higher on one occasion in the factory, the consequence for that noise exposure would be negligible. But in the case of impulse noise, the result could be disaster for the ear. The fact that an 85 dBL_{AEQ8} appears to work as a descriptor across the broad range of exposures is almost certainly a happy coincidence and not a theoretical necessity. The fact that it is easy to measure should not obscure the fact that it may not truly describe stresses to the auditory system.

4.2 Adaptive Middle Ear Muscles

The middle ear muscle system may benefit the ear; but its effect is very difficult to describe. The AHAAH model has made an attempt to do so; but the method requires operator input that is relatively simple for the case of impulses in isolation. A truly excellent program would make the judgement for all exposure conditions automatically and incorporate algorithms for both attack and decay of the response in continuous noise exposures.

5.0 SUMMARY AND CONCLUSIONS

The essential message in this address is that a new analytical tool, the AHAAH model is now available for predicting hearing loss and understanding the mechanisms that operate during exposures at high SPLs. Unlike other methods, it is theoretically based and embodied in a computer program. The model will serve as the basis for noise rating in MIL-STD-1474(e) and is serving within the Society of Automotive Engineers for rating hazard from airbags.

The AHAAH has been validated with more than 70 tests with human data. These tests show that that the AHAAH model accurately predicts the onset of unacceptable changes in hearing sensitivity in over 95% of the cases. In contrast, A-weighted energy is correct about 30% of the time and MIL-STD-1474(d) is accurate about 36% of the time. Errors in prediction for MIL-STD-1474(d) and A-weighted energy tend to be in the over-prediction of hazard for impulses with a lot of low frequency energy (large calibre weapons).

On the other hand, the AHAAH model suggests that small arms impulses may be much more hazardous than previously thought. Given their pervasive presence in the military, it might be a fruitful area for the production of safer weapons.

The AHAAH model predicts hazard for <u>any</u> intense sound, continuous or impulsive. The unanswered question at the moment is how far down in pressure it can go and remain accurate. It is reasonable to assume it is accurate to at least 140 dBP, which could include rms levels of 125 to 130 dB.

The reduced hazard from large calibre weapons impulses can have a major impact on weapon design. Designers now have more leeway to consider more powerful weapons, lighter weight designs, or safer weapons without reduced performance.

The AHAAH model includes a movie feature, which allows the analysis of the evolution of hazard within the inner ear. This feature makes it possible to devise responses that are tailored to the specific issues.

Because hazard is the result of instantaneous stresses within the inner ear, it would follow that hazard analysis needs to be done in the time domain, rather than the frequency domain.

The AHAAH model points out the role of very low frequency energy in modulating the flow of energy into the cochlea. If it is intense enough to cause the stapes suspension to reach its limits, then it affects the flow of energy even though it may be lower in frequency (<20 Hz) than the normal auditory range.

For weapons impulses, HPDs need their best attenuation in the mid-range and less at low frequencies (below 1000 Hz).

With less low frequency attenuation, speech intelligibility and situation awareness are improved.

Given a non-linear middle ear, the current practice of calculating number/intensity trading ratios for exposures is irrational. Once the middle ear has become non-linear, increases in intensity result in proportionately less energy entering the cochlea. It follows that whatever trading ratio fits at one level, must not fit at another level.

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