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IMPLICATIONS OF BASIC RESEARCH IN HEARING FOR THE DESIGN OF SAFER WEAPONS

G. Richard Price

October 1979
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U. S. ARMY HUMAN ENGINEERING LABORATORY
Aberdeen Proving Ground, Maryland

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Continued basic research on auditory function has produced evidence that current thinking on the hazard from weapons impulses may need revision. Specifically, evidence indicates that spectral tuning of the ear results in the prime source of damage being the energy in the mid-range (1.0-3.0 kHz). This is true even though spectral peaks may be much lower in frequency. Given this tuning, it is argued that measures aimed at changing the energy in the mid-range can reduce the hazard appreciably. Two specific suggestions are: lengthening the rise-time of the impulse and using barriers to create sound shadows.		

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FIGURES

IMPLICATIONS OF BASIC RESEARCH IN HEARING FOR THE DESIGN OF SAFER WEAPONS

INTRODUCTION

It has become increasingly true that one of the intractable limits in weapons design is the ability of the human operator to tolerate the impulses produced by the weapons. Recently, continuing basic research on auditory function has produced evidence that indicates that the current thinking on the hazard from impulses, so far as the ear is concerned, may need revision (Kalb, 1979; Price, 1977a; 1977b; 1978; 1979a; 1979b; 1979c). The purpose of this report is to outline these findings, point out their implications for weapons design, and indicate areas to which research and engineering effort might profitably be directed.

THE EAR'S SUSCEPTIBILITY

Even though the details are still being debated today, it has long been apparent that the auditory system is spectrally tuned. The curve of threshold sensitivity shows the ear to be tuned to frequencies in the mid-range (1.0-3.0 kHz) and to be relatively less sensitive to frequencies on either side. Spectral tuning is also apparent in the ear's response to relatively intense occupational noise exposures. In evaluating the effect of such exposures, the A-weighting curve has been found to mimic the ear's response satisfactorily and standards for noise exposure include this frequency weighting.

Until recently, it has not been apparent how the spectral tuning of the ear should be treated in the case of impulse noise exposures. Neither of the damage-risk criteria for impulse noise that are in use in the world today take spectrum into specific account (CHABA, 1968; Pfander, 1975). Although it is possible to arbitrarily apply a spectral weighting to intense impulsive sounds, it has not been demonstrated that in fact it is permissible to do so. The mechanisms that determine auditory sensitivity at very low intensities or losses in threshold sensitivity at levels commonly encountered in industry (perhaps up to 125 dB or so) may not be the same mechanisms that result in hearing loss from weapons impulses of 155 to 185 dB (Price, 1979c).

Much of the spectral tuning of the ear can be attributed to the acoustic properties of the external and middle ears. Their combined effect is that of a band-pass filter tuned to the mid-range; although at very high levels this tuning may change somewhat and show some bias toward the higher frequencies (Price, 1974b). For the most part, however, it is generally agreed that these structures are not themselves changed by the stimuli. The prime site of action, so far as hearing loss is concerned, is within the inner ear.

The action of intense impulsive stimuli within the inner ear has remained unexplored. However, recent experiments on the hazard from spectrally narrow impulses has established the susceptibility of inner ear structures to intense stimulation (Price, 1979b). Based on this work, which was done with the cat ear, and on a reinterpretation of studies with the human ear, Price (1979a, 1979c) has argued that there is a spectrally dependent critical level (L_c) at high intensities where the loss mechanism changes. At very high levels loss apparently results directly from mechanical displacement of structures within the inner ear. When expressed in terms of stapes displacements, this critical level declines at 5.4 dB/oct with increasing frequency (Figure 1). Assuming that a similar slope would apply for the human inner ear as well, allowances for the transfer functions of the human middle and external ears have been combined with this susceptibility function and the free field sound pressure level just reaching L_c has been calculated and is approximated by the two lines presented in Figure 2. The ordinate for this curve is in relative dB; but it does indicate that the ear should be most susceptible to damage from energy in the mid-range of frequencies (around 3.0 kHz) and progressively less sensitive as the spectral frequency departs from this region.

WEAPONS IMPULSES

The "classic" pressure-time history for weapons impulses is presented in Figure 3. There is an instantaneous pressure rise to a peak pressure, a decline to ambient pressure (the time taken for this phase is commonly called the A-duration), a slower and smaller decrease in pressure below ambient and final return to ambient pressure. The spectral peak is located at a frequency that can be expressed as a function of the A-duration:

$$\text{Spectral Peak} = 1.75/2\pi A$$

where spectral peak is in Hz and A-duration is in seconds. The magnitude falls initially at 6 dB/oct at frequencies above the spectral peak and at some higher frequency changes to 12 dB/oct. It will be of interest later

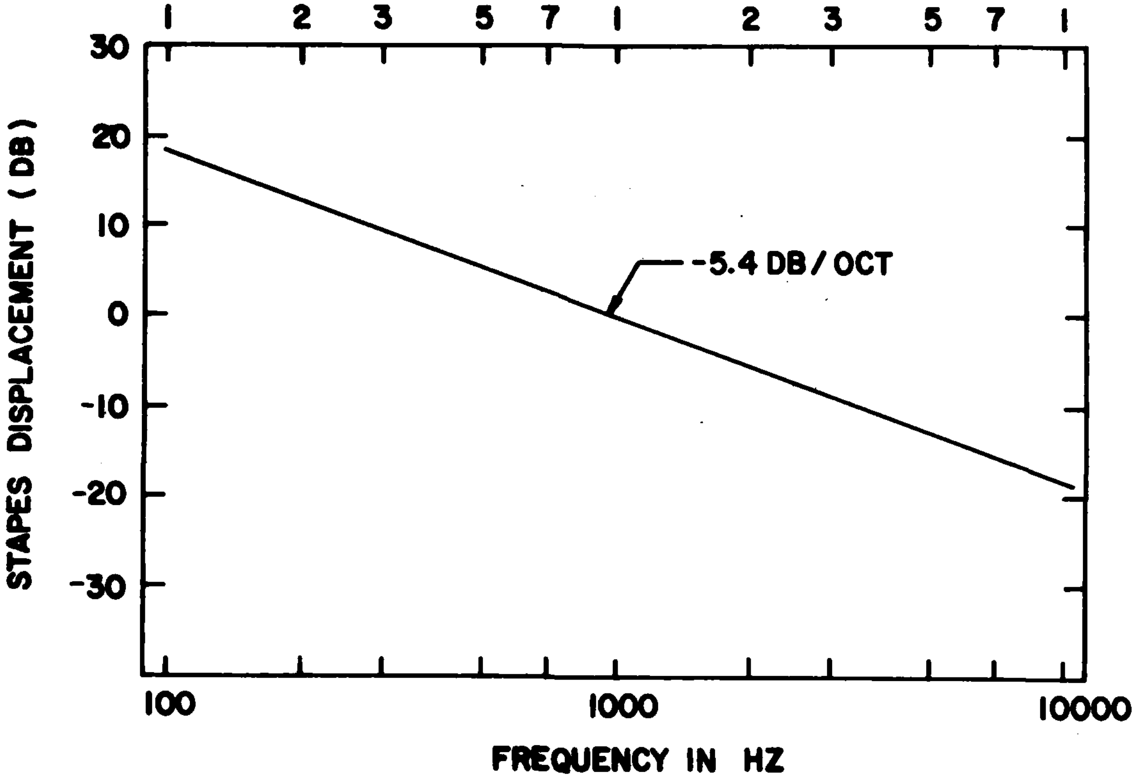

Figure 1. Stapes displacements just reaching the threshold of loss to spectrally narrow impulses of different frequencies. (From Price, 1979b.)

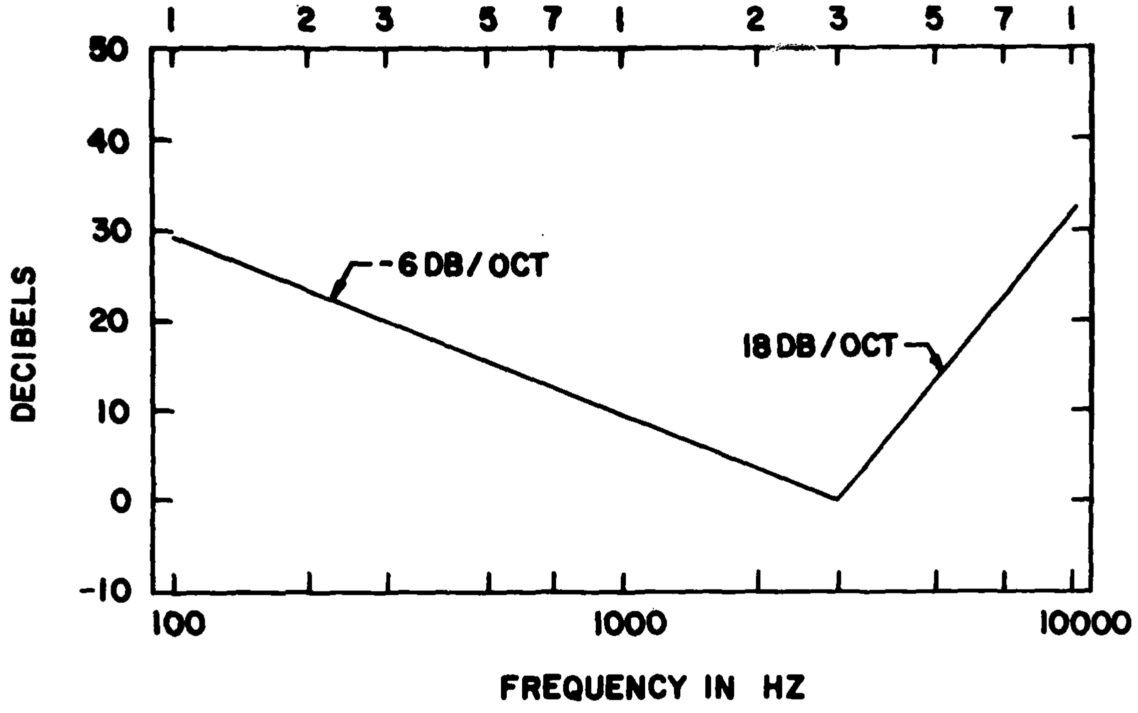

Figure 2. Free field sound pressure just reaching the threshold of loss for spectrally narrow impulsive stimuli as calculated for the human ear. (From Price, 1979b.)

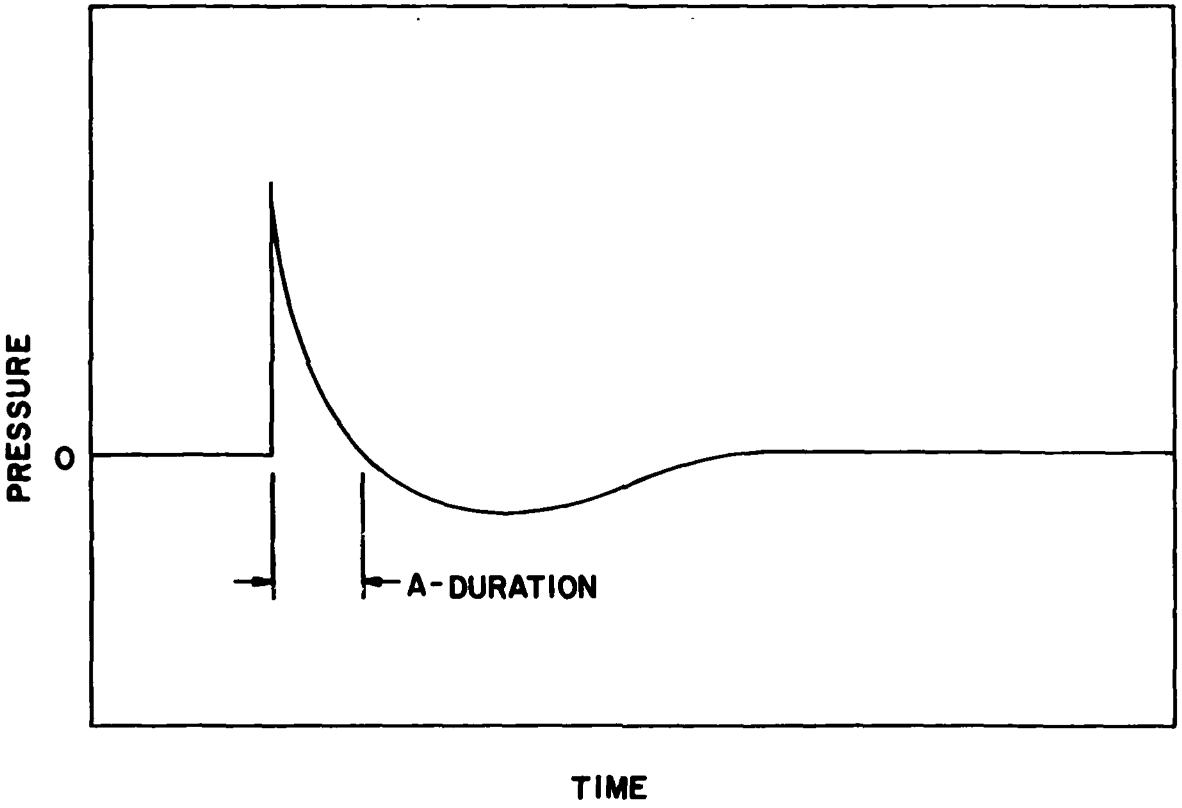

Figure 3. Representation of a pressure-time history for a classic weapons impulse.

to note that the frequency at which this break in slope occurs is a function of the rise time of the impulse.[1] Below the spectral peak, the magnitude falls at 6 dB/oct.

Within the inner ear, a form of frequency analysis occurs which results in the incoming energy distributing itself along the basilar membrane on essentially a logarithmic scale (Schuknecht, 1960; von Bekesy, 1949). If the spectrum of the classic impulse is integrated in the same fashion, then the slopes above the spectral peak are -3 dB and -9 dB/oct and the slope below the spectral peak is increased to 9 dB/oct. The spectrum of this classic impulse is presented in Figure 4.

In practice, of course, the classic weapon impulse is rarely seen in a pure form. The projectile, muzzle brakes, combustion processes within and outside the barrel, reflecting and absorbing surfaces, etc. all tend to make the pressure-time history more complex.

The spectral peak for current weapons tends to fall below 3.0 kHz (A-durations longer than approximately 100 μsec). For rifles, with A-durations in the vicinity of 250 to 350 μsec, the calculated spectral peaks fall in the 800-1000 Hz region. Larger weapons, such as cannons, have A-durations in the 3 to 6 msec region and spectral peaks well below 100 Hz.

If the susceptibility curve for the ear (Figure 2) and the spectrum for a large caliber weapon (Figure 4) are plotted together, as in Figure 5, an interesting prediction becomes apparent. Compared to the tuning of the ear, the spectrum of the weapon impulse is relatively flat. Consequently, so long as the peak is below 3.0 kHz, as it is for typical weapons, the energy that first exceeds the susceptibility curve will be in the midrange. If the foregoing analysis is essentially correct, then it leads to a prediction that, even though the spectral peak for cannon fire is below 100 Hz, the effect on the ear will be seen first as threshold shifts in the midrange. This prediction is in fact borne out by Jacobson, Dyer and Marone (1963) and Murray and Reid (1946). If the picture in Figure 5 is accurate, an essential step toward making weapons less hazardous would be to reduce the energy in the midrange that reaches the ear.

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[1] For weapons impulses, the rise in air is essentially instantaneous. At a practical level, most measurement systems impose a minimum rise time of about 10 μsec and if a spectral analysis is done with such data, the break in slope is seen at about 25 kHz. However, this is not a serious measurement error, so far as the inner ear is concerned. Measurements of a rifle impulse arriving at the ear drum position of an acoustic ear model showed that the structure of the external ear degrades the rise time to longer than 20 μsec depending somewhat on the angle of incidence (Price, 1974a). Consequently, the ear drum never sees the instantaneous rise of the impulse in air!

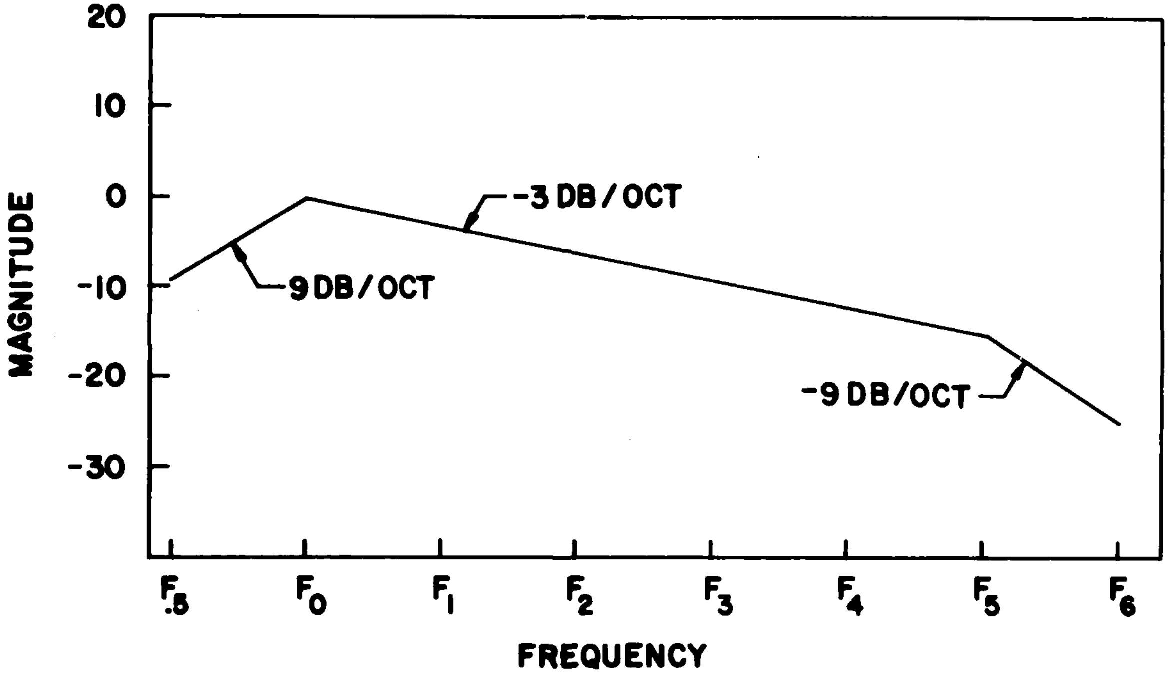

Figure 4. Spectrum for a classic weapons impulse when energy is integrated as in the inner ear.

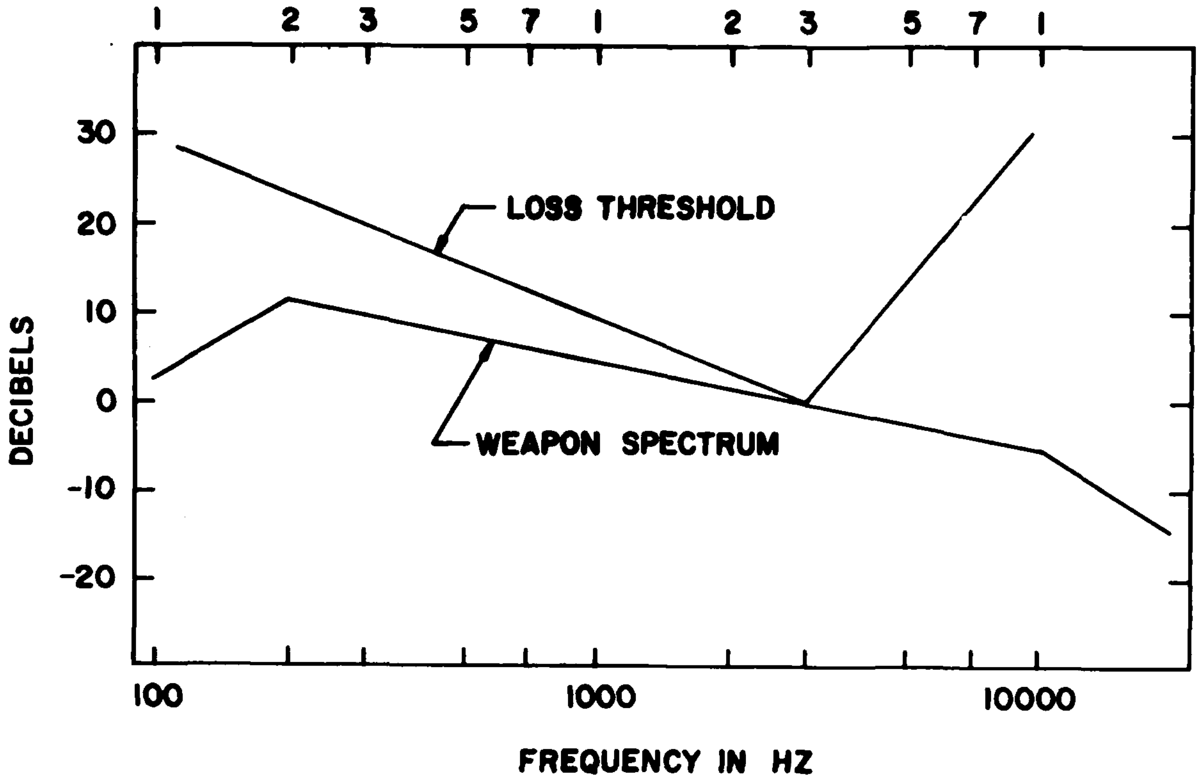

Figure 5. The weapon spectrum with the loss threshold just tangent to it demonstrating that loss would be predicted to occur first in the 3.0 kHz region.

PRESCRIPTIONS FOR SAFER WEAPONS

There are two different general strategies for reducing the energy in the midrange that reaches the ear. The first is to eliminate the energy at the source and the second is to prevent it from reaching the ear. These strategies are not mutually exclusive and could both be profitably pursued. Within each of these strategies, the goal could be achieved by either reducing the overall level or by altering the energy in the midrange (by reflection, absorption, or by shifting it to some other frequency region). In general, reducing the overall level would be highly desirable but unfortunately, theoretical and practical considerations often dictate against making the problem go away in this direct fashion. Therefore, the approaches most likely to succeed will follow the routes of absorbing, reflecting or altering the spectrum of the impulse.

The foregoing considerations are not new in the annals of noise control. What is new is that the emphasis is on dealing with the energy in the midrange of the acoustic spectrum of an impulse. Given this new thrust, there are a number of possible solutions that have not been seriously considered before. In the next sections of this report various strategies for reducing the hazard will be briefly discussed. The purpose of this presentation is to indicate directions in which acoustical research and engineering effort might profitably be directed, based on newly developed information about the response of the ear to intense sound. Detailed engineering analyses and cost/benefit judgments for specific weapons systems are beyond the scope of this report.

CHANGING THE SOUND AT THE SOURCE

Most of the obvious answers in this area also have practical consequences that dictate against their acceptance. For example, usually, charge size and peak pressure are directly related. The acoustic problem could be solved if the charge were reduced; but the accompanying performance penalty would be unacceptable. A second example would be the elimination of the muzzle brake which is responsible for directing a great deal of acoustic energy into the crew area. The problem, of course, is that the recoil absorbing mechanism would then have to do more work and would be heavier; an undesirable consequence.

One answer could lie in the development of a more efficient propellant that would develop more thrust and less noise. Such an effort is complex and would involve not only the creation of a new propellant chemistry but also the design of a new cannon to take advantage of the properties of the new propellant. It is unlikely that current weapons could benefit from such a breakthrough.

However, there is one attractive possibility. It will be recalled that the spectrum of a weapons impulse shows an increase in slope at high frequencies. The location of this change in slope is a function of the rise time of the impulse (Figure 4). If it were possible to give the impulse a rise time of 1 to 2 msec, then the hazard, based on arguments developed earlier, would be reduced as diagramed in Figure 6. The spectral slope would change to -6 dB/oct at about 300 Hz with the result that the peak pressure could be increased approximately 10 dB before the threshold of loss would be crossed. The engineering problem is how to achieve the slower rise time. One approach would be as follows. Assuming muzzle velocities in the vicinity of 1000 to 2000 fps, the projectile would move through distances of 1 to 4 feet during a 1 to 2 msec rise time. If it were possible to bleed out the gases during this period through progressive ports in a new muzzle brake/barrel design, instead of "uncorking" the bore as is presently done, then the rise time might be lengthened sufficiently. If the rise is on the order of 100 microseconds or less, then the effect on the spectrum would be above the midrange and would probably not benefit the ear. However, as is apparent in Figure 6, any lengthening of the rise beyond 100 microseconds will be of some benefit.

At first glance, the foregoing possibility is attractive. There are, however, many design considerations that need to be addressed. Weapon performance should not be degraded, weight must be kept at a minimum, unbalanced forces must not be applied to the weapon, there should be no unusual signature, and maintenance should be minimal. There is also the possibility that a shock front could re-form in air some distance from the muzzle and effectively negate the benefit. These and other issues should be resolved and represent an area that might be profitably addressed in an acoustical/engineering research program.

If the desired result could be attained, then the advantages of such a system are considerable. Performance penalties would be small, it is likely that the design could be applied not only to new weapons but could also be retrofitted to existing weapons, and the mode of protecting the crew is optimal. That is, it requires no administrative controls, can't be forgotten or lost, isn't uncomfortable, does not have to be issued to each crew member, and will not interfere with crew performance by being in the way or by making communication difficult.

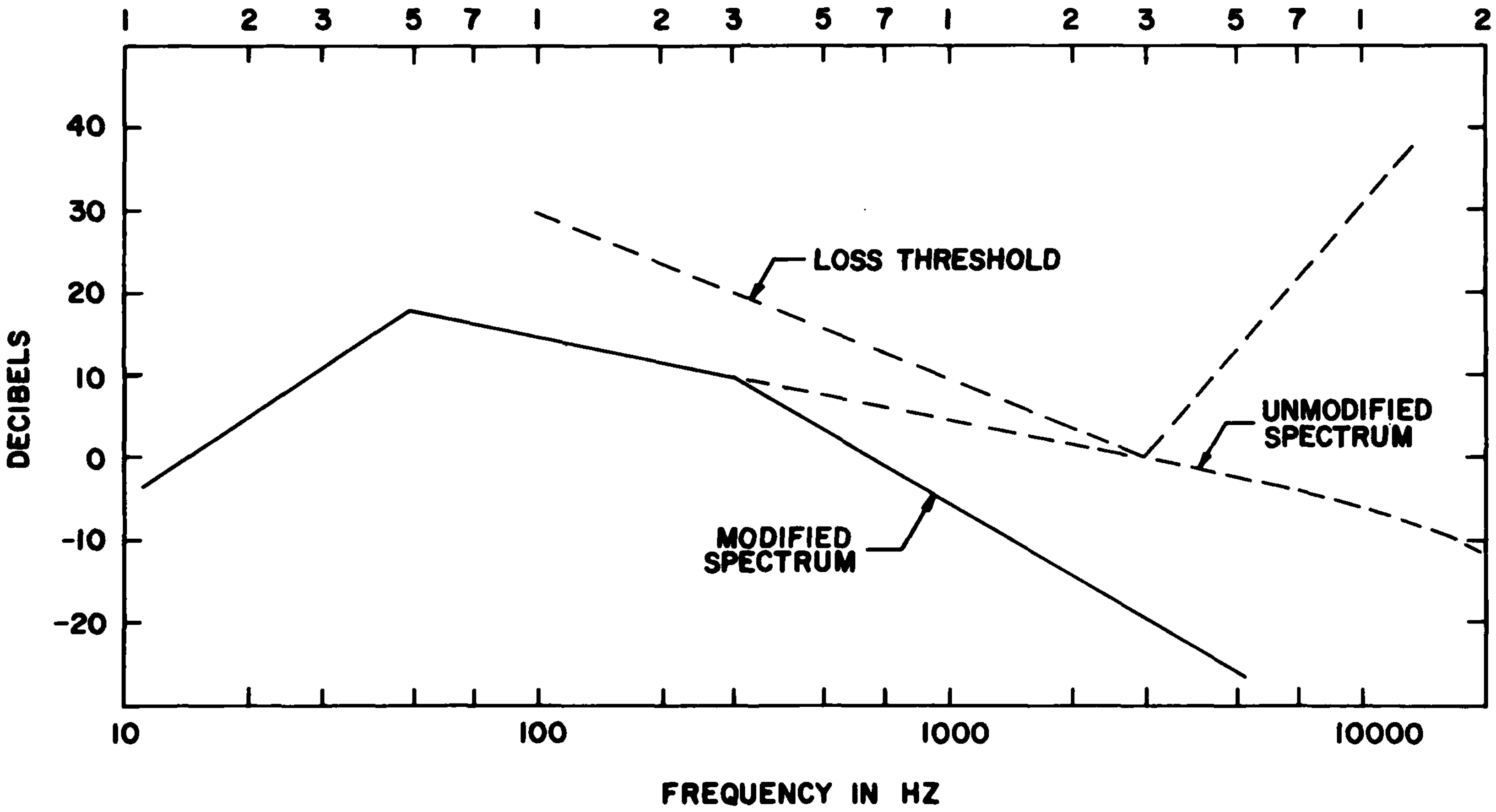

Figure 6. The loss threshold tangent to the spectrum from a classic impulse (dotted lines) and the spectrum from an impulse with an extended rise time (solid line). [The space between the modified spectrum and the loss threshold is the amount by which the modified impulse is safer than the unmodified impulse.]

ALTERING THE SOUND ON THE WAY TO THE EAR

With the role of spectrum defined, the problem of preventing the sound from getting to the inner ear is structured so that potentially it can be dealt with effectively. Protective devices in the form of ear plugs, circumaural muffs and/or helmets are already available. Assuming that there is no nonlinearity in their response at very high intensities (which should be tested), then they can now be meaningfully rated for effectiveness for impulse noises, which has not been possible in the past. While such devices can be effective, the practical difficulties associated with their use are well documented. Even though they may provide needed protection, people often fail to use them, or if they use them, may not use them effectively. It would be better if protective systems could be designed so that the active participation of the individual were not required.

Given that frequencies in the midrange of the spectrum are the primary cause of damage, then the potential exists for making use of modest sized barriers as protective devices. In the past, when peak pressures and durations were measured to evaluate noises, small barriers did not appear to have much effect. In reality, obstacles in a sound field whose dimensions are on the order of the wave length of the sound involved can provide significant "shadows." In the present context this means that barriers with dimensions of 1/2 m or a little less can provide a significant shadow. The specific considerations are complex, involving the transmission characteristics of the barrier material, its dimensions, the angles and distances between the source and barrier, and the barrier and ear, etc. However, it is conceivable that given specific weapons systems, barriers could be worked into the crew areas in such a way that they would provide protection without requiring the active participation of the personnel. If such barriers were constructed of materials that could resist the penetration of foreign bodies, then they could provide a measure of ballistic protection as well. While it is premature to propose a general purpose barrier design or specific barriers for specific weapons, it is reasonable to suggest that here is another area where acoustic and engineering research, in conjunction with biological validation studies, might prove profitable. Innovations in this area could be applied to both existing weapons and to new designs.

APPLICATION OF SPECTRAL MEASUREMENTS IN ESTABLISHING L_c

In the preceding discussion, the concept of spectrum as a factor in establishing noise hazard has been used rather loosely. The ideas as presented are consistent with the data and assumptions as noted. However, it would be inappropriate to leave this discussion without pointing out the complexity inherent in the L_c concept and the implications this has for application of common measurement techniques.

The concept of spectral tuning in the case of complex stimuli, such as weapons impulses, must be applied very cautiously. This restriction, discussed at somewhat greater length in Price (1979c), comes about because the ear operates in both the time and frequency domains. That is, a form of frequency analysis is performed on the basilar membrane with the result that energy entering the inner ear is distributed along the sensory surface according to its frequency composition. It will be remembered that the basis for the L_c concept is that some critical displacement is exceeded at specific places along the sensory surface. If one attends to the magnitude spectrum only, ignoring the phase information, then the possibility for serious error exists. To illustrate: the magnitude spectrum in Figure 4 could have been produced by either bands of continuous noise or by a weapons impulse. In the first case, the ear would have been subjected to thousands of vibratory cycles whose total activity in one second would have added up to the level in Figure 4. In the second case, the ear would have been subjected to a few very large excursions containing the same energy. Assuming that the L_c concept is valid, then it is apparent that the weapons impulse could have exceeded L_c, whereas the continuous noise might not have. Equal spectral levels do not necessarily lead to equal displacements of the inner ear. As has been pointed out, the frequency content of the impulse is important too.

The result of the foregoing considerations is that the L_c concept cannot be applied in a direct way when measuring with conventional instruments. In the hope of alleviating this difficulty, research is presently under way in this laboratory which is aimed at producing a mathematical model of inner ear displacements given pressure-time data in the free field (Kalb, 1979). Until such a model and the accompanying instruments are developed, however, these concepts must be applied with considerable caution. Given that weapons impulses tend to be similar in form, it follows that their displacement patterns in the inner ear will be similar. It should, therefore, be possible to rank pulses with respect to one another based on some common measures, such as peak and A-duration. If, however, the waveforms are altered in a dramatic way, then one can rank them with much less confidence. And in the end, until the models are developed and validated with real ears, the ultimate test of the effect of any alteration in waveform will have to be empirical. That is, tests will have to be run in which real ears are exposed to the new impulse and its effects measured.

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