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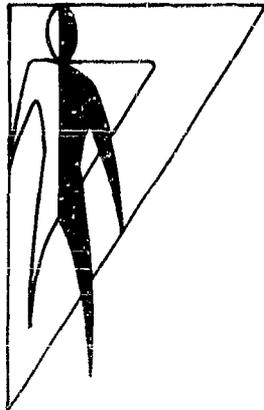
A MAJOR PROBLEM

Robert F. Chaillet
Georges R. Garinther

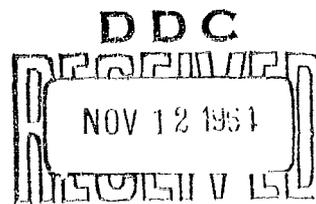
David C. Hodge
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August 1964

HUMAN ENGINEERING LABORATORIES



**ABERDEEN PROVING GROUND,
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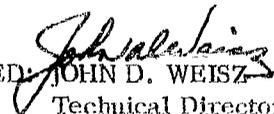
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APPROVED:


JOHN D. WEISZ

Technical Director
Human Engineering Laboratories

U. S. ARMY HUMAN ENGINEERING LABORATORIES
Aberdeen Proving Ground, Maryland

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HIGH-INTENSITY IMPULSE NOISE:

A MAJOR PROBLEM

INTRODUCTION

During the past decade there has been a trend in weapon-system development that has made these weapons psychologically unpleasant and physiologically dangerous to our own forces. Three major changes have occurred to develop this trend:

First, weapons are being made as light as possible for air mobility. To lighten the weapons, tubes are shortened, placing the origin of the impulse sound pressure closer to the gun crew. Recoil mechanisms are of lighter construction and capable of absorbing less energy, necessitating the use of a muzzle brake which, in turn, deflects the impulse sound pressure back toward the crew.

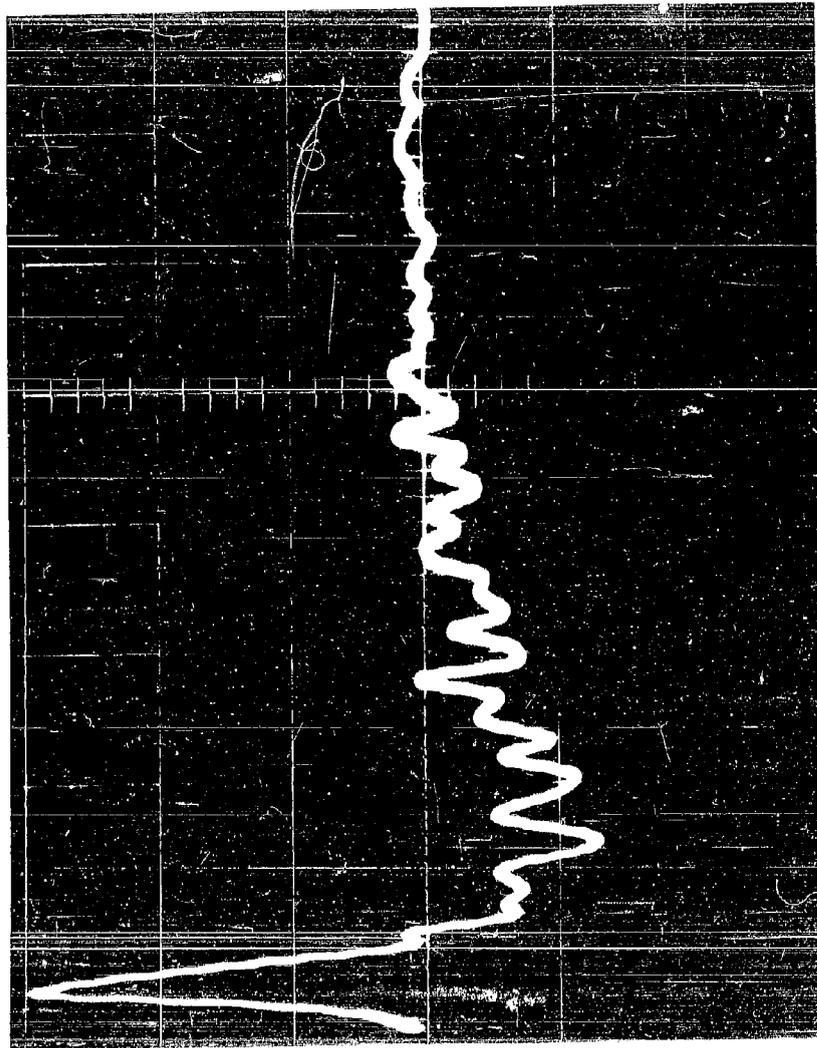
Second, with the advent of nuclear and other sophisticated ammunition, it has become advantageous to propel our projectiles to greater distances, which requires higher pressures and results in an increased noise level.

Third, increased firepower results in a greater number of impulse sound pressure insults to the operator's ears per unit of time. Thus, increased firepower, with increased pressures, in shorter tubes, together result in exposing the gun crew to dangerous impulse sound pressures.

When weapons, such as rifles, mortars, cannons, and bombs, are fired or detonated, several physical phenomena occur. First, the chemical reaction of the explosion takes place, after which there is an extremely rapid one-way flow of the gaseous products of combustion from the detonation center outward. This expansion moves faster than the speed of sound, thereby creating a shock wave in a manner similar to the way a shock wave is created by an aircraft moving at supersonic speed. The spherical shock wave, which is the second physical phenomenon to occur, continues to move outward, producing an abrupt increase in pressure (rise time of less than one microsecond). As the shock wave moves out, it begins to lose energy and several changes occur:

- a. Velocity decreases
- b. Peak pressure decreases
- c. Impulse decreases
- d. Duration increases

When its speed reaches sonic velocity, it is classified as an impulse sound wave.



Sound-Pressure Level

Time (milliseconds)

Fig. 1. A TYPICAL IMPULSE SOUND-PRESSURE WAVE FORM

When discussing hearing damage to personnel firing weapons, we are concerned with the pressure patterns caused by shock and impulse waves. Both of these phenomena are transient in nature and may be distinguished from steady-state sound waves by the fact that their peak pressure levels are very high, compared to their root mean square (rms) pressure levels.

Two factors which distinguish shock waves from impulse sound waves for auditory perceptual purposes are amplitude and rate of pressure increase and decay. The amplitude of a shock is greater than that of an impulse sound wave, and the time required for the pressure to reach its maximum and to decay is shorter. Therefore, for the purpose of this paper, we shall refer to a transient pressure wave, regardless of the phenomena causing it as an impulse sound-pressure wave. Also, the maximum pressure achieved will be referred to as the peak sound-pressure level. Figure 1 is a representation of a typical impulse sound-pressure wave form created by small arms.

PROBLEM

The repeated high pressures developed by new weapons have their greatest effect upon the ears of the personnel. By the time the pressure becomes so great that other bodily organs are affected, the unprotected ear will have been irreparably damaged.

Even if the long-term, hearing-loss effects upon the man were to be disregarded, field commanders still have to consider the short-term lowered efficiency of partially deafened gun crewmen when these crewmen are assigned to other duties, such as night perimeter guard.

Basic to the entire impulse-noise problem is the development of a hearing-damage-risk criterion. Until the hearing-loss effects that impulse noises have on man are determined accurately, the degree to which these pressures should be reduced cannot be specified.

Many parameters must be considered in establishing a damage-risk criterion. Among these are the following:

- a. Peak pressure
- b. Sound frequency-energy spectrum
- c. Rise time
- d. Total duration

Given: $1 \text{ psi} = 6.895 \times 10^4 \text{ dynes/cm}^2$ and

$$db = 20 \log_{10} \left(\frac{p}{0.0002 \text{ dyn/cm}^2} \right)$$

then $db = 20 \log_{10} \left(\frac{\text{psi} \cdot 6.895 \times 10^4}{2 \times 10^{-4}} \right) = 20 \log_{10} (\text{psi} \cdot 3.4475 \times 10^8)$

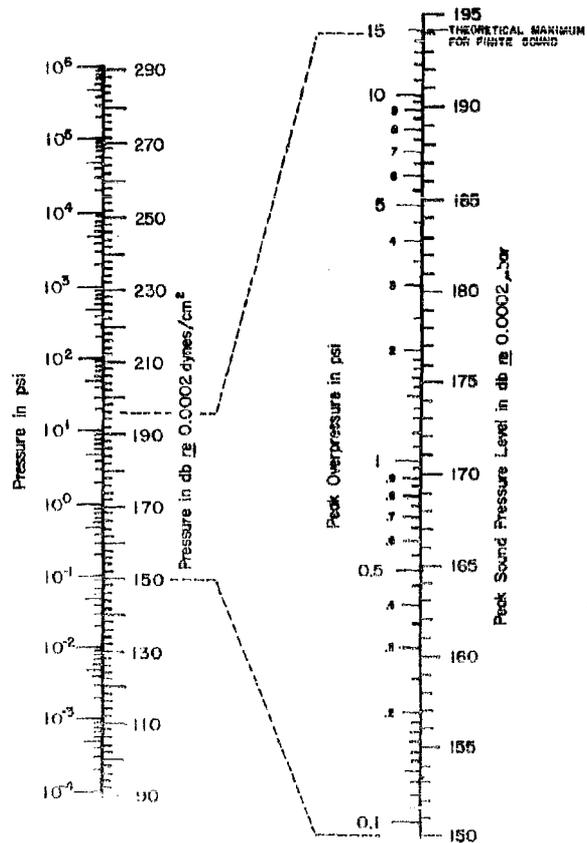


Fig. 2. RELATIONSHIP BETWEEN PRESSURE IN psi AND SOUND-PRESSURE LEVEL IN db

- e. Repetition rate
- f. Total number of exposures

Areas which must be investigated include the following:

- a. How consistent is temporary hearing loss within one individual?
- b. How consistent is the hearing loss among different people exposed to a given condition?
- c. What is the relationship between temporary hearing loss and permanent hearing loss, caused by impulse noise?
- d. How do peak pressure, rise time, and duration interact in causing temporary hearing loss?

Prominent among the weapons under development that produce pressures much greater than those experienced in the past are the 107mm mortar and the M102 howitzer, which produce noise loud enough to rupture the eardrum. Also under development are highly effective small arms that produce impulse sound-pressure levels substantially greater than the M-14 rifle. Since the M-14 is loud enough to cause both temporary and permanent hearing loss to the unprotected ear, the development of these new small arms serves to increase the problem.

Peak sound-pressure levels may be reported in one of two ways:

- a. In pounds per square inch (psi).
- b. In decibels (dB) above a reference point of 0.0002 dynes per square centimeter.

Figure 2 depicts the relationship between these two measures. In isolated cases, pressures have been reported in pounds per square foot.

POSSIBLE SOLUTIONS

There are various avenues of approach which may be taken in an attempt to reduce the weapon crew's exposure to high impulse sound pressures:

- a. The impulse sound pressure may be reduced at its source. To accomplish this we might develop propellants that maintain or increase projectile range while keeping muzzle pressure at a minimum. This means a high chamber pressure with a rapid pressure-travel decay; or a mechanical method of attenuating the impulse sound pressure may be devised.



Fig. 3. SHOCK WAVE CREATED WHEN WEAPON IS FIRED AND THE PROJECTILE SHOCK WAVE

b. The operator may be separated from the impulse-sound pressure source by either distance or a barrier.

c. Ear-protective devices, such as earplugs or earmuffs, may be provided for the crew. This category might also include conditioning the ear so that it becomes less sensitive to noise.

All three of these approaches are being explored.

The first approach is a difficult one, but the most desirable if achieved. The mechanical methods of attenuation involve placing a device on the muzzle to either deflect the excessive impulse sound pressure away from the crew or reduce the peak sound-pressure level, or both.

Figure 3 indicates the phenomena that occur at the muzzle of a weapon as a projectile leaves the muzzle. The expanding gases are released from the muzzle at speeds greater than the speed of sound, thereby causing a shock wave, or a "sonic boom." Simultaneously, as the projectile emerges, it produces its own shock wave because it also is moving faster than the speed of sound. Where a muzzle brake is used, the problem of keeping the expanding gases away from the crew and dissipating the "shock bottle" is intensified.

One solution is the development of a muzzle brake-silencer. A muzzle brake-silencer traps most of the exiting gases, then cools, expands, diffuses, and expels these trapped gases over an expanded time frame. Trapping these gases also reduces the recoil momentum. A recent Human Engineering Laboratories (HEL) effort used this principle to increase firing stability of two light automatic rifles -- the M-16 and the Stoner Assault rifle. Figure 4 shows the standard M-16 rifle. The development phases of the M-16 muzzle devices are shown in Figures 4 through 9.

The standard M-16 rifle's peak sound-pressure level, at the gunner's ears, is 154 dB. Figure 5 shows an adjustable muzzle-brake. Although effective in the reduction of recoil impulse, it increased the peak sound-pressure level (SPL) to over 160 dB.* Figure 6 shows a similar device which was more efficient, but also noisier -- the peak SPL again exceeded 160 dB. In an attempt to attenuate the noise while taking advantage of the recoil reduction, a single-baffle combination brake-compensator was made as shown in Figure 7. This device reduced the peak SPL to 152 dB. The latest design (Fig. 8) features a double baffle with smaller-diameter outlet holes than the previous design. This arrangement gave the lowest peak SPL -- 148 dB. This SPL was 6 dB less than the standard M-16 rifle, yet it provided excellent stability. Figure 9 depicts the latest design, showing the twin baffles and gas-collection area.

* Instrumentation for measurement was calibrated up to and including SPL measurements of 160 dB. The reliability of readings over 160 dB is questionable and therefore not reported.



Fig. 4. STANDARD M-16 RIFLE

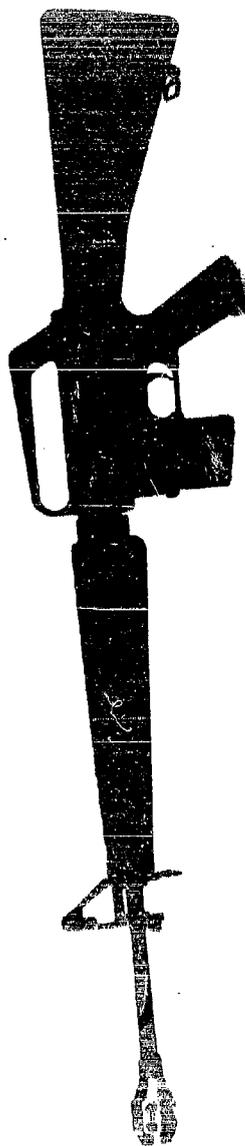


Fig. 5. M-16 RIFLE WITH ADJUSTABLE MUZZLE BRAKE



Fig. 6. M-16 RIFLE WITH MODIFIED MUZZLE-BRAKE COMPENSATOR

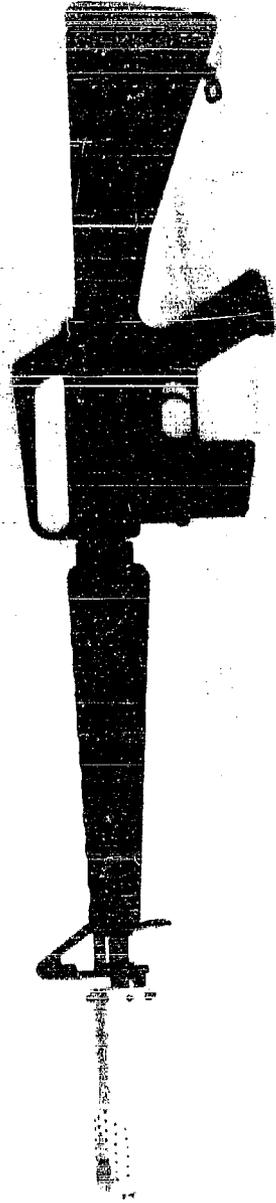


Fig. 7. M-16 RIFLE WITH SINGLE-BAFFLE COMENATION BRAKE-SILENCER

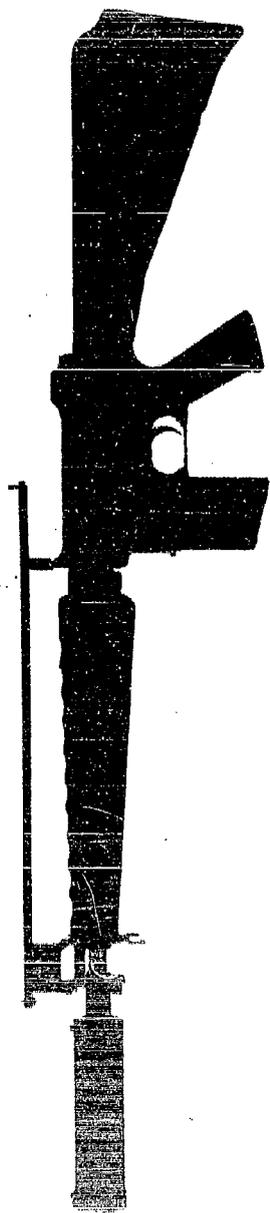


FIG. 8. M-16 RIFLE WITH DOUBLE-RAFFLE COMBINATION BRAKE-SILENCER

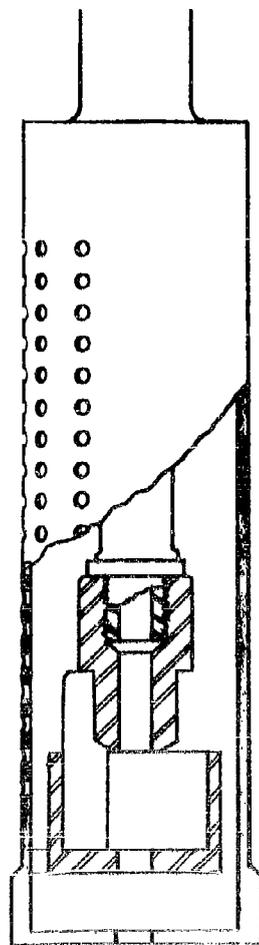


FIG. 9. SECTIONAL DRAWING OF DOUBLE-RAFFLE COMBINATION BRAKE-SILENCER

The HEL has recently been engaged in a crash program to produce a device similar to the one shown in Figures 8 and 9, to fit the muzzle of a new mortar. This weapon, designed for long-range firing, had a very high muzzle pressure. The high muzzle pressure, coupled with the close proximity of the loader's head to the muzzle, presented a challenging human factors impulse-noise problem. Failure to reduce the overpressure would most probably have required a new, lengthy and costly program to develop a radically different-type round of ammunition.

An impulse sound-pressure attenuator was designed, fabricated, and tested by the HEL. Test data indicate that this attenuator reduced the 10 psi overpressure by 60 percent.

Since it appears that this device is quite effective on both rifle and mortar, it is reasonable to assume that a similar device would be effective on the M102, or any other weapon of similar configuration. Figure 10 shows the mortar without attachment. Figure 11 shows the mortar with attachment. Figure 12 depicts a sectional drawing of the attachment.

The second approach involves placing a barrier between the source and the crew. The most obvious mechanical shielding is the gun shield itself. In the case of a tank, the very massiveness of the hull and turret provides an effective shield for the crew in the tank, but this mass provides little if any protection to the infantryman walking beside the tank when the major caliber weapon is fired, or to the tank commander, whose head may be outside the cupola at the time.

For use with field pieces, shields, as such, have very minimal impulse sound-pressure-deflecting properties. A case in point is the M102, 105mm Howitzer equipped with an impulse-noise shield (Fig. 13).

This weapon was recently tested by HEL in the following manner: transducers were arranged behind the weapon to provide data for plotting equal peak SPL contours. Measurements were made during firings at elevations of 0° , 45° , and 68° ; with charges of 85 percent and 100 percent; with three different muzzle brakes and without any muzzle brake; and with and without a shield.

Figure 14 shows a few representative equal-pressure contour lines measured in three of the many tests. The firings depicted in Figure 14 were conducted with a 100 percent charge and an 800-mil (45°) angle of elevation. It was found that the shield did not significantly reduce the peak SPL in the crew area.

Placing the crew farther from the impulse sound-pressure source would probably reduce the weapon's effectiveness because operating it would either take longer or require development of complicated remote controls.

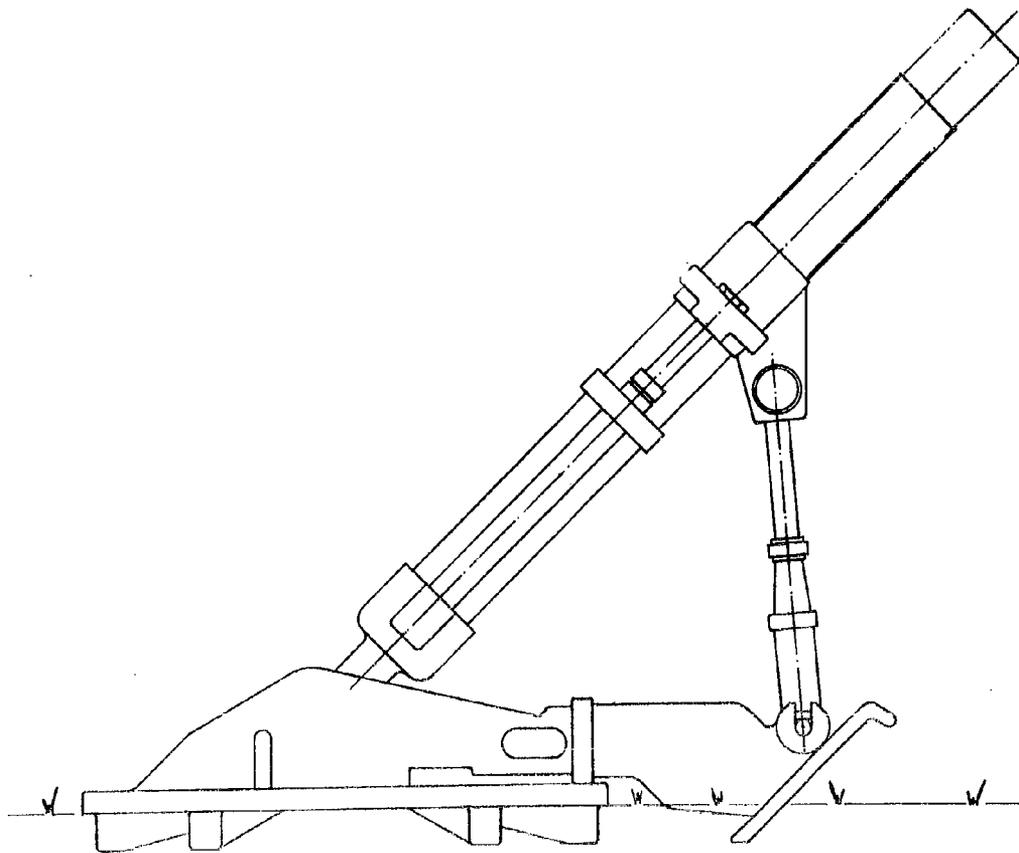


Fig. 10. STANDARD 107mm MORTAR.

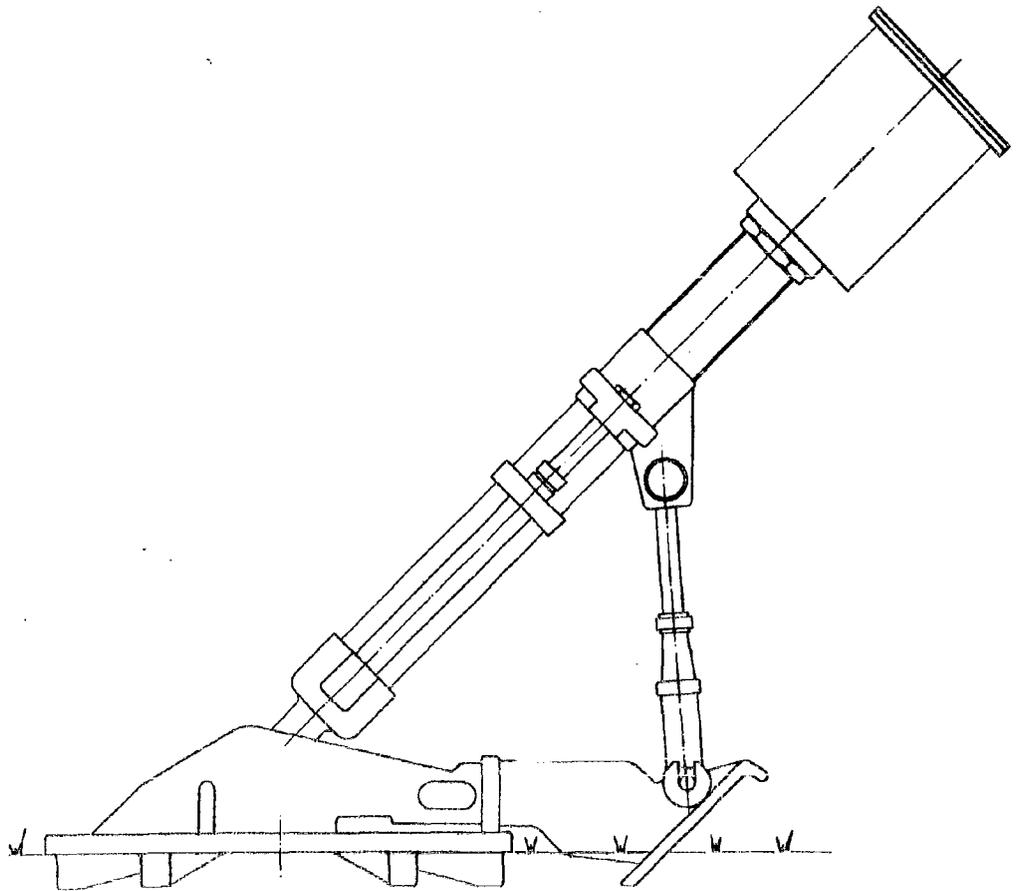


Fig. 11. 107mm MORTAR WITH ATTENUATOR

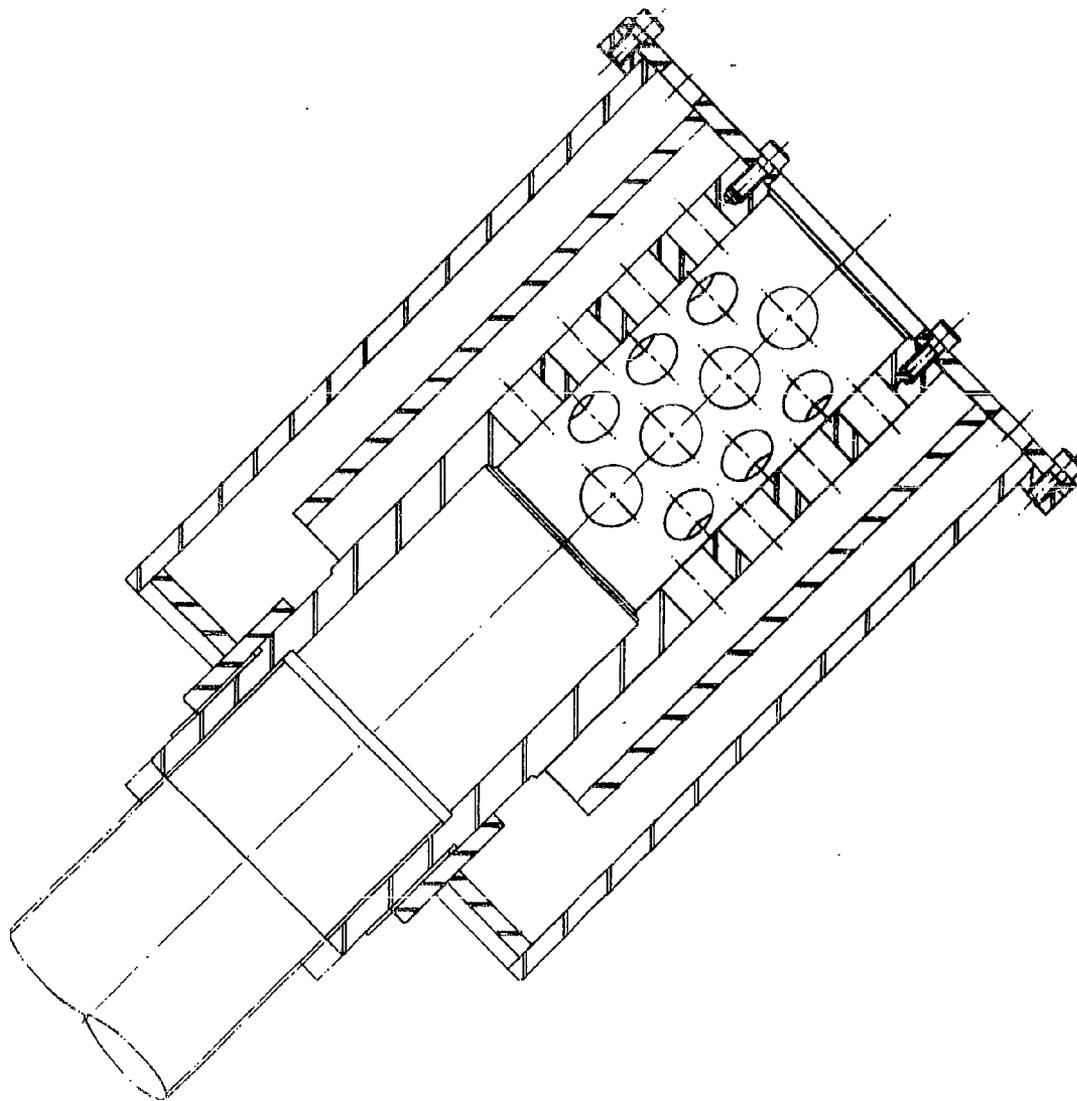


Fig. 12. ATTENUATOR FOR 107mm MORTAR

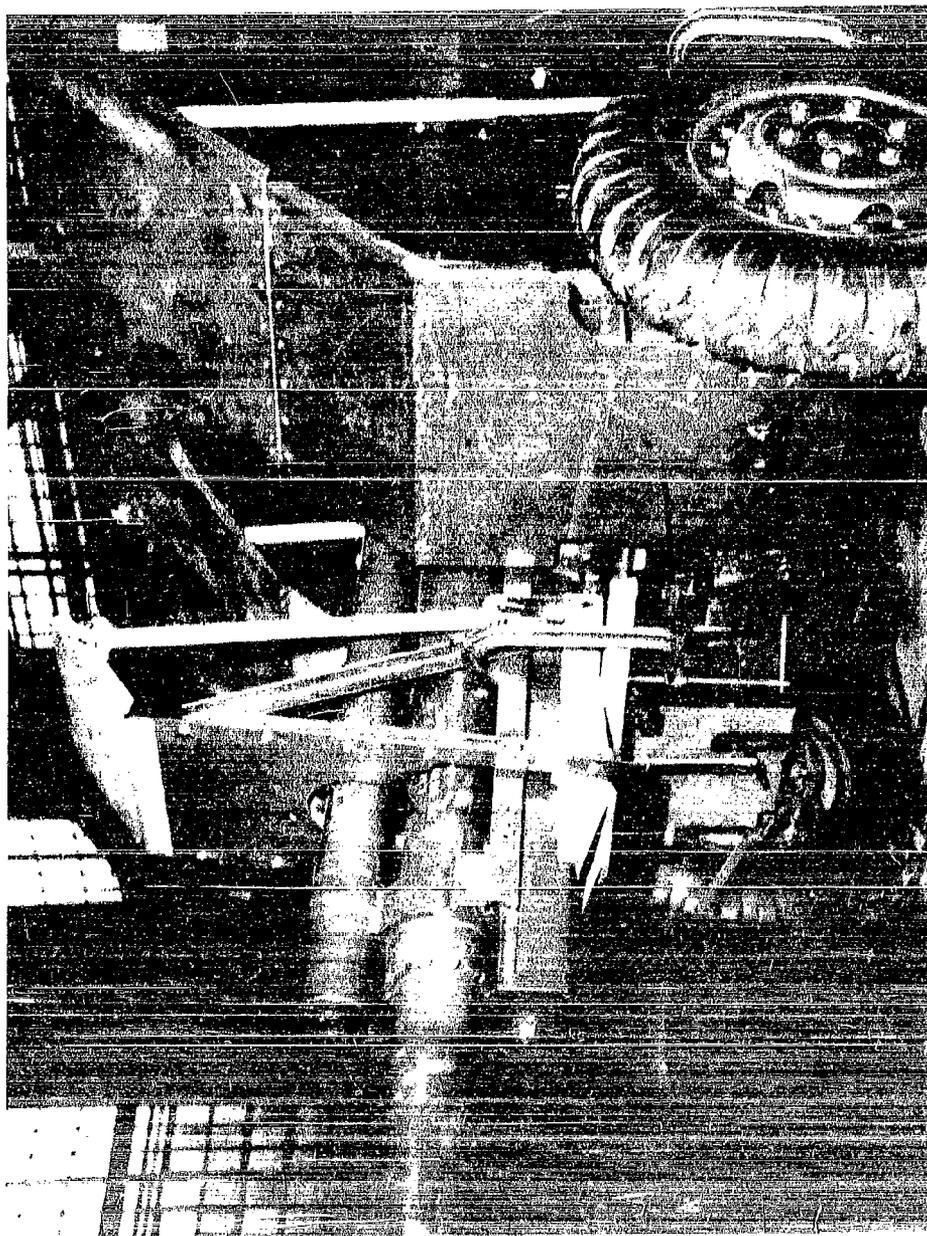
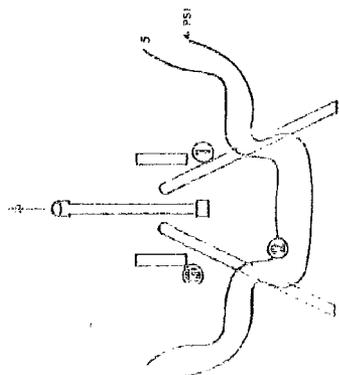
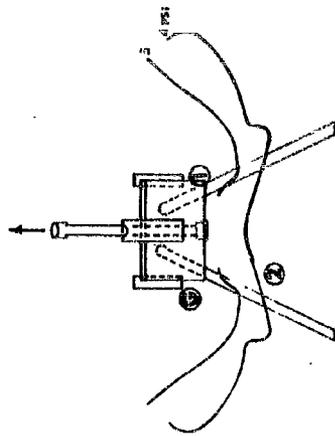


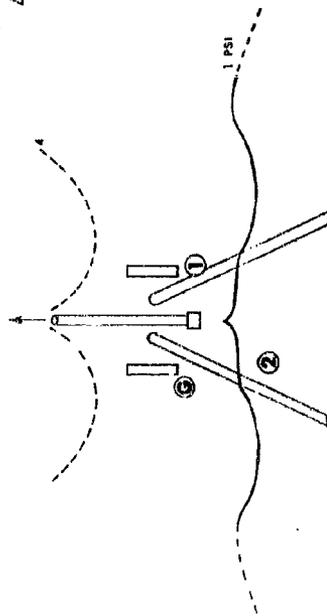
Fig. 13. HOWITZER WITH AN IMPULSE-NOISE SHIELD



No Blast Shield
WTY - F3207 Brake



With Blast Shield
WTY - F3241 Brake



No Blast Shield
No Brake

Fig. 14. OVERPRESSURE CONTOURS
(Positions 1, 2, and 3 are normally occupied by personnel during firing.)

The third approach involves using protective devices applied directly to the ear. There are three possibilities: (1) placing a device in the ear; (2) placing a device over the ear; (3) conditioning the ear so that it becomes less sensitive to noise.

The method of conditioning the ear appears to have promise. It has proved quite effective in certain instances and may afford almost as much protection as an ear-plug. This method complements a natural physiological protective mechanism of the ear by eliciting, before firing, the contraction of certain ear muscles, thereby reducing the transmission of impulse sound pressures. This activation is produced by giving sharp pulses of sound over an intercommunication system for about 0.1 second prior to firing the weapon. This device would probably be of greatest value to tank and self-propelled artillery crews.

Because so little is known about the physiological effects of impulse pressure on man's ear, there is no highly accurate information about the pressure-attenuating characteristics of the various types of ear protectors.

Personnel can wear several types of pressure-attenuating devices. The most common and practical are:

a. The earplug: At present the Army is using the extremely effective V-51R earplug (Fig. 15).

b. The earmuff: At present the earmuff is not available as a standard supply item. Figure 16 shows representative samples of earmuffs.

c. The helmet: The standard combat-vehicle crewman's helmet -- CVC (T56-6) -- (Fig. 17), used in tanks and self-propelled howitzers, provides very little noise attenuation.

Typical ear-protective devices provide good attenuation at high frequencies (above 1000 cycles per second), but relatively poor protection at lower frequencies. Figure 18 shows attenuation as a function of frequency for an average earmuff, for the standard Army-issue V-51R earplug, for the CVC helmet, and for the combination of earplugs and earmuffs. The number in parentheses below each device are estimates of the attenuation (in dB) that these devices give in an impulse-noise environment. It will be noted, in Figure 18, that a combination of earmuff and earplug was not as effective as the earmuff alone for frequencies around 1200-2400 cps (11).

Earplugs have a number of major deficiencies:

a. They must be properly fitted and inserted to achieve the attenuation shown in Figure 18.

b. Even though they have been properly inserted originally, they may work loose through jaw movement.

c. As with earmuffs, faint sounds cannot be heard. A speaker must raise his voice to be understood. This last objection is especially significant since, in many combat situations, it is vitally important to perceive faint auditory cues, and loud talking cannot be allowed. One solution to this problem would be an ear-protective device that attenuates loud noises but does not attenuate faint sounds. A proposal to produce such a device has been submitted by an acoustical engineering firm.

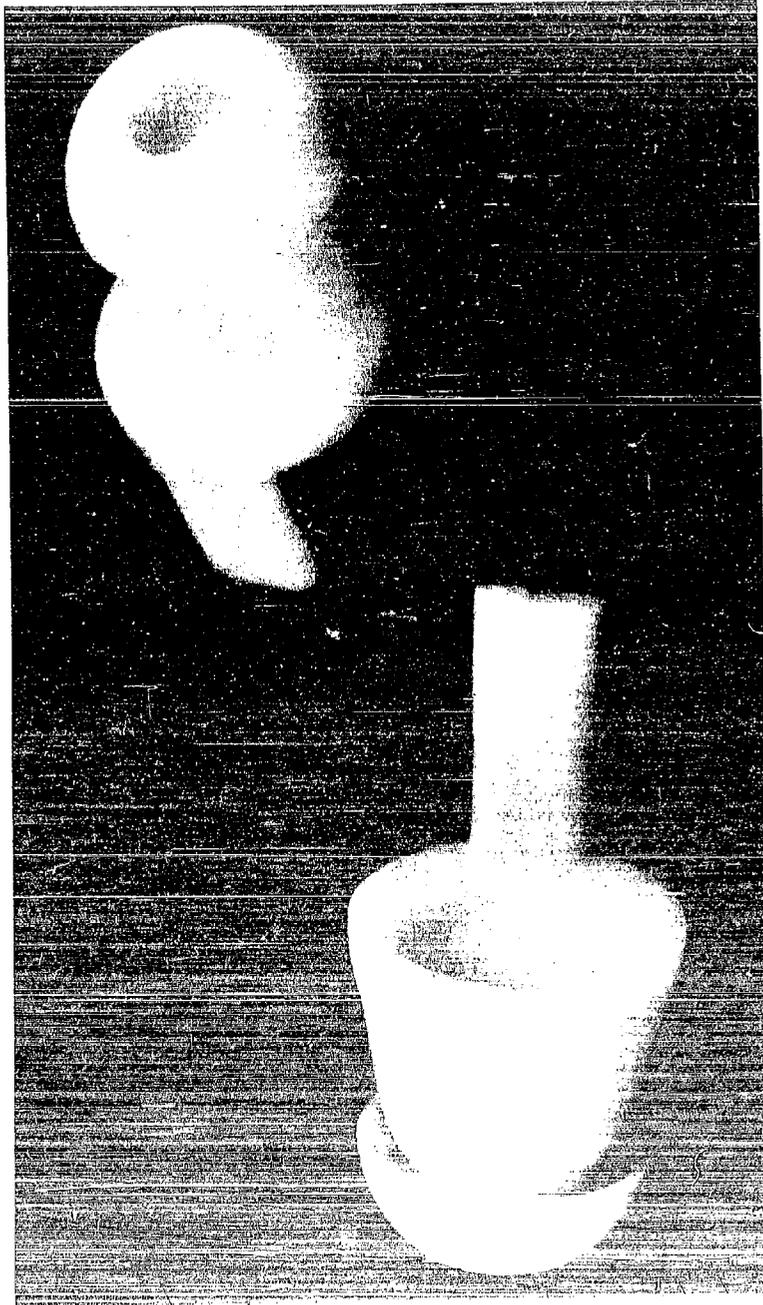


FIG. 15. V-5IR BARPLUGS



Fig. 16. TYPICAL EARMUFFS

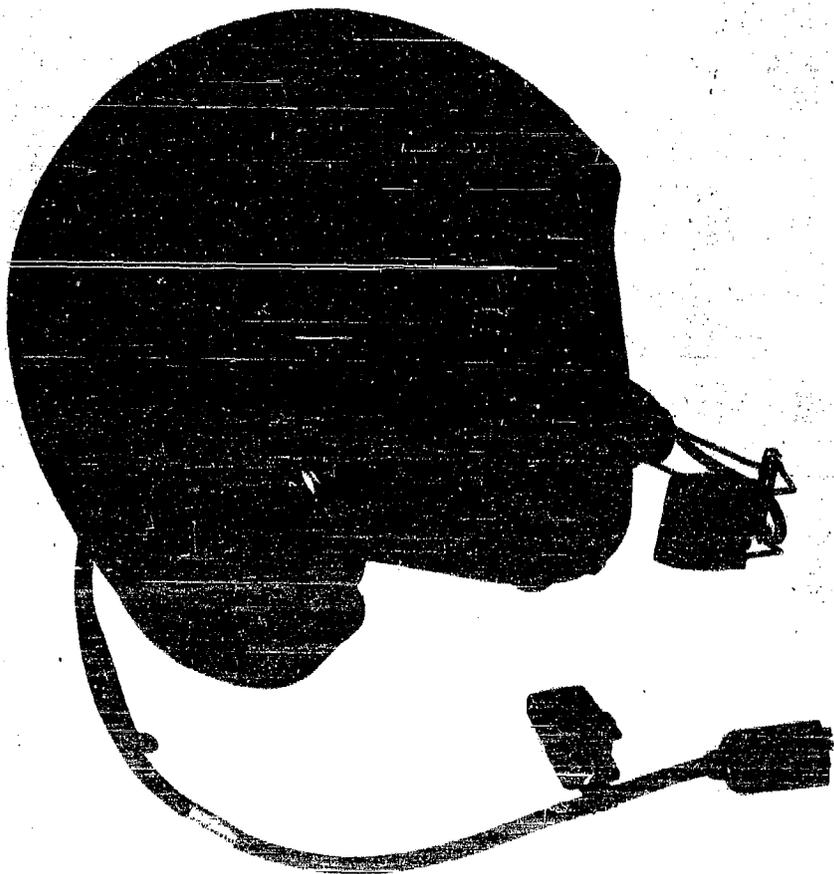


Fig. 17. COMBAT-VEHICLE CREWMAN'S T56-6 HELMET

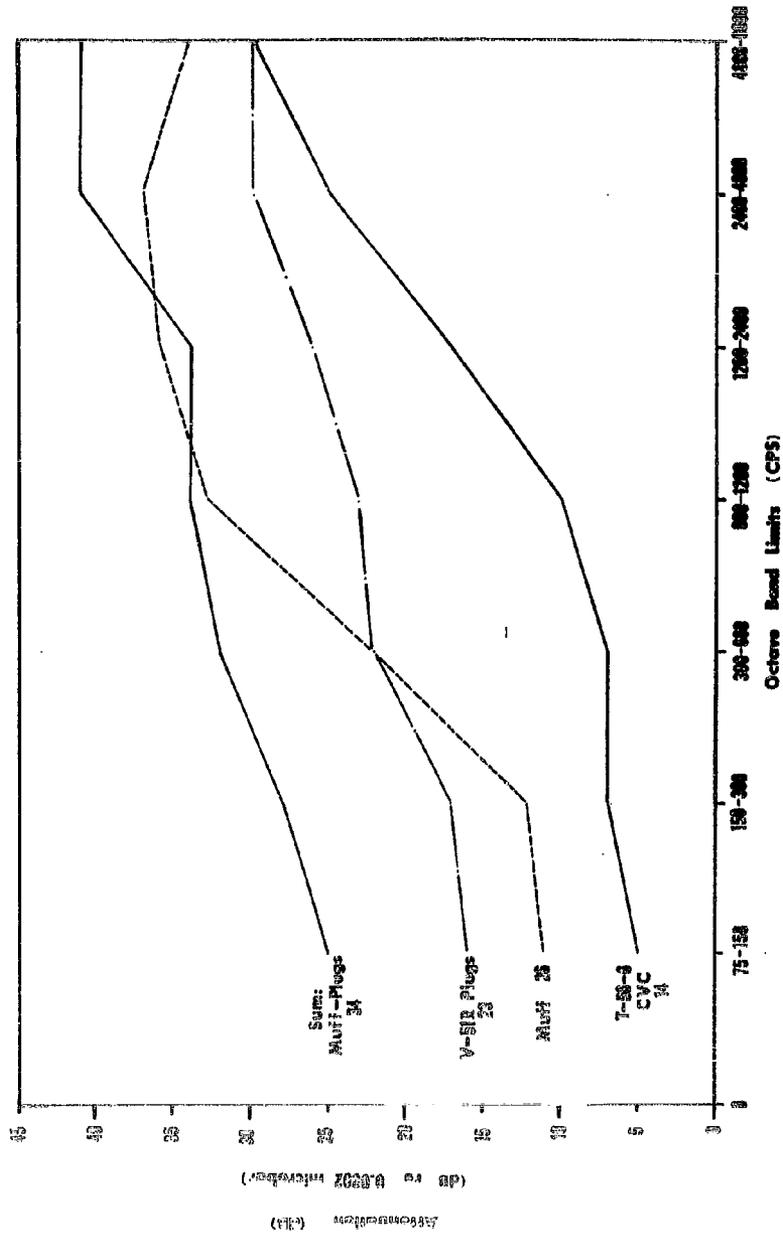


Fig. 18. ATTENUATION CHARACTERISTICS (in dB) OF VARIOUS TYPES OF EAR-PROTECTIVE DEVICES

DISCUSSION

The Atomic Energy Commission has sponsored a considerable amount of research to determine the effects that high-intensity shock waves, from actual and simulated nuclear explosions, have on animals and on men. This research has established tentative lethality limits and thresholds of injury for various bodily organs. But, as has already been pointed out, man's hearing mechanism can be temporarily or permanently damaged by exposure to shock waves or impulse-noise conditions which are far below the threshold limit for damage to the lungs or other bodily organs. Thus the research programs which are being carried out by various laboratories are aimed at studying noise and shock-wave conditions which may cause temporary or permanent damage to hearing, or decrements in human performance, but which are not considered to carry the threat of death, or a threat of physiological harm other than to the hearing mechanism.

A short digression will clarify the sites of hearing damage. Figure 19 shows a cross-sectional view of the peripheral portion of the human hearing mechanism, including the external, middle, and inner ear. Impulse noise of high intensity (above 180 dB) may cause rupture of the eardrum or damage to the chain of three ossicles (bones) in the middle ear. But most temporary or permanent changes in hearing are believed to be due to physiological damage inside the inner ear, or cochlea. In this case, airborne acoustic energy is transmitted to the eardrum, through the chain of ossicles or bones in the middle ear, and through the fluid inside the inner ear. Histological studies of animals exposed to high noise levels have shown that damage to the hair cells of the Organ of Corti inside the cochlea is characteristic, and this damage is believed to be responsible for temporary and permanent hearing loss.

The present state of our knowledge about the effects of impulse sound-pressure levels on hearing is very sketchy -- partly because of a lack of research on the problem, but also because of poor or inappropriate methods which have been used in a number of studies.

The first systematic studies of how impulse sound-pressure levels affect humans were published in 1946 by Murray and Reid (7). These Australian scientists exposed enlisted men to a variety of small arms and artillery noises and, in spite of crude methods and instrumentation, provided the first quantitative data about how impulse sound pressure affects hearing. One of the investigators exposed himself in this study and suffered a ruptured eardrum. Figure 20 shows some of the results. Note that exposing subjects to ten rounds at a peak sound-pressure level of about 188 dB -- comparable to noise in the crew area of a current U. S. Army 105mm howitzer -- produced temporary hearing losses of 85 dB.

Judging from the literature, the impulse-sound-pressure problem area was dormant from 1946 until sometime in the 1950's. The next study of note was published by Harbold and Greene in 1961 (4). These men, from the Naval School of Aviation Medicine (Pensacola), established that personnel going through Machine Corps basic

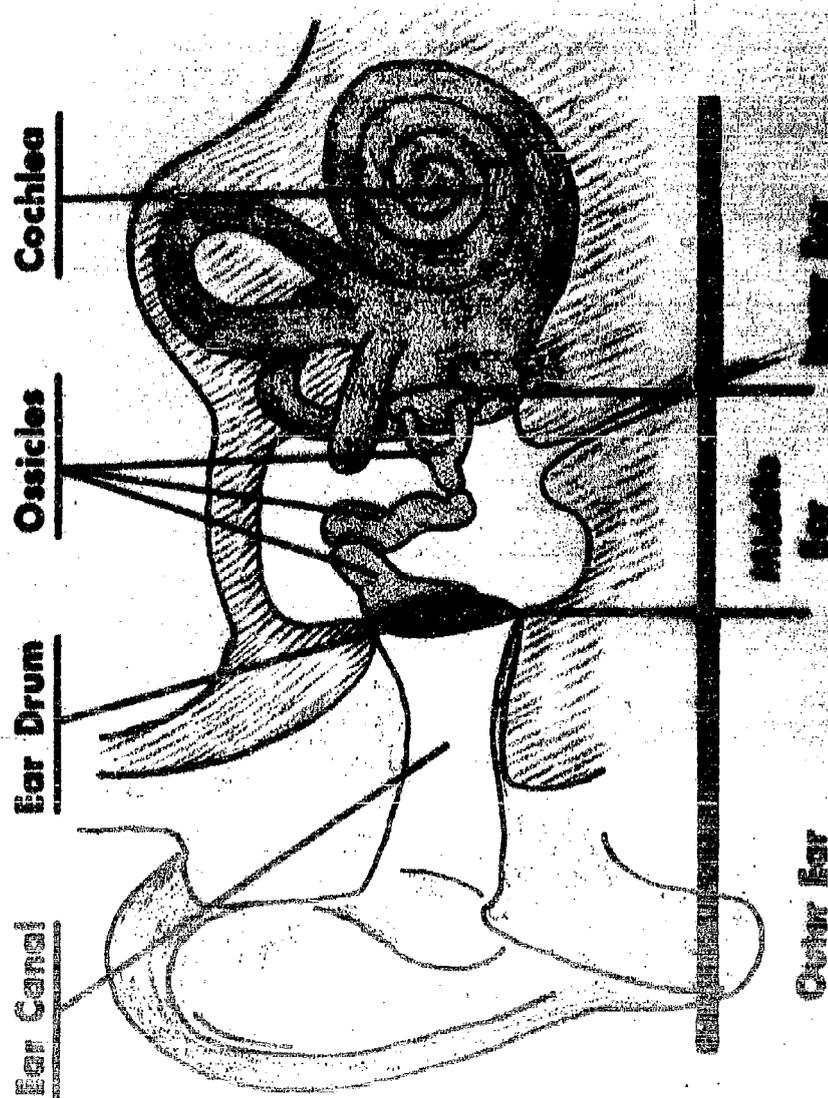


Fig. 19. CROSS-SECTIONAL DIAGRAM OF THE EAR

training did get small, but permanent, hearing losses. Needless to say, this finding sparked considerable interest in the impulse-sound-pressure problem, in spite of some obvious methodological shortcomings of the study.

In the past four years a considerable amount of research has been conducted on the impulse-sound-pressure problem, much of it carried out or sponsored by Army research laboratories. Again, methodological shortcomings cast some doubt on the usefulness of much of this work.

Since it is impractical for many researchers to use firearms as noise sources, and equally impractical to fire weapons indoors under rigidly controlled laboratory conditions, investigators have had to use other sources of impulse sound pressures. A number of artificial impulse-sound-pressure generators have been constructed, but all those known have the same limitation: the acoustic pulses these generators produce are sufficiently unlike those produced by Army weapon systems that there is some doubt about the usefulness of data obtained with them (5). In other words, the amounts of temporary hearing change, i.e., temporary threshold shift (TTS), which have been attributed to certain noise conditions, are often questionable. However, the qualitative relationships among various exposure conditions are probably valid.

Assuming, then, that at least the qualitative relationships are valid, our present knowledge in this area may be summarized as follows:

a. There are very large individual differences in susceptibility to impulse-sound-pressure effects, both in the Army population and in the population of Americans in general. The data in Figure 21, from a study by Carter and Kryter (1), illustrates this wide variability. It can be seen that the subject represented by the top curve sustained a TTS of 41 dB from exposure to 20 impulses at a peak sound-pressure level (SPL) of 156 dB, while another subject represented by the bottom curve sustained a TTS of only about 2 dB after exposure to 40 impulses -- twice as many -- of a louder sound with a peak SPL of 168 dB. The impulses used in this study were generated by an artificial impulse-sound-pressure source, but similar variation in susceptibility has been reported by Smith and Goldstone (8) and Donley (2) using the M-14 rifle as a noise source in studies at the HEL. It has been estimated that at least five percent of the Army population are extremely susceptible to impulse-sound-pressure effects, while at least five percent are extremely resistant to these effects.

b. Other conditions equal, it appears that the higher the peak SPL, the greater the resulting TTS will be. This relationship has already been illustrated with the Murray and Reid data in Figure 20. The unknown quantity, however, is the lowest peak SPL which will cause a measurable TTS in the average subject. Figure 22 shows some data from Ward, Selters, and Glorig (10), in which a measurable TTS was produced by exposure to 75 impulses with a peak SPL of only 132 dB. It can also be seen that about 12 dB of TTS was produced when the peak SPL was 141 dB. These data were gathered using another artificial sound source.

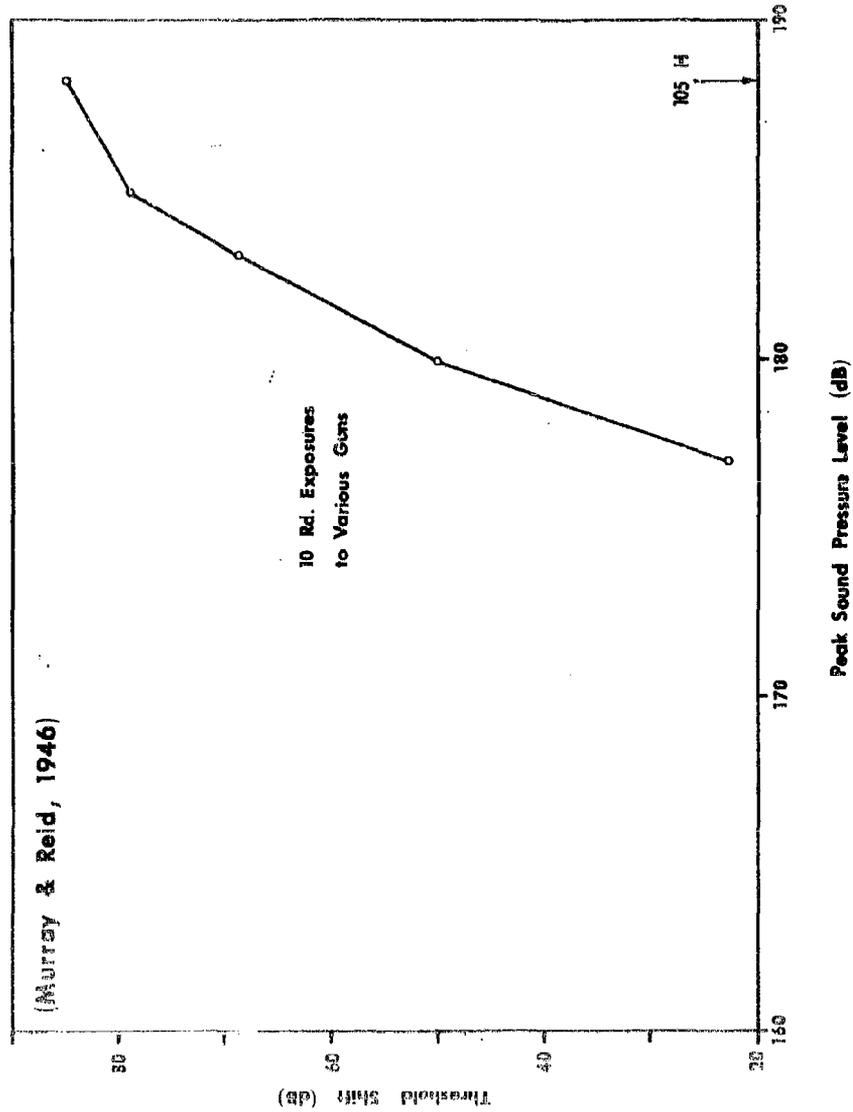


Fig. 20. TEMPORARY THRESHOLD SHIFT AS A FUNCTION OF PEAK SOUND-PRESSURE LEVEL

On the other hand, experiments now in progress at HEL have shown negligible TTS after exposure to 100 gunfire impulses with a controlled peak SPL of 140 dB. Thus, while it is logical to assume some relationship between peak SPL and amount of TTS produced, existing data are neither sufficient nor adequate to answer the question: "What is the critical peak SPL where hearing damage can be expected to begin to occur?"

c. The rate of exposure has been shown to be an important variable. Ward (9) demonstrated, as shown in Figure 23, that when the rate of exposure was between one impulse per second and one impulse each nine seconds, there was no significant difference in the amount of TTS produced. However, when the rate was decreased to one impulse each 30 seconds, the TTS was considerably less, indicating that some recovery occurred in the 30 seconds between successive impulses.

A number of studies by the Army Medical Research Laboratory (Ft. Knox) have shown that, as the rate is increased to more than one impulse per second, the TTS decreases. This and other evidence seems to indicate that the acoustic reflex of the middle ear muscles is activated and sustained in activation, thus providing a certain amount of protection from the subsequent impulse sound pressure (3).

d. There is also some evidence to indicate that the more impulses the person is subjected to, for a given peak SPL and rate of exposure, the larger the TTS will be, but more study is required to clarify this relationship.

Briefly, then, here is a summary of the knowledge available today:

- a. There are large individual differences in susceptibility;
- b. higher peak sound-pressure levels mean more hazard to hearing;
- c. rate of fire is important; and
- d. number of impulses is important.

There are few data to indicate how these variables interact, or what type of trade-offs can be made between, or among, impulse-sound-pressure parameters.

Also, there is no information about the effects of rise time or duration of individual impulses because, at the present time, it is not possible to generate the type of acoustic impulses needed for research. Existing instrumentation limits search to the use of either:

- a. Artificial sources which, while giving some control over rise time, duration, peak SPL, and repetition rate, generate impulses which are quite unlike gunfire, or

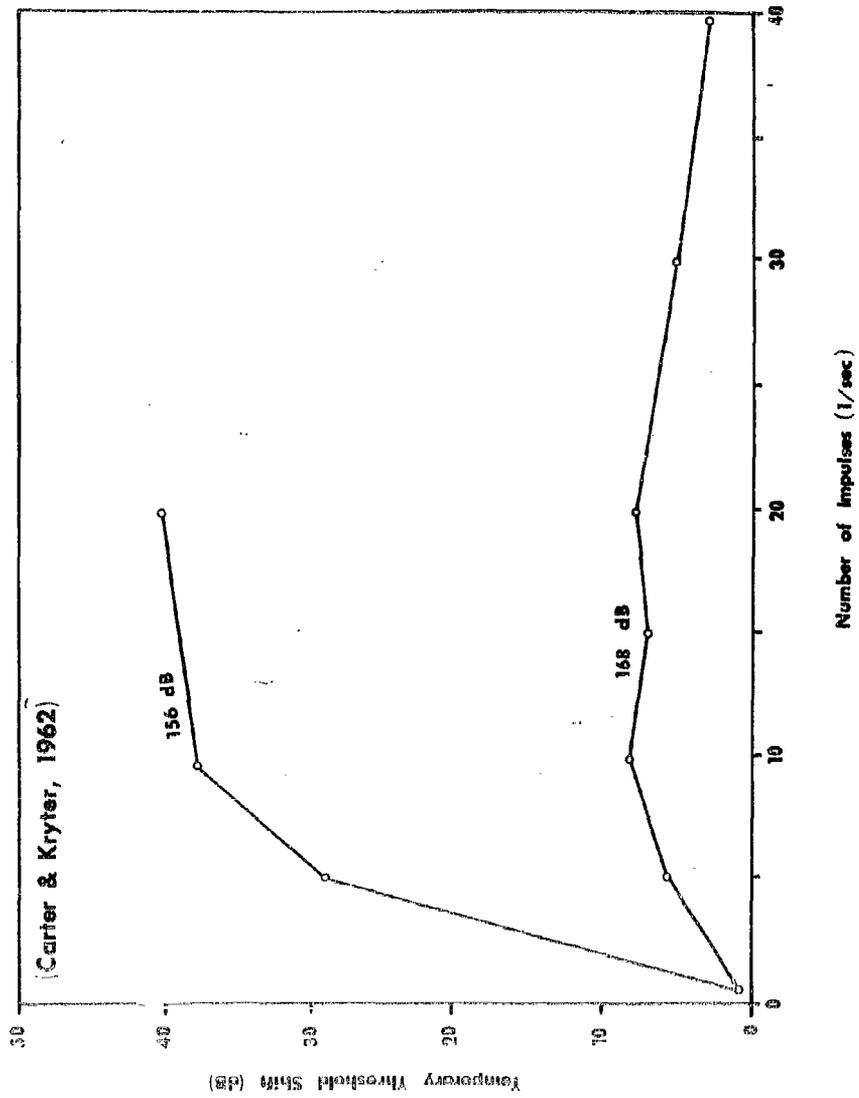


Fig. 21. AN EXAMPLE OF INDIVIDUAL DIFFERENCES IN SUSCEPTIBILITY TO TEMPORARY THRESHOLD SHIFTS

b. Actual small arms and artillery whose impulse sound-pressure characteristics are, in general, invariant and can be modified only by placing the subject at various distances from the muzzle.

In the former case only qualitative data can be obtained, while in the latter case only the hazards associated with specific weapons can be established. It is difficult at best to generalize the data to intermediate noise conditions, and similarly difficult to attack the problems of the importance of rise time and duration. Duration, incidentally, was a very significant variable in the high-intensity, shock-wave studies carried out by the Atomic Energy Commission.

In the impulse-sound-pressure studies now in progress at HEL, two approaches are being pursued, both of which generate impulse sound pressures by firing weapons. One approach is a very systematic examination of some of the problems in this area, while the other approach sacrifices a certain amount of precision in order to acquire sufficient data for the publication of an interim impulse sound-pressure-level exposure standard. The latter approach will generate an interim damage-risk criterion, but the conclusions drawn from studies conducted in this manner will require eventual systematic verification before a final criterion can be established.

Until this research is complete, the nearest approach to a damage-risk criterion is that recommended by the National Research Council's Committee on Hearing, Bio-Acoustics and Bio-Mechanics (CHABA). This committee recommended that the unprotected ear should not be subjected to peak sound-pressure levels above 140 dB (.03 psi). Every standard weapon that the Army uses, including small arms, exceeds this level. Therefore the armed services are faced with the formidable problems of determining: how hazardous to the user are the various weapons; how much must the sound-pressure level of these weapons be reduced; and how can this reduction be accomplished.

The United States is not the only nation concerned about this problem. German medical and acoustical specialists met with weapon developers on 18 - 19 April 1962 at Meppen, Germany, to start studying the problem of ear injuries in artillery crews. Their initial approach to this problem was to evaluate the pressure patterns for all weapons and firing conditions. The type of ear protection to be used with these weapons will then be determined, after which injury-producing levels will be studied and defined. The Germans stated at this meeting that they would like allied countries to cooperate in establishing standard criteria and requirements for ear protectors.

It is obvious that, in one more field, technology has caught up with and exceeded man's psychological and physiological limitations. To restore a safe balance between man and machine, human factors research effort must be accelerated.

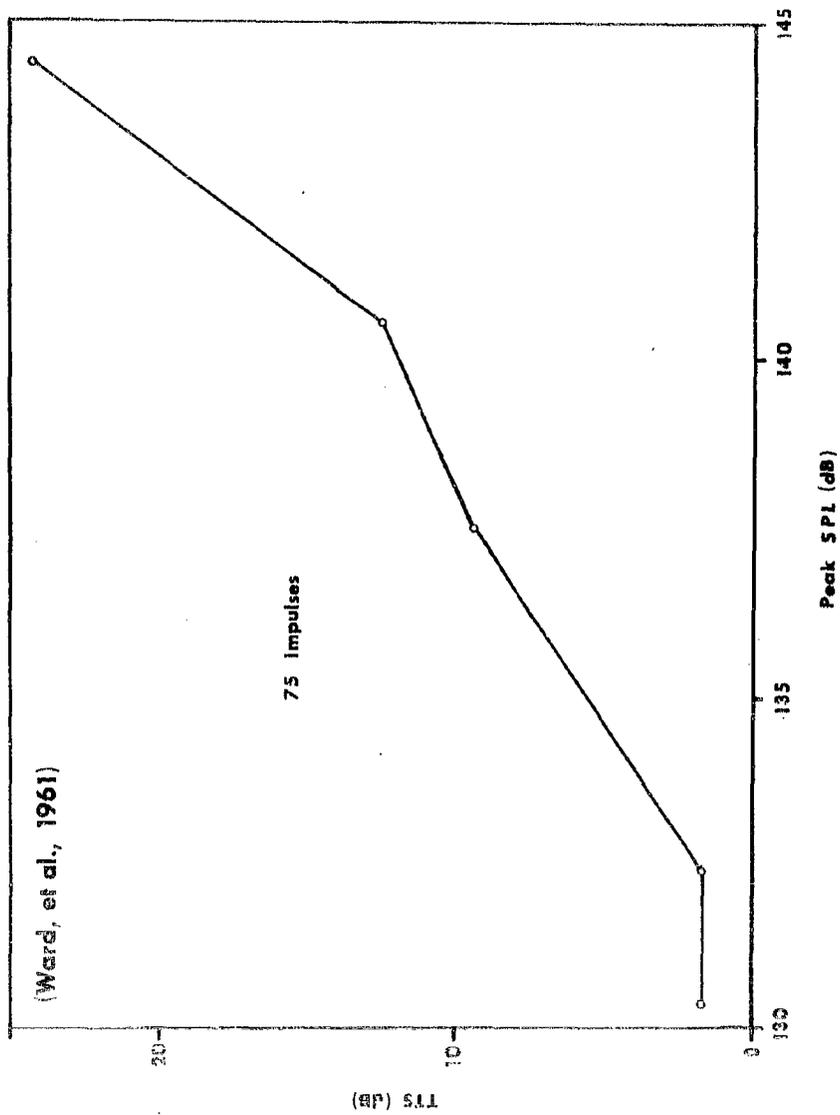


FIG. 22. MEAN TEMPORARY THRESHOLD SHIFT (TTS) AS A FUNCTION OF PEAK SOUND-PRESSURE LEVEL

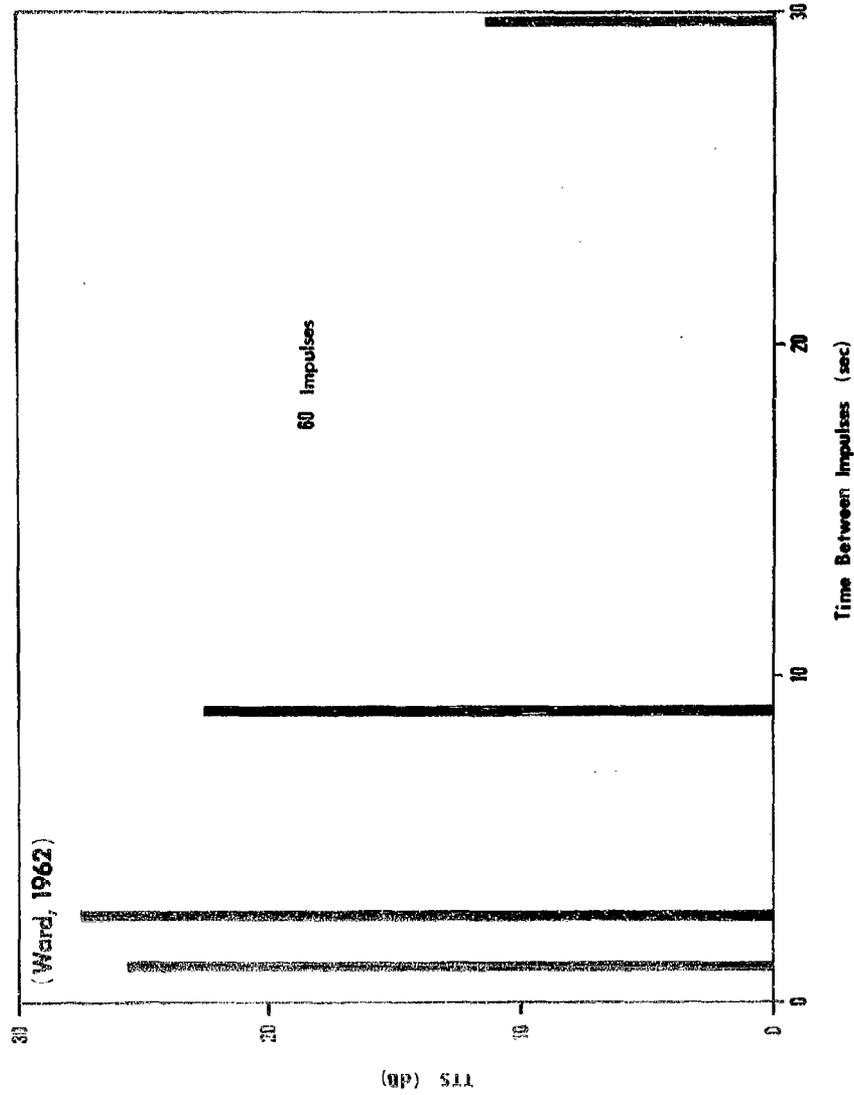


Fig. 23. TEMPORARY THRESHOLD SHIFT (TTS) AS A FUNCTION OF EXPOSURE RATE

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