THE POSITION OF EARDRUM RUPTURE AND HEARING LOSS IN THE SCALE OF INJURIES FROM NUCLEAR BLAST Report 3789

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20034

LIBE

[redacted]

THE POSITION OF EARDRUM RUPTURE AND HEARING LOSS IN THE SCALE OF INJURIES FROM NUCLEAR BLAST

AD 737 643

by
Joseph Gesswein and Paul Corrao

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

STRUCTURES DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

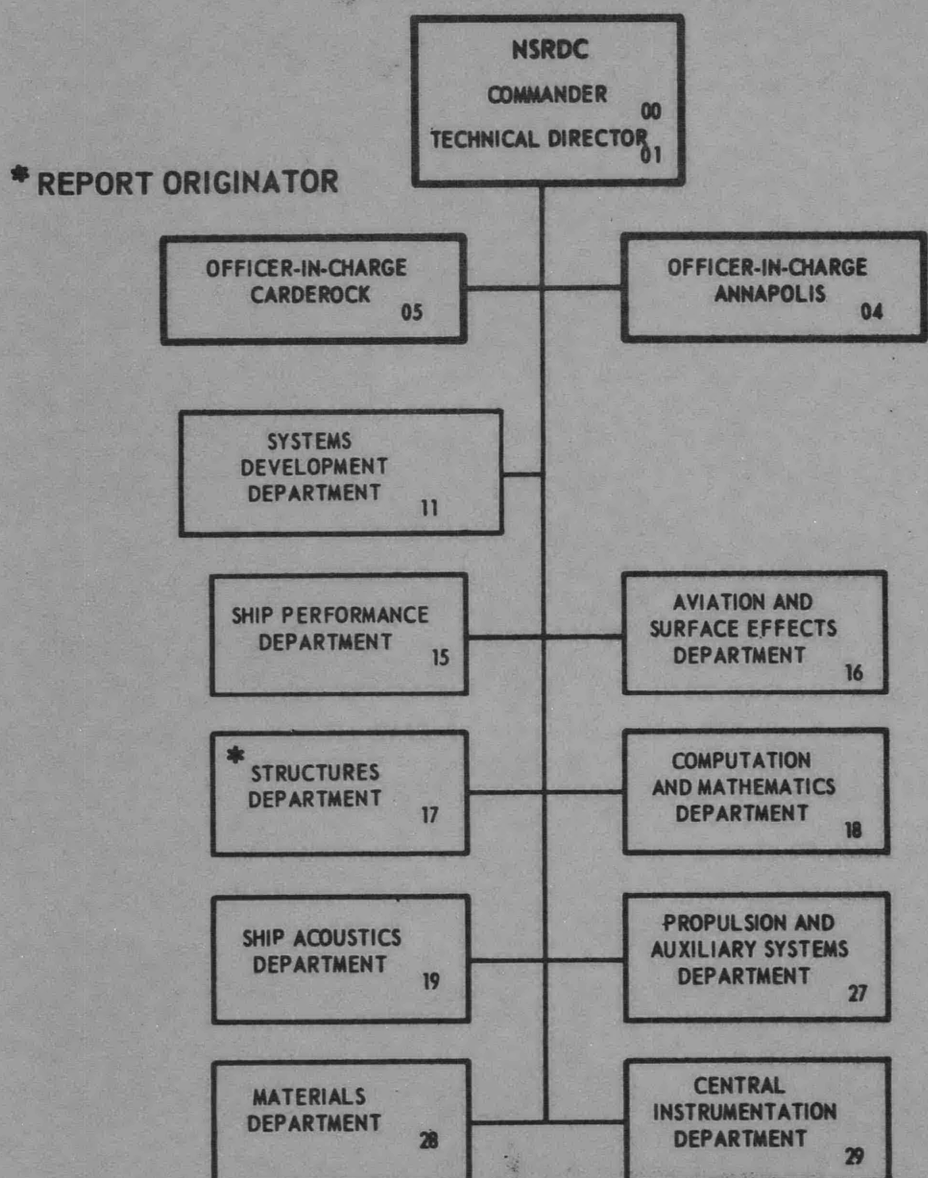
Property of U.S. Navy

February 1972 Report 3789

The Naval Ship Research and Development Center is a U. S. Navy center for laboratory effort directed at achieving improved sea and air vehicles. It was formed in March 1967 by merging the David Taylor Model Basin at Carderock, Maryland with the Marine Engineering Laboratory at Annapolis, Maryland.

Naval Ship Research and Development Center
Bethesda, Md. 20034

MAJOR NSRDC ORGANIZATIONAL COMPONENTS



NDW-NSRDC 3960/44 (REV. 8/71)
GPO 917-872

DEPARTMENT OF THE NAVY
NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
BETHESDA, MD. 20034

THE POSITION OF EARDRUM RUPTURE AND HEARING LOSS IN THE SCALE OF INJURIES FROM NUCLEAR BLAST

by

Joseph Gesswein and Paul Corrao

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

February 1972

Report 3789

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The scanty data available on human eardrum rupture from blast pressure suggest a normal distribution of rupture about a median overpressure of 15 psi. More abundant data are available on blast-induced eardrum rupture in animals, but their value is limited because of the lack of scaling laws. Consequently, predictions for human injury stem from clinical experiences.

As an injury mode to shipboard personnel, eardrum rupture will be of secondary importance to other blast-induced injuries. In fact, rupture itself may be beneficial to the individual by preventing damage to the middle ear. However, hearing loss associated with blast pressure or rupture itself will compromise normal voice communication. Although ear protection is advisable, it should be made available only in conjunction with protection against other blast effects.

ADMINISTRATIVE INFORMATION

The project and report were authorized by the Naval Ship Systems Command and funded under Task Area SF 35.451.101, Subtask 01817.

INTRODUCTION

Eardrum rupture is one form of injury to which personnel are exposed during air blast. Any resulting hearing loss could create confusion by compromising communication aboard ship. However, the effect of blast on hearing and the resultant impairment of normal communications have not previously been considered. This report is specifically concerned with eardrum rupture from single blasts, especially its initiation and growth with overpressure. The loss of hearing which results is weighed in relation to other effects of blast in order to obtain a better overall perspective of the problem.

A detailed review of the literature reveals little quantitative information that relates blast overpressure to eardrum rupture in man. Rupture predictions have been derived from human experiences at Hiroshima and Nagasaki and from accidental exposure to explosions. Medical aspects were well documented for these cases, but physical parameters could only be estimated. A vast amount of animal data gathered during the nuclear tests of the 1950's is not directly applicable to man since scaling laws have not yet been worked out. The indications are, however, that if the response of the human ear to blast is similar to that of animals, there will be great variations in individual tolerance to the pressure required to cause rupture.

After briefly describing the ear mechanism, the report discusses ear injury from intense sounds or blast pressures, notes other effects of blast, and relates the effects of blast-induced injury to these factors as well as to ship operations.

THE EAR MECHANISM

The ear can be divided into three regions: the outer ear, the inner ear, and the middle ear. The outer ear consists of the auricle (the visible portion of the ear) and the external auditory meatus, a short tube which leads into the head itself. The tube is sealed distally by the tympanic membrane or eardrum. This membrane, which separates the middle from the outer ear, is roughly oval in shape (8.5 x 9.5 mm along diameters) and is conelike near the center by virtue of its attachment to the malleus. It is about 70 mm^2 in area, 0.1 mm thick, and weighs about 14 mg.[1] The membrane edges are attached to a groove in an almost complete ring of bone in the wall of the auditory meatus. The exception is the notch of Rivinus where the membrane attaches to a portion of the malleus extending from the notch. Under normal conditions, the membrane simply vibrates elastically in response to pressure, but under high blast pressures, it can apparently stretch considerably, thinning as it does so until eventually the fibers separate and perforation occurs. When this happens, air flows through the opening directly into the middle ear and equalizes the pressure on both sides of the membrane, thus ending further rupture. More intense pressures can also tear the membrane free of its attachments. The rupture strength of the membrane as determined from static pressure measurements is surprisingly high--about 20 psi (within rather wide limits).

Membrane motions are transmitted to the inner ear via the three bones of the middle ear. Here sound vibration in air is transmitted as pressure

---

[1]References are listed on page 28.

vibration by means of fluid contained in the cochlea. The cells in the cochlea sense the vibrations and pass on their new impulses to the brain where the sensation of hearing occurs. A common cause of permanent hearing loss is damage to these cells as a result of too long an exposure to too high a sound intensity. Damage to these cells from a single blast has not been described in the literature.

The middle ear is basically a cavity containing the three smallest bones in the body: the malleus, the incus, and the stapes. Together they weigh only 55 mg. Membrane motions are transferred to the malleus which moves the incus which, in turn, moves the stapes. The system can be likened to an impedance-matching device which conveys the motion of air particles to the fluid in the cochlea. Atmospheric pressure is maintained in the middle ear by means of the eustachian tube which communicates with the pharynx. The bones are held in position by various muscles and ligaments that are primarily of anatomical interest. However, two muscles should be mentioned, the tensor tympani, which attaches to the malleus and tenses the tympanic membrane, and the stapedius, which attaches to the stapes. They comprise the system known as the protective ear reflex, and their action stiffens the whole system making it more resistant to the effects of intense sound.

PRESSURE AT THE EARDRUM

An object introduced into a sound field disturbs the field and modifies the local pressure levels. A head-size sphere, for example, causes a maximum increase in pressure of about 10 dB over a frequency range from 200 to 6000 Hz. The human head will affect the field similarly although with a less uniform increase in pressure over the frequency range. In one investigation, a subject was rotated through a full circle in a sound field while pressure measurements were made at one ear. Analysis of extensive measurements indicated that the effect is not only frequency dependent but also directionally sensitive. Figure 1, taken from Weaver and Lawrence,[1] illustrates this effect. At 300 Hz, sound pressure was essentially unchanged with angular position of the head. As frequencies were increased, the circular shape became increasingly distorted into the more oval shape shown for pressures measured at 15,000 Hz. It appears that an increase in sound pressure at one ear is accompanied by a decrease in pressure at the other ear. This relative differential in ear pressure, caused by the sound-shadow effect on the far side and amplification on the near side, aids in localizing the direction of sound and is important for blast-wave effects because of the relative protection it may afford the far ear for the frequencies involved.

Free-field pressures are also changed at certain frequencies by the resonance effect of the ear canal. The canal is characterized by a resonant frequency near 3000 Hz. Pressure measurements at the membrane show a broad resonance effect, which peaks at about 3800 Hz, with increases in pressure at this frequency as high as 12 dB observed.[1] Pressures associated with frequency components of blast waves near this value would be amplified above those in the approaching wave.

Thus, the diffraction and reflection effects of the head and the resonance effect of the ear canal act to change the pressure on the eardrum from that in the undisturbed sound field. Exposure to a blast wave should also result in a pressure differential in the ears; the exact magnitude of this differential would be uncertain for the high pressures of blast waves.

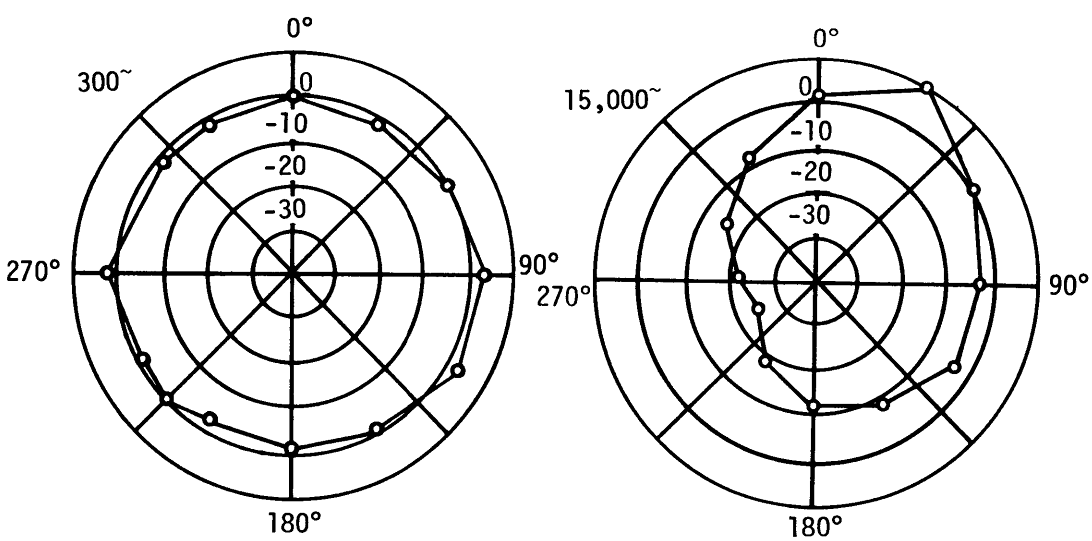


Figure 1 - Effect of Azimuth Angle and Frequency on Sound Pressures at One Ear
(From Weaver and Lawrence[1])

EFFECTS OF INCREASED SOUND INTENSITY

Obviously loud sounds are unpleasant. Apparently, there are limits to the amount of energy that the ear can tolerate since the middle ear is equipped to reduce energy transmission into the inner ear and prevent damage to its structure. The stapes, which fits into the oval window of the cochlea, performs one of the protective actions.[2] At ordinary sound intensitites, it rotates about an axis by which the largest displacements are transmitted to the fluid of the cochlea. If this mode of vibration persisted at higher sound intensities, increased energy would pass into the cochlea. However, at sufficiently high sound intensities, the stapes changes from one mode of vibration to another wherein a minimum of energy is imposed on the cochlea fluid. This action prevents overstimulation of the inner ear.

Excessive sound energy transmission is also limited by the action of two muscles, the tensor tympani and the stapedius. Both are brought into action by the intensity of the sound sensation, which eventually causes them to contract. Contraction of these muscles, called the acoustic reflex, stiffens the eardrum and the ossicular chain and increases its resistance to deflection. This action takes time, however. Estimates of contraction time vary; Perlman[2] indicates from 10 to 70 msec whereas Hodge[3] suggests from 35 to 150 msec. As will be shown later, these action intervals are too long to be effective against blast waves.

Weaver and Lawrence point out that the acoustic reflex is more effective in reducing low frequency than high frequency tones.[1] Fletcher and Riopelle[4] confirmed this by means of measurements of temporary threshold shift induced by machine gun fire; see Figure 2. The acoustic reflex brought about an overall reduction at all frequencies, but the conversational frequencies appeared to have suffered the least shift. However, judging from the convergence of the curves and the minor reduction at 400 Hz, it appears that the acoustic reflex would not be effective down to steady-state pressures. In other words, for a long-duration blast such as occurs from a nuclear explosion, the acoustic reflex may not have much effect on a spectrum rich in the lower frequencies.

The malleus-incus joint is also endowed with protective capabilities; its efficiency in transmitting motion is impaired at high sound intensities involving large motions.[2] Some dislocation can occur in this complicated articulation, thereby limiting or preventing the transmission of large membrane displacements to the incus. However, this action could be detrimental to the eardrum because during slippage, the membrane would be deprived of the reaction force exerted against it by the malleus. Thus, this protective mechanism of the middle ear which prevents inner ear overstimulation may weaken the resistance of the membrane to pressure.

On the other hand, the membrane itself may be a sort of fuze or safety valve for the ear structure. It has been observed that the ossicular chain is usually not damaged when eardrums do rupture. Since damage to the structure of the middle ear leads to a permanent hearing loss as far as air conduction is concerned, eardrum rupture, if it must occur at all, must be classified as a favorable happening for an individual.

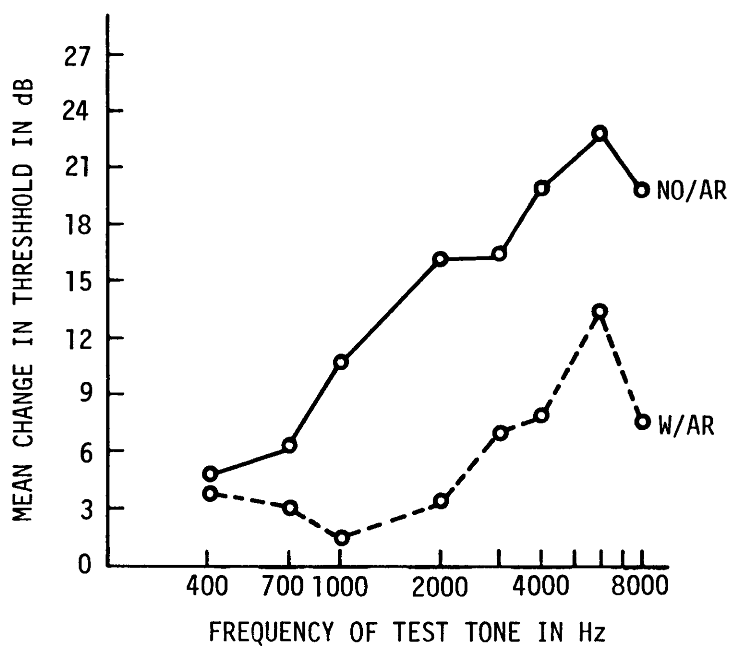


Figure 2 - Average Temporary Threshold Shift in Test Subjects with and without Acoustic Reflex Excitation

(From Fletcher and Riopelle[4])

Even when physical injury does not occur, excessive sound intensities, can temporarily deteriorate hearing to the extent that normal voice communication may be rendered difficult. Because of this deleterious effect, called a temporary threshold shift (TTS), the sound level formerly considered adequate must be increased to maintain the same subjective auditory levels. Some idea of this can be gained from Figure 3.[5] The left graph represents the mean of three exposures at the stated frequencies for each of three subjects exposed to 105 dB of noise for 30 min. The right curves show how hearing ability returned toward normal after the exposure. Note that the higher the frequency, the higher the shift and the more slowly the return to normal hearing. Whereas hearing awareness was still down 20 and 10 dB at 6000 and 4000 Hz after 1 hr, it had practically returned to normal at the 2000 Hz frequency after 20 min. The 2000-Hz curve has the greatest significance in terms of personnel incapacitation for its frequency is in the middle of the conversational range. The 10-dB shift would not in itself create a conversational problem, but it should be noted that these results were obtained at relatively low sound intensities. In a blast wave, pressures would be considerably higher and the anticipated shift greater.

Although the results of Figure 3 were based on steady noise effects, Perlman indicates that the same type of event--an initial loss followed by a gradual return to normal hearing--will occur for blast-type waveform.

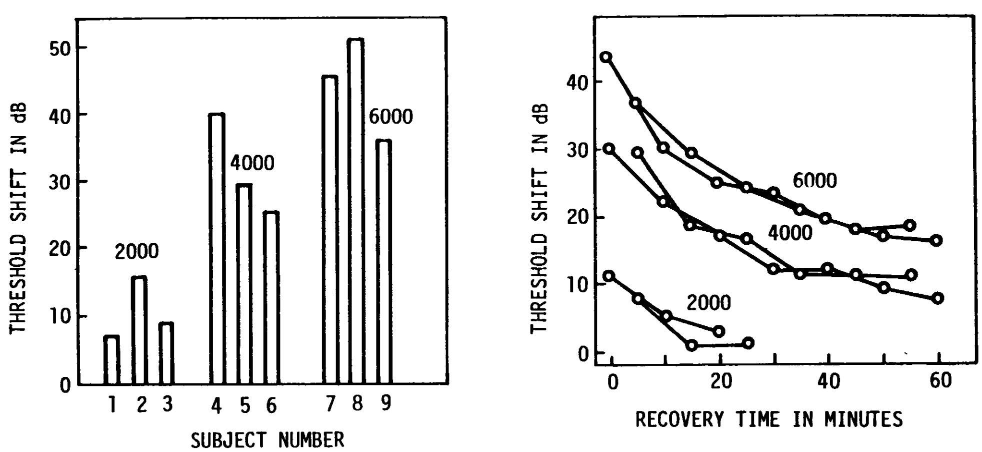


Figure 3 - Temporary Threshold Shift and Recovery Times Following Exposure to Noise

(From Rosenblith et al.[5])

He reports that recovery from the blast effect of a 0.32 blank cartridge fired 3 ft from the ear occurred in about 30 min. He also states that audiograms showed good hearing for low tones and an abrupt high tone loss for both air- and bone-conducted sound.[2] For nuclear blast where the pressure duration is measured in seconds and not in microseconds as for pistol reports, the low and conversational frequencies may suffer as well.

Bakken calculated the sound level in a blast wave in relation to its overpressure.[6] Unfortunately, he related his findings to a base of 4×10^{-16} w/cm^2, the lowest audible sound detectible by the human ear, rather than to the usual base of 1×10^{-16} w/cm^2 used with a sound pressure level (SPL) reference base of 0.0002 $dynes/cm^2$. Conversion of the data to a more conventional scale is possible, however, by adding 6 dB to the values of sound level as shown in Figure 4. The SPL curve, referred to 0.0002 $dynes/cm^2$, which is used for description of environmental noise has been included for comparison of blast noise and decibel values associated with ordinary noise.

Table 1 (taken from Reference 7) and Figure 5 (taken from Reference 8) give an idea of the intensity of more common sounds. Note that pain occurs at 140 dB. According to Figure 4, this value would be associated

TABLE 1

Loudness of Common Noises

Source or Effect of Noise	Loudness in dB
Threshold of pain in ears	140
Pneumatic rock drill	130
Loud automobile horn	120
Punch press	110
Automatic lathe	100
Noisy factory	90
Truck passing	80
Noisy office	70
Conversational speech	60
Private business office	50
Average residence	40
Broadcast studio	30
Rustle of leaves	20
Average threshold of hearing	15
Acute threshold of hearing	0

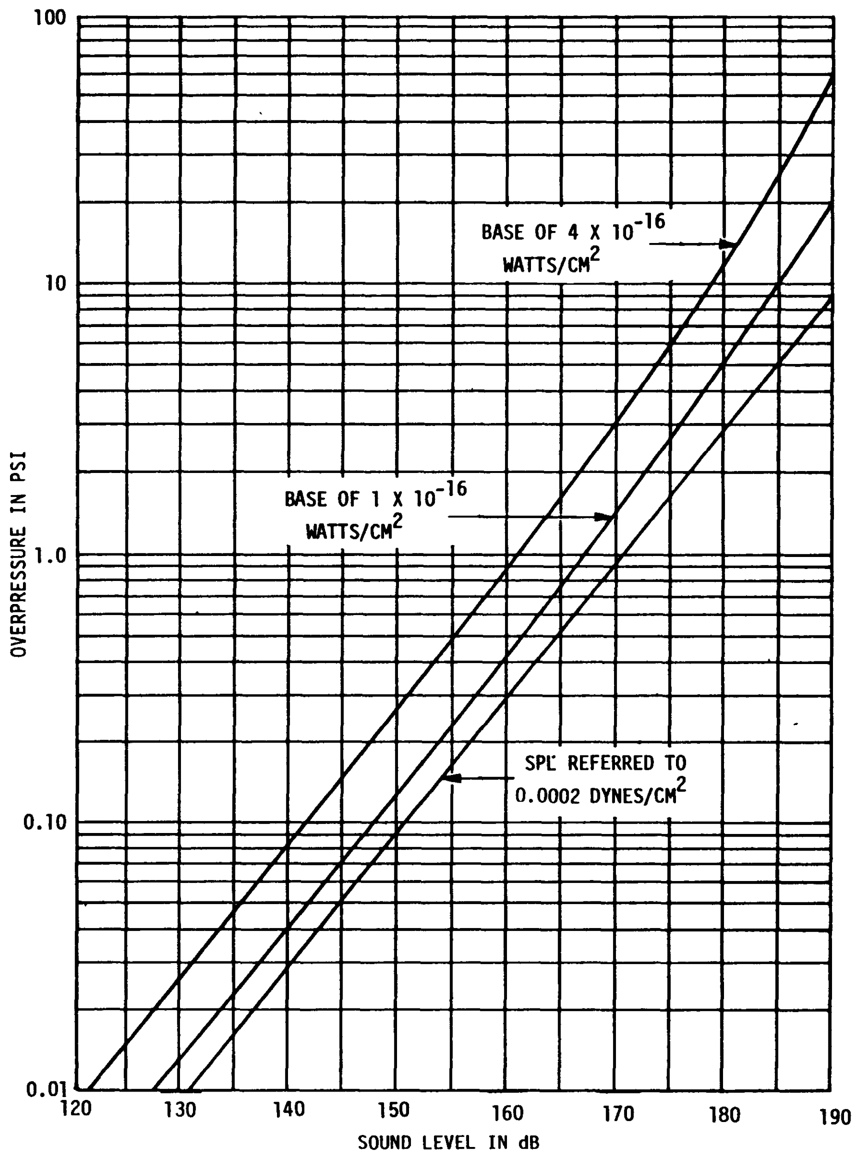


Figure 4 - Overpressure versus Sound Intensity for Blast Wave (After Bakken[6])

with an SPL pressure level of 0.03 psi and a blast wave pressure of only 0.04 psi; pain then begins at relatively low values of overpressure. It would be more intense at higher pressures, but the effect on the individual is not clear. Apparently pain of this nature does not last long once the stimulus has been removed. It is interesting to note that there is little reference in the clinical literature to sound-induced ear pain. Similarly, when eardrums are ruptured, clinical reports do not stress patient discomfort from the associated pain. Apparently, the effect is immediate and of little importance.

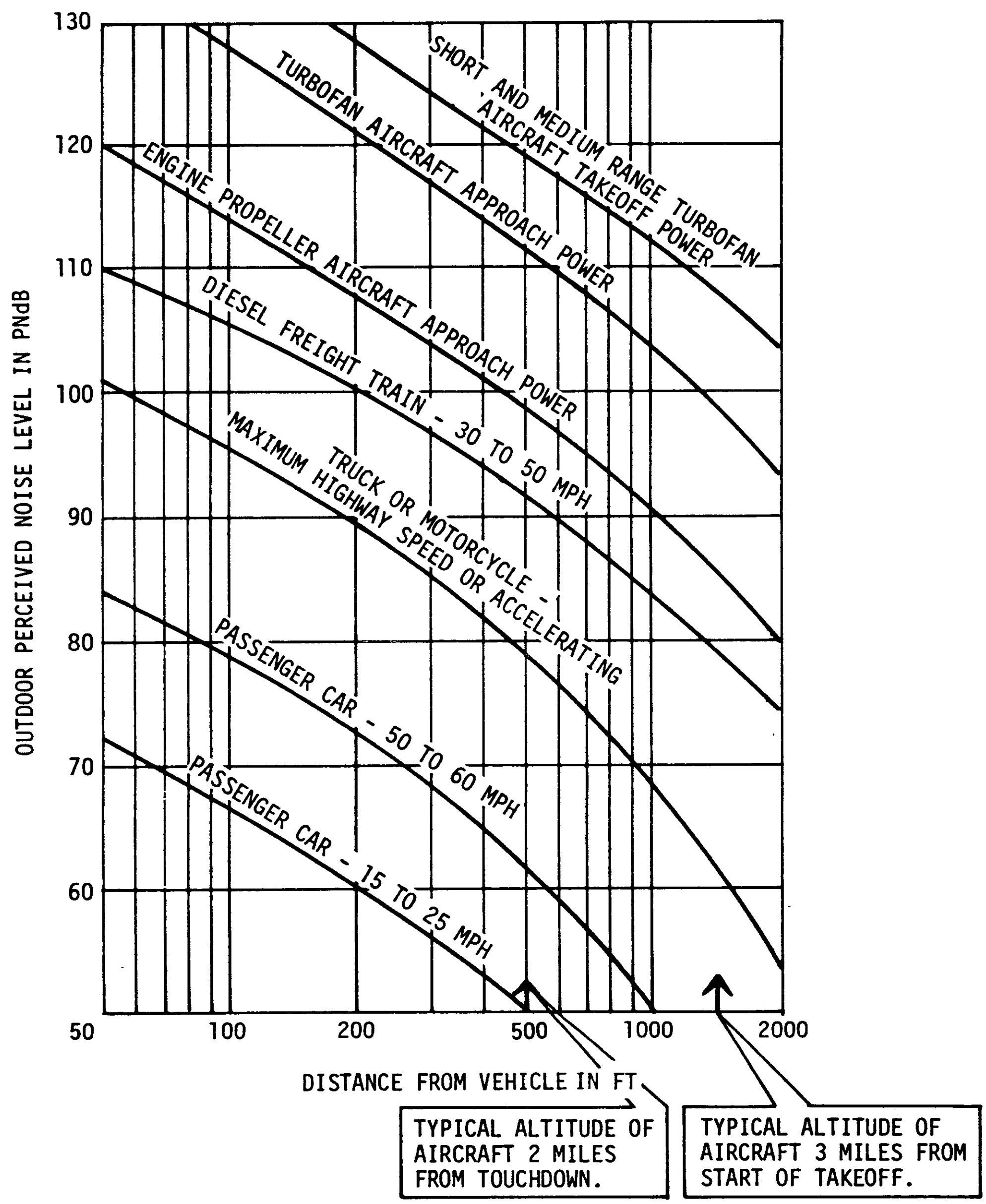


Figure 5 - Noise versus Distance for Familiar Noise Sources
(After Kryter[8])

Figure 6 (taken from Reference 9) gives an idea of distances at which conversation can take place with various degrees of background noise. Two people can converse satisfactorily in normal voices at a separation of up to 18 ft when the preferred octave speech interference level (PSIL) is 40 dB. As the noise level increases, satisfactory conversation can be achieved at the normal voice level only if the distance is decreased. When

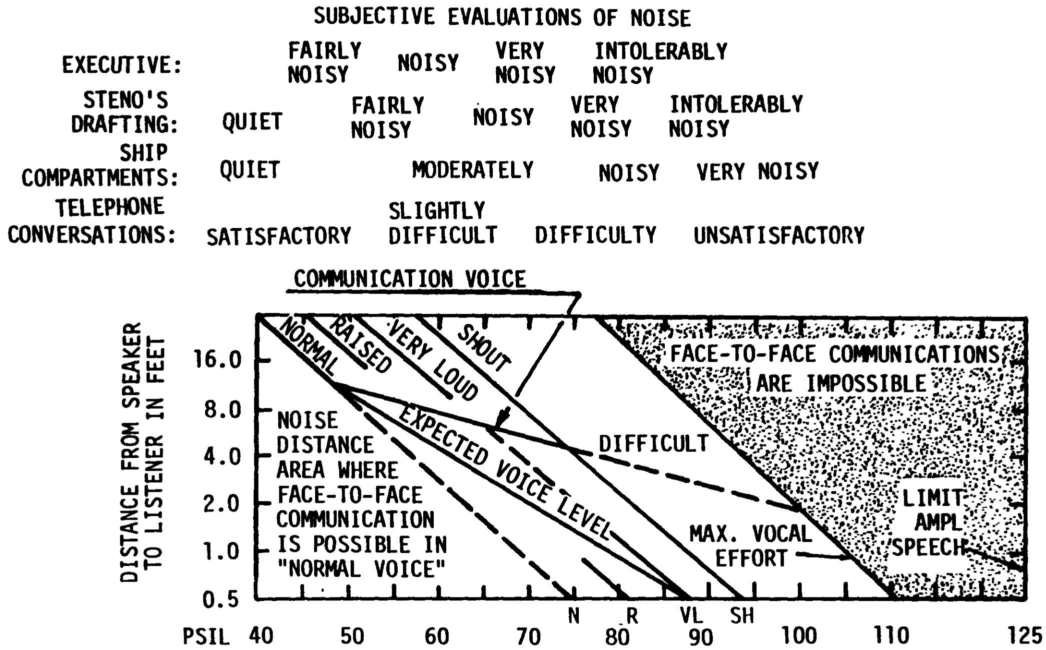


Figure 6 - Preferred Frequency Speech Interference Levels (PSIL) versus Distance for Various Voice Levels

(From Webster and Lepor[9])

(PSIL is a measure of the average noise in the octaves centered at 500, 1000, and 2000 Hz)

the background noise increases to 75 dB, normal voice communication can be achieved at a distance no greater than 6 in. between individuals. For a further increase in noise level, the voice level must be raised, and at 95 dB of background noise, one must shout, even at a 6-in. distance in order to be understood. Face-to-face communication is virtually impossible at noise levels above 110 dB.

These values represent a broad average, and considerable variation exists among individuals. For example, in using the term "normal voice," we must appreciate the fact that there is a range of 8 dB involved in the makeup of sound pressures used by individuals who are conversing casually.[5] Similarly, in the matter of producing threshold shifts, a great variation is evident among individuals exposed to the same apparent noise; some show marked evidence of deafness while others maintain relatively normal hearing. In fact, there is considerable variation between the response of each ear of a subject under the same test conditions. In their tests on the prevention of TTS by the use of the acoustic reflex, Fletcher and Riopelle[4] found that the same machine gun firing noise which caused a hearing shift in 35 subjects did not produce a TTS in four other subjects. This would suggest that following air blast, uniformity in hearing response among individuals could be expected only within wide limits.

EFFECTS OF IMPULSE NOISE

The previous section dealt with the hearing response of man to relatively continuous noise as opposed to impulsive-type noise. The latter more closely characterizes the single blast generated by a nuclear weapon. This discussion of impulse noise considers data on how hearing is affected by small arms or howitzer fire. The associated hearing loss is of concern to the armed forces not so much because of the sound intensity of each discharge but because of cummulative effects of a succession of individual charges. Consideration of the effects of repetitive impulses will afford a good preliminary step to the analysis of effects of a single blast.

The pressure-time waveform produced by gunfire is similar in shape to that produced by nuclear explosions. It consists of a sharp immediate rise to a peak value followed by an exponential-type decay to an underpressure phase. The major difference is in duration; overpressures from nuclear weapons can be measured in seconds whereas those from gunfire are measured in microseconds. Accordingly, the frequency spectrum from both blast sources differs considerably. Gunfire spectra are rich in the higher frequencies whereas spectra from nuclear weapons are rich in the lower frequencies. In general, energy concentration in a frequency spectrum tends toward the low end as the explosive weight increases.

Consequences of this energy distribution have been observed in threshold shift measurements. Spark discharge noise causes a temporary dip in the hearing curve at approximately 12 kHz. For long-duration smaller arms fire, the greatest temporary loss occurs near 6 kHz; for gunfire, the hearing dip is lower still at 4 kHz.[10] The progression of the affected hearing region toward lower frequencies implies that longer duration pressures will produce major threshold shifts in the region of conversational frequencies (500-3000 Hz) even if eardrum rupture does not occur.

Damage risk criteria (DRC) have been evolved for impulse and steady-state noise to relate sound intensity and pressure to frequency of exposure. Figure 7 gives one criterion, based on tolerance to 100 impulses received at normal incidence to the ear within a minimum time period of 4 min.[11] The intent of this curve is to limit TTS_2 in all but 5 percent of exposed individuals to levels established by the National Research Council Committee on Hearing and Bioacoustics (NRC-CHABA). Since only long-duration blast is of significance in this report, the sloping portion of the curve that indicates a pressure-duration dependence is of little concern. What is important is the level portion of the curve which suggests that the threshold shift will be constant for durations greater than 1 msec. Apparently pressure duration itself cannot cause further injury once the initial injury has been produced.

For long-duration waves, then, hearing may be impaired somewhat by exposure to successive impulses of 152-dB level. This value corresponds to a pressure of about 0.12 psi. Although rather insignificant in terms of blast overpressure, the value is indicative of the fact that hearing difficulties arising from repeated impulses are of concern even at this low pressure. If the number of exposures decreases, an increase in pressure level can be tolerated, although how much is rather indefinite. Ward states that the correction factor given at the bottom of Figure 7 is based on very limited data.[11] If only one impulse occurs, an increase of 10 dB in pressure can apparently be tolerated. Even with the increase, the pressure corresponding to 162 dB (0.33 psi) remains inconsequential among ship damaging blast pressures. The point is that the danger of permanent hearing loss in exposed personnel is thought to be present even at these low pressures where eardrum rupture is not likely. However, as will be seen in the next section, permanent hearing loss from high overpressures need not occur even if the eardrum does rupture.

EFFECTS OF SINGLE-BLAST NOISE

Nuclear-blast waves differ from gun-blast in that nuclear overpressure durations are long enough so that eardrum rupture can be described in terms of pressure alone. With pressure durations ranging from 0.25 sec for a 1-kt

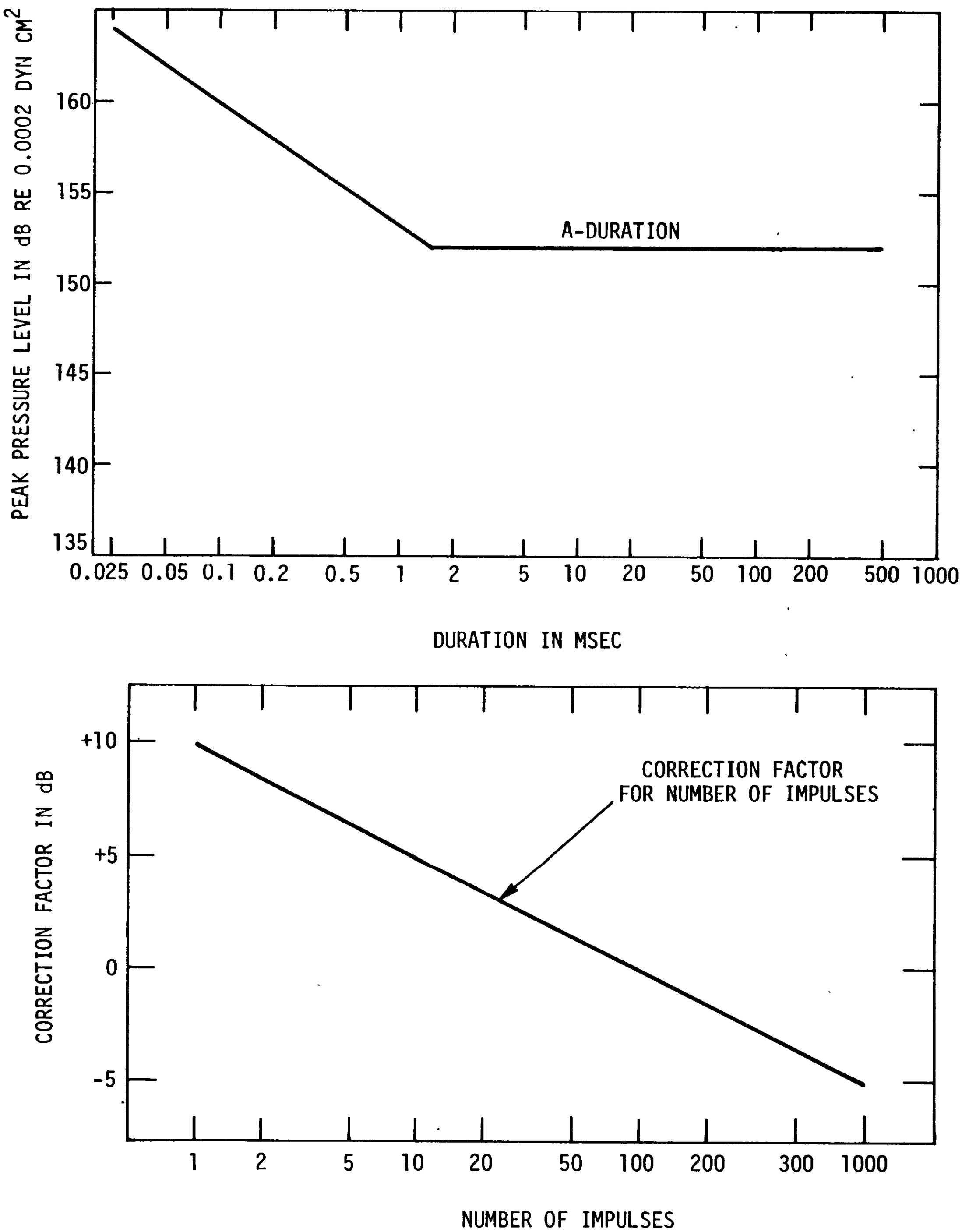


Figure 7 - Damage Risk Criteria: Peak Pressure versus Duration, Based on 100 Impulses (From Ross et al.[10])

yield to 2.5 sec for a 1-mt yield, there is no need to introduce a time factor to describe ear injury potential such as is needed for conventional gunfire. The shape of the wave front, however, does have a bearing on injury. In the absence of obstructions, the shock front rises almost instantaneously to its peak value. This type of wave front has been found to have the greatest injury potential not only for the ear but also for the body in general. When obstructions are present, diffraction and reflection effects distort the blast front so that a sharp rise in pressure does not occur and a noticeable length of time is required for the pressure to reach its maximum value. A wave of this type does not have as great an injury potential as does a sharp-rising wave front. Reflection also has an important bearing on eardrum rupture; when it occurs, peak pressures will be increased by at least a factor of two, with a corresponding effect on injury potential. On the blast side of ships where decks and large vertical surfaces are present, reflected rather than incident pressure would more likely be the major cause of ear injury.

The major source of data on eardrum rupture in large animals, and perhaps the most useful for our purposes, stems from the nuclear tests of the 1950's and simulated nuclear tests of the 1960's using high explosives. These tests were conducted with actual weapons under controlled conditions where blast pressure and durations were recorded. Additionally, assessments of injury were made following each test. Unfortunately, no proven scaling method was available for extending the results to man. Measurements of physical parameters are generally not available for human eardrum rupture data derived from clinical observation and wartime casualty records. Information on industrial accidents or war injuries is usually obtained through reconstruction of the injury event; the distance from the explosion as well as the type and quantity of explosive are frequently unknown. Moreover pressures calculated from known standoff distances were often inaccurate because shells and bombs can penetrate the ground some distance before explosion, thus forming craters whose conical shape directs blast energy, in part, upward.

Table 2 (compiled from References 12-14) gives results of eardrum rupture in goats and dogs exposed to either nuclear blast or shock tube pressures. The goat tests were conducted with the animals positioned in

TABLE 2

Eardrum Rupture in Goats and Dogs
Exposed to Overpressures

Goats Exposed Side-On in Open to Blast from 500 Tons of TNT

Maximum Overpressure psi	Number of Eardrums			Animals Examined
	Ruptured		Intact	
	Right	Left		
58	2	1	1	2
54	1	1	0	1
50	4	3	1	4
43	4	3	1	4
40	3	1	2	3
35	3	2	1	3
29	2	2	2	3
15	8	5	6	10*
10	6	5	9	10

*One eardrum not examined.

Dogs Exposed Side-On to Shock Tube Reflected Pressure

Maximum Pressure psi		Eardrums Ruptured	Number of Animals
Incident	Reflected		
3.7	9.2	2	20
5.6	13.5	18	20
7.6	19.9	14	20
9.5	25.6	20	20
10.8	31.2	20	20
12.4	35.8	19	20

Dogs Within Shelters Exposed to Blast Pressures

Maximum Pressure psi	Eardrums Ruptured	Number of Animals
1.3	0	2
2.6	0	2
3.7	0	2
4.1	1	2
4.3	0	2
4.6	1	2
6.7	0	10
8.0	1	12
9.5	0	5
10.5	0	17
12.5	0	2
14.3	1	8
18.5	2	2
22.1	8	6
22.5	1	7
25.5	8	8
30.3	12	8
33.8	10	10
38.0	5	4
40.9	2	2
42.8	2	2
53.0	3	2
66.6	10	6
71.6	4	2
85.6	4	2

the open with the right ear exposed to fast-rising blast pressures. Since this "near" ear would be affected by dynamic pressure as well as by side-on pressure, when rupture occurred, it would be expected to occur for the right ear more frequently than for the left ear. The table shows this general trend, especially at high pressures where the contribution of the dynamic pressure to the total pressure is greatest. The sheltered ear may also benefit from diffraction or shadow effects produced by a head in a sound field. In any event, it is apparent that the "near" ears did suffer more severely.

We can also observe that at the lowest test pressure (10 psi) roughly one-half of the goats suffered ear rupture; six-goats had the right eardrum ruptured and five the left. When the blast pressure was 15 psi, presumably the median point had been passed, and rupture was more likely to occur. At higher pressures the absence of eardrum rupture becomes the exception; all right eardrums were ruptured above 29 psi while 11 out of 17 left eardrums were ruptured. However, rupture of all eardrums was never complete; even at 58 psi one eardrum was spared.

When ears are subjected to reflected pressure, rupture shows a variation similar to the effects of incident pressure only. The data on dogs in Table 2 were gathered from shock tube studies in which the animal was placed against the end plate of the tube. In this position the ears were assaulted first by the incident and then, at short intervals later, by the reflected pressure wave. The story is much the same for reflected pressures as for incident pressures; the number of ruptured eardrums increased with pressure but some eardrums always seemed to escape rupture. At the average reflected pressure of 9.2 psi, only two out of 20 possible ruptures occurred; at 13.5 psi 18 out of 20 eardrums ruptured; and at 19.9 psi, the figure was 14 eardrums out of 20. The median pressure for dogs appears to be less than 12 psi. As with goats, a level at which all eardrums would rupture was not attained; one eardrum failed to rupture at a reflected pressure of 35.8 psi. However, sufficient tests were run to enable the conclusion that the vast majority of eardrums would rupture on exposure to reflected pressure near 30 psi.

For pressures that rise slowly, or perhaps in increments to a peak value, the same sort of variation in response is experienced as for fast-rising pressures, but the average pressure at which eardrum rupture occurs is increased. For example, when dogs were placed in shelters which blocked the direct impingement of a blast wave, rupture occurred in only three out of 116 eardrums at pressures up to 12.5 psi. Although the data showed considerable variation, it appears that 50-percent rupture among exposed eardrums occurred at pressures as low as 18.5 psi and as high as 42.8 psi. Roughly, then, the halfway mark for eardrum rupture would be near 30 psi. Thus, much more pressure was necessary to cause rupture when the pressure built up slowly as when it peaked instantaneously.

It is reasonable to assume that this nonuniformity in the picture of animal eardrum rupture may also be true of humans, by virtue of the similarity of ear structure. In considering this question, White al al.[14] pointed out that there is a natural variation in eardrum anatomy due to individual differences in scarring, thickening, thinning, or other factors which might alter the strength of the membrane. They further suggest that it is possible for a counteracting pressure to build up in the middle ear that would resist the insult pressure by either leakage through the membrane itself, as it thins by stretching, or by large membrane deflections that would substantially compress the limited air volume in the middle ear. Sharp irregularities touched by the displaced and thinned membrane might also cause rupture. Additionally, response times of the eardrum could influence rupture especially for pressure waves that differ in duration. Finally, they point out that rupture may occur during the negative pressure phase in a membrane already weakened by positive pressure effects.

Notwithstanding, variations do exist and make the accuracy of rupture predictions at known pressures somewhat uncertain. In his review of overpressure effects on the ear, Hirsch[15] pointed out the difficulties of numerically relating overpressure and ruptures to human eardrums. He nevertheless proceeded doggedly to arrive at the desired relationship by deriving estimates of rupture pressures from clinical observations of men who had been exposed to blast pressure from shells, bombs, or industrial explosions. He was unable to determine the precise magnitude of the fast-rising pressure to which they were exposed since it was based on a reconstruction of events, utilizing explosion size and standoff distance. Using the log normal plot of three groups of data (percentage of ruptures at 6, 17, and 30 psi overpressure), he specified 15 psi as the pressure most likely to cause 50 percent ruptures (Figure 8). On this basis, 5- and 95-percent rupture would occur at 5 and 50 psi. The median pressure is below that given by Glasstone[16] who suggested 20 to 30 psi overpressure as a 50-percent rupture interval.* This estimate for humans is similar to that obtained for dogs exposed to shock tube pressure (Figure 8). The increased slope of the curve for dogs, however, implies that their ears would be more susceptible to rupture than those of man as overpressures increase.

The results of static tests of eardrums are pertinent here. Weaver and Lawrence cited early work (1906) by Zalewski[17] on the breaking strength of cadaver eardrums under slowly applied pressure. Tests on 111 normal-appearing membranes indicated an average breaking strength of 1.61×10^6 $dynes/cm^2$ with extremes of 0.4 and 3.0 $dynes/cm.^2$ This spread amounts to an 80- to 90-percent variation in rupture pressures. The average breaking strength for 12 membranes judged to appear abnormally thin was 0.52×10^6 $dynes/cm.^2$ For another 12 membranes that showed scar tissue, rupture occurred at the mean value of 0.3×10^6 $dynes/cm.^2$ Of course, the physical properties of cadaver tissue are different from those of live tissue, but the results are roughly comparable nonetheless. On the basis of these results, which showed a great variation about a mean for normal as well as abnormal eardrums, it is felt that there must be a similar variation in the membranes of living men.

This variation is not limited to humans. Similar static tests in dogs revealed a mean strength of 1.0×10^6 $dynes/cm^2$ bounded by extremes of 0.6 and 1.6×10^6 $dynes/cm.^2$ All in all, then, it should not be surprising that rupture from blast pressure shows a similar variation in eardrums of men.

*The derivation for this median is not stated in the paper; it may possibly be data from Hiroshima and Nagasaki.

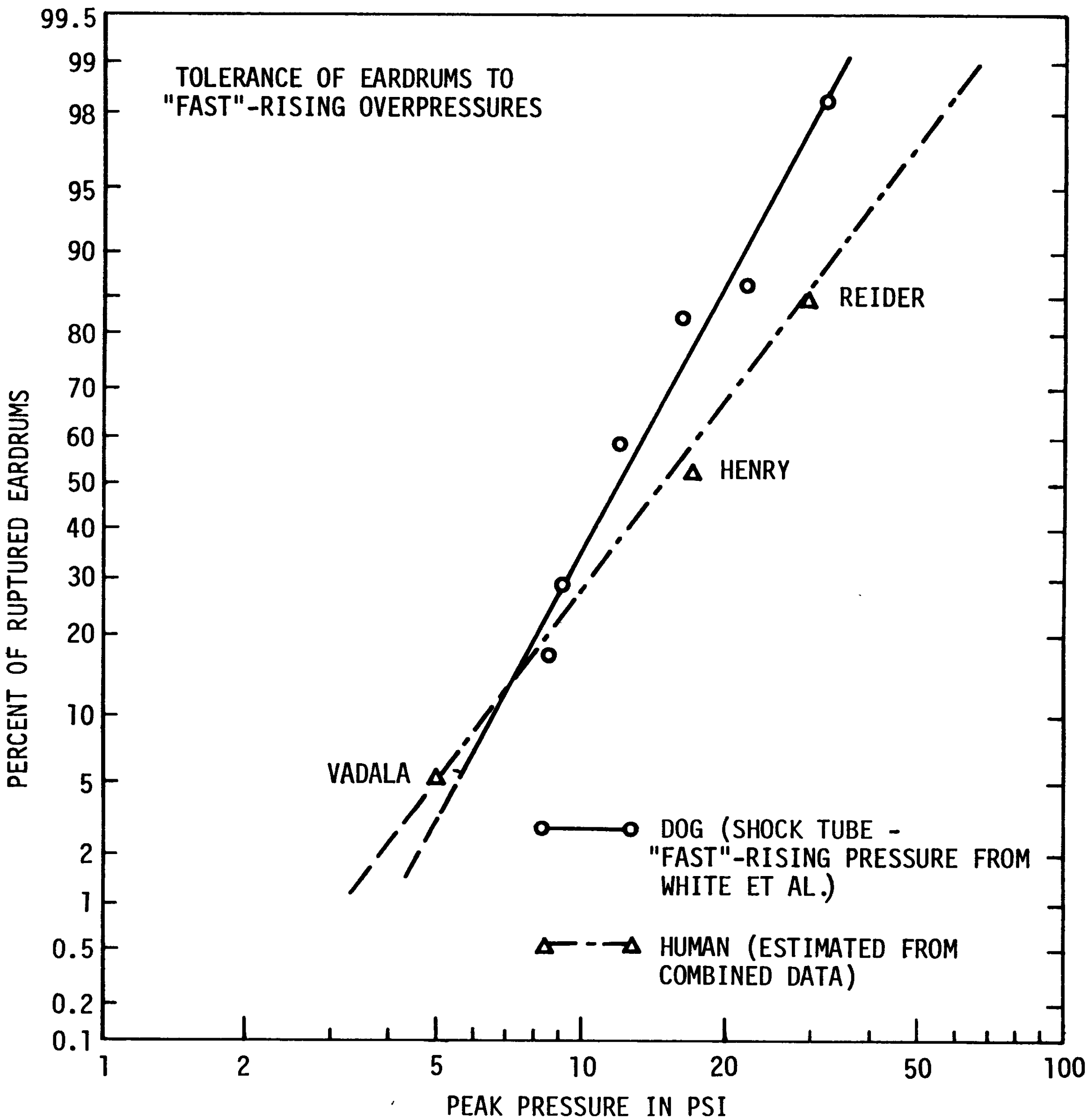


Figure 8 - Peak Pressure versus Percentage of Ruptured Eardrums (From Hirsch.[15] Work by Henry, Vadala, and Reider are cited in his report as References 37, 39, and 41.)

IMPORTANCE OF EAR INJURY TO SHIPBOARD PERSONNEL

DEGENERATION IN COMMUNICATION

Insofar as the available data permit, the previous section established the pressures required to rupture eardrums. The present section examines the possible effects of such injury on communications.

If a ship is in a state of battle readiness, only those personnel located topside would be affected by a blast wave short of one sufficient to cause structural failure. These could include personnel manning gun or missile stations, lookouts, talkers, and bridge personnel. Their locations would influence injury potential. Crew members on the blast side of the ship would likely be exposed to incident as well as pressure waves reflected from the deck or nearby vertical surfaces. These men would be in an area of greater potential injury than men on the shielded side where the steep front of the blast wave would be changed to a less abrupt rise through diffraction effects. Likewise, men in compartments where blast would enter only through a restricted opening would experience a more gradual rise in pressure. Thus, uniform injuries would not occur (1) because of the expected difference in the form of the blast wave with personnel location and (2) because of inherent variations in individual ear injury potential.

In addition, whether rupture occurs or not, there will be a certain shift in hearing associated with the trauma. How much occurs at the time of rupture is not certain because audiometric examinations are not generally obtained immediately following exposure to intense blast pressure. Reports have been made, however, of hearing loss present some time after blast exposure. Korkis[18] gives the audiogram of a man who was exposed at some previous time to a blast which did not cause rupture. This man exhibited a loss of 10 to 20 dB up to 1000 Hz followed by a rapid drop to about 80 dB. In another individual, whose eardrums had been ruptured, a loss of 30 to 40 dB was measured at 128 Hz, with a roughly linear decrease to 15 dB recorded at 4000 Hz. An audiogram obtained from an individual apparently some time after injury indicated a 35-dB reduction in hearing ability in the conversational range.[15] This much of a loss would not present great difficulty in communication.

In discussing the results of a fenestration operation, Weaver and Lawrence observe that the lack of complete recovery (20-30 dB down) would not particularly handicap a person.[1] Blast-induced hearing losses can be greater, however. The audiogram of a man whose middle ear structure was completely missing revealed a loss of 70 dB in the conversational range.[15] This much of a loss would create a serious conversational problem. To illustrate, a hearing loss may be likened to an increase in background noise, with the associated difficulty in communication. The noise level in a quiet ship compartment may be about 40 dB (PSIL). An increase of 70 dB would raise the background noise to 110 dB; at this point, according to Figure 6, communication becomes impossible.

Actually, things are probably much worse after blast-induced ear trauma than we have indicated thus far. The records of hearing loss cited were obtained long after the injury had been incurred and probably after recovery was as complete as possible, so that only the minimum hearing loss was recorded. Hearing loss would be at a maximum at the time of the blast and would then decrease exponentially with time in the manner of recovery from a temporarily induced threshold shift as indicated in Figure 3. Neither the peak hearing loss nor the recovery time from such peaks has been measured. In addition, as Korkis has noted, other symptoms besides deafness may be present. Of 31 blast-deafened patients studied, he found tinnitus in 90 percent of the cases, vertigo in 66 percent, earaches in 50 percent, bleeding from the ear canal in 25 percent, and headaches in 50 percent.[18] Linn and Stein[19] have reported incidents of psychiatric incapacitation as a result of blast injury to the ear. In combination with an induced hearing loss, these complications could easily incapacitate a man, especially if any persisted.

The above considerations identify the effects of blast on the ear, but they fail to include overall effects on the body. Clearly, both will occur under attack conditions. Accordingly, the relative contribution of ear injury to combat ineffectiveness will now be discussed.

EARDRUM RUPTURE IN THE SCALE OF BLAST INJURIES

Although eardrum rupture will be a significant problem in a nuclear blast, it should be borne in mind that the tympanic membrane may escape injury even at pressures as great as 60 psi.[14] However, ear damage would not be a matter of concern at such high overpressures because survivability of the individual would be doubtful following such blast effects and, in addition, radiation accompanying the blast would be most harmful, if not actually fatal, to the entire crew.

Accordingly, although the idea of developing a complete spectrum for eardrum rupture may be of theoretical interest, the upper end of the spectrum would have little practical value. On the other hand, the lower end of that spectrum would be very important because eardrum rupture and the associated hearing loss would be one of the first types of injury to occur. Consider again the relationship of injury to overpressure and its effect on eardrums.

Figure 8 suggests that rupture will increase from a few percent at 5-psi overpressure to about 50 percent at 15 psi. In this range of pressure there may also be bodily injury from other effects of the blast. An overpressure of 10 psi will serve as a convenient example to illustrate the relationship among various injury mechanisms that can occur at low overpressures. Not more than 20 percent of topside personnel would be expected to sustain ruptured eardrums at this pressure (see Figure 8). However, other injuries would result from blast winds, from ionizing radiation, and from thermal radiation.

Figure 9 shows the effects of these injury mechanisms in terms of pressure and weapon yield. Since eardrum rupture will depend only on pressure, its occurrence can be represented as a line of constant pressure. Accordingly, in all three graphs, the horizontal line at 10 psi indicates the condition for 20-percent eardrum rupture. Other nuclear effects cannot be presented as easily because they exhibit a more complicated variation with pressure. Ionizing and thermal radiation effects are considered first in the two upper graphs.

Data from Reference 20 were used for the curve showing how fatal doses of these radiations vary with pressure and yield for surface bursts.

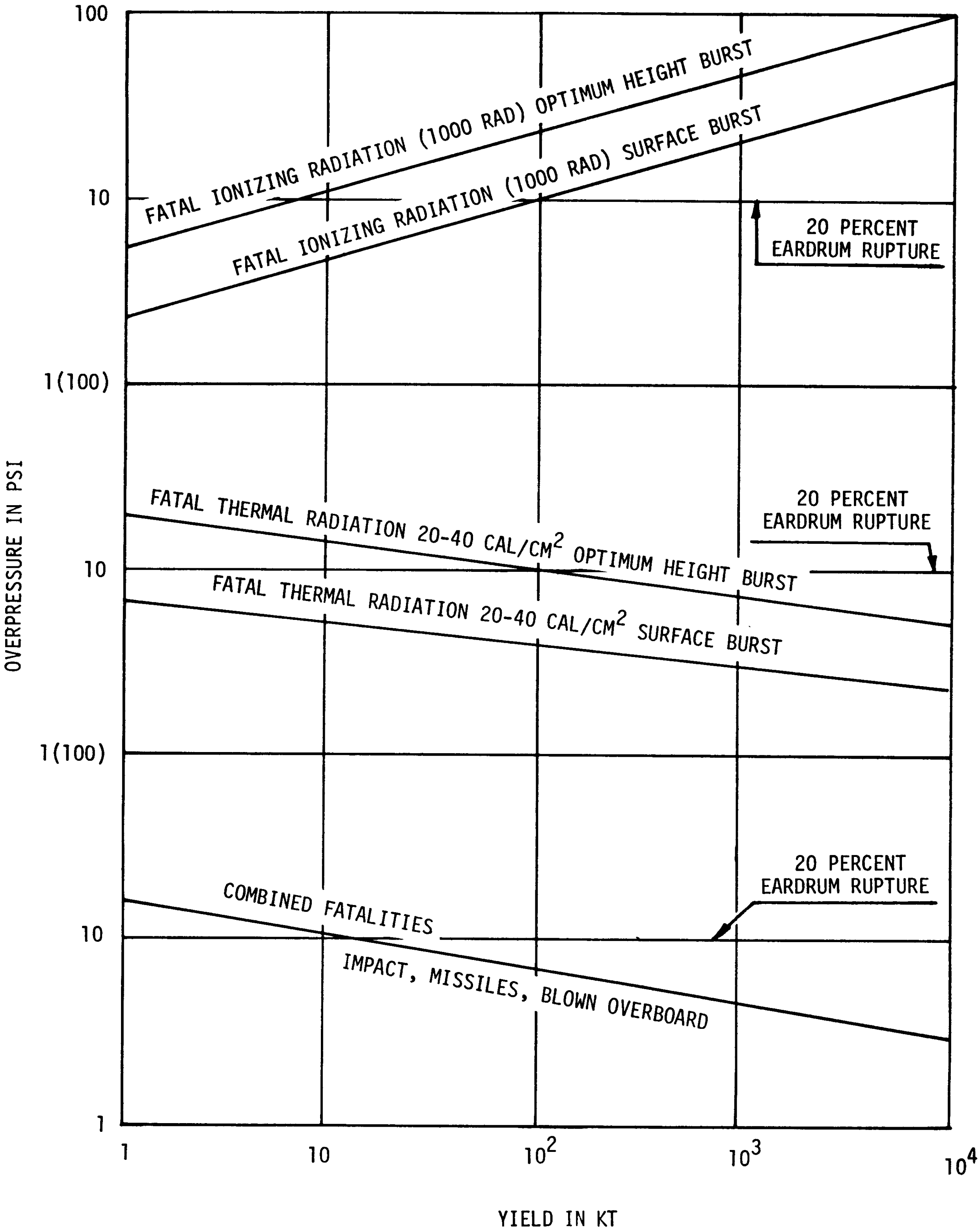


Figure 9 - Overpressure for 20-Percent Eardrum Rupture Compared with Pressures at Which Fatal Blast Effects Occur (Data from White et al.[21])

For a particular yield, the surface burst curve gives the most radiation at the least pressure. However, it does not apply to altitude bursts because pressure-distance relationships (radiation output varies with distance) are not constant. Other curves are possible. An upper bound to such curves will occur at the burst height which makes the pressure on the ground a maximum. The two curves in Figure 9, one for surface bursts and the other for optimum height bursts, are extreme bounds for pressures at which a fatal dose of radiation, either ionizing or thermal, will occur. All variations in pressure accompanying fatal radiation will occur between these bounds.

The bottom graph illustrates fatal effects from blast winds. This curve does not consider possible fatalities from the pressure squeeze, which requires higher pressure, but combines three other injury modes; impact at 30 ft/sec, being blown overboard or being struck by missiles. This curve was developed in consideration of simple horizontal blast winds, but it should also be applicable for blast waves that approach at angles of incidence up to about 60 deg. As the angle increases, the curve becomes less applicable until it is no longer valid for a burst directly overhead.

The upper graph shows that for yields up to 10 kt, and in some cases up to 100 kt, personnel would likely receive a fatal radiation dose before even 20 percent of them experienced eardrum rupture. As weapon yield increases, ionizing radiation output occurs at ever higher overpressures and fatalities from this radiation would not occur before 20-percent eardrum rupture. However, as ionizing radiation output decreases, thermal output increases so that fatalities would again occur to exposed personnel at pressures below which 20-percent eardrum rupture is indicated. In addition, as the bottom graph shows, fatalities from impact would also increase to the point where the incidence of eardrum rupture would be of little concern. As overpressures increase, the situation worsens; already lethal effects will be intensified and initial manifestations of structural failure will appear in the ship which may lead to other casualties in interior compartments. Since men could experience all effects of a nuclear burst, it would appear that eardrum rupture would occur only in concert with other more serious injury mechanisms and that its contribution toward producing casualties must therefore always be of a secondary nature.

EAR PROTECTION

It may be possible to use ear protectors to prevent blast pressures from affecting the eardrum and thus eliminate rupture as a cause of incapacitation. Several methods such as cotton wads, ear plugs, and ear muffs have long been available for defeating noise; in addition, the use of a tone signal has been employed more recently to stimulate the acoustic reflex. The old standby of placing the thumbs over the tragus to block off the ear canal is not only effective in reducing noise but also in sealing the ear canal and preventing entrance of pressure. If topside personnel were free to use it, this method would be advisable.

A realistic appraisal, however, suggests the need for some form of ear protection. Tests have demonstrated the effectiveness of ear plugs in preventing rupture from howitzer blast pressures. Unfortunately, such plugs reduce all sounds and restrict normal voice communication. An earmuff protector which included a speaker to permit normal voice communication might effectively circumvent this problem. A tone signal might offer some protection for others whose ears must remain uncovered. This method has been tested for use by tank crews where TTS and hearing loss have occurred from noise generated by the firing of the tank's own gun. The tone signal must be given a fraction of a second in advance of the blast in order for the ear reflex to react and stiffen the inner ear muscles. How effective the reflex would be for high-pressure, long-duration blast is not known.

In any event, ear protectors are generally uncomfortable and even when available, personnel tend to avoid using them unless absolutely necessary. For instance, jet engine testers and ground personnel use protectors only during the time they are exposed to extreme noise. A suitable device may become available indirectly through development of a protector for personnel exposed to noise during missile firing. Measurements taken at various locations aboard missile ships have indicated that the noise level is above that established in damage risk criteria for safe exposure.

Comfort would have to be of major concern in the design of an ear protector for long-term use e.g., if it were to be worn continuously in anticipation of attack. Otherwise, long-term comfort could be subordinated to interests of protection. Finally, a necessary feature of any design would be a secure clamping mechanism to keep the device in place over the ears during blast winds of high magnitude. However, ear protection alone without accompanying protection for other blast effects would seem to be a misdirected effort.

CONCLUSIONS

1. Eardrum rupture from fast-rising blast waves is normally distributed about a median value of 15 psi. The lower limit for the onset of rupture is probably 5 psi and the upper limit is probably greater than 40 psi.

2. Early rupture relieves loading on the middle ear structure and protects it against subsequent damage. Ruptured eardrums generally heal with little resultant loss in hearing acuity.

3. Eardrum rupture represents a secondary cause of incapacitation; other injury mechanisms from nuclear explosions would be more serious.

4. For a period immediately following a blast, it is likely that hearing in exposed personnel would be sufficiently impaired to compromise normal voice communications aboard ship. Much of the hearing loss would ultimately be recovered. Suitable ear protection could eliminate the temporary impairment.

REFERENCES

1. Weaver, G.E. and Lawrence, M., "Physiological Acoustics," Princeton University Press (1954).

2. Perlman, H.B., "The Effect of Explosions on the Acoustic Apparatus," Transactions American Academy of Ophthalmology and Otolaryngology (Jul-Aug 1943).

3. Hodge, D.C. et al., "Growth of Temporary Threshold Shift from Impulse Noise: A Methodological Study," Human Engineering Laboratories, Aberdeen Proving Ground Tech Memo 1967 (May 1967).

4. Fletcher, J.L. and Riopelle, A.J., "Protective Effect of the Acoustic Reflex for Impulsive Noises," Journal of the Acoustical Society of America, Vol. 2, No. 3, pp. 401-404 (Mar 1960).

5. Rosenblith, W.A. et al., "Handbook of Acoustic Noise Control, Vol. II, Noise and Man," Wright Air Development Center Technical Report 52-204 (Jun 1953).

6. Bakken, B.A., "The Sound Intensity of a Blast Wave as Related to Overpressure," Defense Atomic Support Agency, DASA Technical Analysis Report 540 (Oct 1961).

7. Campbell, J.S., "The Basic Terminology of Noise," Machine Design, Penton Publishing Co., Cleveland, Ohio (Apr 12 1962).

8. Kryter, K.D., "Concepts of Perceived Noiseness, Their Implementation and Application," The Journal of the Acoustical Society of America, Vol. 43, No. 2, pp. 344-361 (Feb 1968).

9. Webster, J.C. and Lepor, M., "Noise, You Can Get Used to It," The Journal of the Acoustical Society of America, Vol. 45, No. 3, pp. 751-757 (Mar 1969).

10. Ross, R. et al., "Criteria for Assessing Hearing Damage Risk from Impulse-Noise Explosion," Human Engineering Laboratories, Aberdeen Proving Ground Tech Memo 13 67 (Aug 1967).

11. Ward, W.D., "Proposed Damage-Risk Criteria for Impulse Noise (Gunfire)," National Academy of Sciences - National Research Council, Washington, D.C. (Jul 1968).

12. Richmond, D.R. et al., "Air Blast Studies with Eight Species of Animals," Defense Atomic Support Agency Report 1854 (Aug 1966).

13. Richmond, D.R. et al., "Blast Biology - A Study of the Primary and Tertiary Effects of Blast in Open Underground Protective Shelters," Operation Plumbob Report WT-1467 (Feb 1959).

14. White, C.S. et al.. "The Relationship between Eardrum Failure and Blast-Induced Pressure Variations," Defense Atomic Support Agency Report 2064 (Aug 1967).

15. Hirsch, F.G., "Effects of Overpressure on the Ear--A Review," Defense Atomic Support Agency Report 1858 (Nov 1966).

16. Glasstone, S., "The Effects of Nuclear Weapons," U.S. Atomic Energy Commission (Apr 1962).

17. Zalewski, T., "Experimentelle Untersuchungen Uben die Resistenzfahigkeit des Trommelfells," Zeits. f. Ohrenheilk, Vol. 52, pp. 109-128 (1906). Cited, not read.

18. Korkis, F.B., "Effect of Blast on the Human Ear," British Medical Journal, pp. 198-201 (Feb 1946).

19. Linn, L. and Stein, M., "A Psychiatric Study of Blast Injuries of the Ear," U.S. Army Mediterranean Theatre of Operations Medical Bulletin, Vol. 1, No. 6 (June 1944).

20. White, C.S., "Tentative Biological Criteria for Assessing Potential Hazards from Nuclear Explosions," Lovelace Foundation, Albuquerque, New Mexico (Oct 1963).

INITIAL DISTRIBUTION

Copies	
1	Deputy Chief of Naval Operations (Development) 1 NOP 07E
3	NAVSHIPSYSCOM 1 SHIPS 03423 2 SHIPS 2052
6	NAVSEC 1 SEC 6105 1 SEC 6105B 1 SEC 6105C 1 SEC 6105C1 1 SEC 6105C2 1 SEC 6105G
2	CHBUMED 1 NM & S 71B 1 NM & S 71F
1	DNA Medical Directorate
2	DDC

CENTER DISTRIBUTION

Copies	Code
1	17
1	174
1	1747
1	177

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Ship Research & Development Center Bethesda, Maryland 20034	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

THE POSITION OF EARDRUM RUPTURE AND HEARING LOSS IN THE SCALE OF INJURIES FROM NUCLEAR BLAST

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Joseph Gesswein and Paul Corrao

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1972	33	20

8a. CONTRACT OR GRANT NO b. PROJECT NO. SF 35.451.101 Subtask 01817 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 3789 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Ship Systems Command (03423) Washington, D.C. 20360

13. ABSTRACT

The scanty data available on human eardrum rupture from blast pressure suggest a normal distribution of rupture about a median overpressure of 15 psi. More abundant data are available on blast-induced eardrum rupture in animals, but their value is limited because of the lack of scaling laws. Consequently, predictions for human injury stem from clinical experiences.

As an injury mode to shipboard personnel, eardrum rupture will be of secondary importance to other blast-induced injuries. In fact, rupture itself may be beneficial to the individual by preventing damage to the middle ear. However, hearing loss associated with blast pressure or rupture itself will compromise normal voice communication. Although ear protection is advisable, it should be made available only in conjunction with protection against other blast effects.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Air Blast						
Eardrum Rupture						
Personnel Protection						