

Excerpted from "A Manual for the Prediction of Blast and Fragment Loadings on Structures," US Department of Energy, August 1981.

<http://www.osti.gov/bridge/servlets/purl/5892901-5PuqGG/> (775pp, 34MB)

#### 4.6 HAZARDS TO PERSONNEL FROM AIR BLAST

Literature concerning the harmful effects of blast on humans has been published as early as 1768. However, knowledge of the mechanisms of blast damage to humans was extremely incomplete until World War I, when the physics of explosions were better understood. Since that time, numerous authors have contributed considerable time and effort in the study of blast damage mechanisms and blast pathology. Each accident situation has its own unique environment with trees, buildings, hills, and various other topographical conditions which may dissipate the energy of the blast wave or reflect it and amplify its effect on an individual. Because of these different variational factors involved in an explosion-human body receiver situation, only a simplified and limited set of blast damage criteria will be included here. The human body "receiver" will be assumed to be standing in the free-field on flat and level ground when contacted by the blast wave. Excluding certain reflected wave situations, this is the most hazardous body exposure condition. Air blast effects can be divided into four categories: primary blast effects, tertiary blast effects, ear damage, and blast generated fragments (Ref. 4.61). Secondary effects involving fragment impact by missiles from the exploding device itself or from objects located in the nearby environment which are accelerated after interaction with the blast wave (appurtenances) shall be discussed in Chapter 6.

##### 4.6.1 Primary Blast Damage

Primary blast effects are associated with changes in environment pressure due to the occurrence of the air blast. Mammals are sensitive to the incident, reflected and dynamic overpressures, the rate of rise to peak overpressure after arrival of the blast wave, and the duration of the blast wave (Ref. 4.61). Specific impulse of the blast wave also plays a major role (Refs. 4.62 and 4.63). Other parameters which determine the extent of blast injury are the ambient atmospheric pressure, the size and type of animal, and possibly age. Parts of the body where there are the greatest differences in density of adjacent tissues are the most susceptible to primary blast damage (Refs. 4.61, 4.64, and 4.65). Thus, the air-containing tissues of the lungs are more susceptible to primary blast than any other vital organ (Ref. 4.66).

Pulmonary injuries directly or indirectly cause many of the pathophysiological effects of blast injury (Ref. 4.67). Injuries include pulmonary hemorrhage and edema (Refs. 4.61 and 4.67), rupture of the lungs (Ref. 4.61), air-embolic insult to the heart and central nervous system (Ref. 4.61), loss of respiratory reserve (Ref. 4.61) and multiple fibrotic foci, or fine scars, of the lungs (Ref. 4.64). Other harmful effects are rupture of the eardrums (to be discussed later) and damage to the middle ear, damage to the larynx, trachea, abdominal cavity, spinal meninges, and radicles of the spinal nerves and various other portions of the body (Ref. 4.61).

Bowen, et al. (Ref. 4.65) and White, et al. (Ref. 4.62), have developed pressure versus duration lethality curves for humans which are especially amenable to this document. Some of the major factors which determine the extent of damage from the blast wave are the characteristics of the blast wave, ambient atmospheric pressure, and the type of animal target, including its mass and geometric orientation relative to the blast wave and nearby objects (Ref. 4.62). Although Richmond, et al. (Ref. 4.63) and later White, et al. (Ref. 4.62), both from the Lovelace Foundation, discuss the tendency of the lethality curves to approach isopressure lines for "long" duration blast waves, their lethality curves demonstrate dependence on pressure and duration alone. Since specific impulse is dependent on pressure as well as duration, pressure-impulse lethality or survivability curves appear to be more appropriate. The tendency for pressure-impulse lethality curves to approach asymptotic limits is also very aesthetically appealing from a mathematical point of view. Also, since both pressure and specific impulse at a specified distance from most explosions can be calculated directly using methods described in this document, it is especially appropriate that pressure-impulse lethality (or survivability) curves be developed. This has been done and is described in Reference 4.59. These curves and their use are reproduced here as Figure 4.68.

Simplifying Lovelace's scaling laws in such a manner that only the human species or large animals are considered, one is able to arrive at the following relationships or scaling laws:

1. The affect of incident overpressure is dependent on the ambient atmospheric pressure. That is,

$$\bar{P}_s = \frac{P_s}{P_o} \quad (4.70)$$

where  $\bar{P}_s$  is scaled incident peak overpressure,  $P_s$  is peak incident overpressure, and  $P_o$  is ambient atmospheric pressure.

2. The effect of blast wave positive duration is dependent on ambient atmospheric pressure and the mass of the human target. That is,

$$\bar{T} = \frac{T_p^{1/2}}{m^{1/3}} \quad (4.71)$$

where  $\bar{T}$  is scaled positive duration,  $T$  is positive duration, and  $m$  is weight of human body.

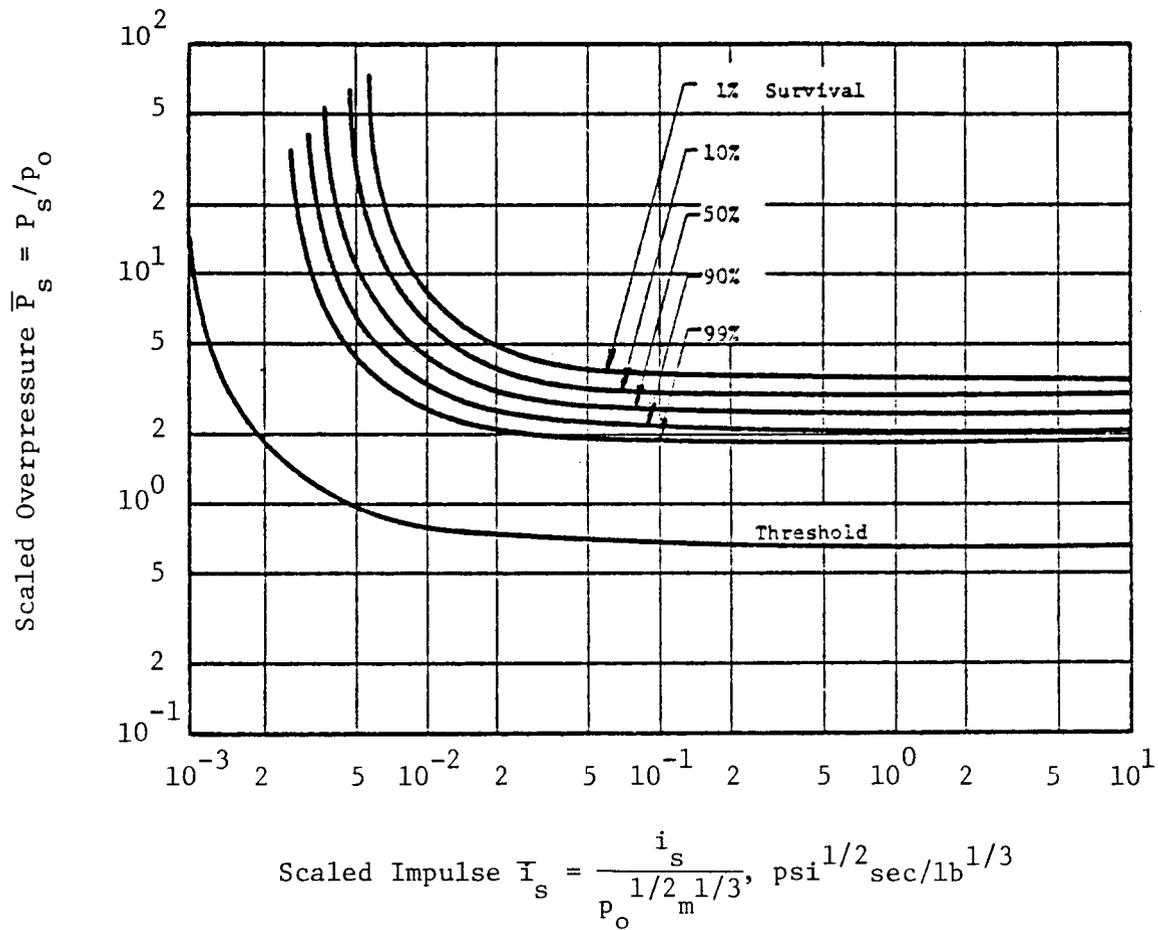


Figure 4.68 Survival Curves for Lung Damage to Man

3. Impulse  $i_s$  can be approximated by

$$i_s = \frac{P_s T}{2} \quad (4.72)$$

Equation (4.72) assumes a triangular wave shape and is conservative, from an injury standpoint, for "long" duration blast waves which approach square wave shapes because it underestimates the specific impulse required for a certain percent lethality. It is also a close approximation for "short" duration blast waves which characteristically have a short rise time to peak overpressure and an exponential decay to ambient pressure, the total wave shape being nearly triangular. Applying the blast scaling developed at the Lovelace Foundation for peak overpressure and positive duration to the conservative estimate for specific impulse determined by Equation (4.72) above, one can arrive at a scaling law for specific impulse:

$$\bar{i}_s = \frac{1}{2} \bar{P}_s \bar{T} \quad (4.73)$$

where  $\bar{i}_s$  is scaled specific impulse. From Equations (4.71), (4.72), and (4.73)

$$\bar{i}_s = \frac{1}{2} \frac{P_s T}{P_o^{1/2} m^{1/3}} \quad (4.74)$$

or from Equation (4.72)\*

$$\bar{i}_s = \frac{i_s}{P_o^{1/2} m^{1/3}} \quad (4.75)$$

Thus, as indicated by Equation (4.75), scaled specific impulse  $\bar{i}_s$  is dependent on ambient atmospheric pressure and the mass of the human target.

Reconstructed curves from Reference 4.59 are shown in Figure 4.68. It should be noted that these curves represent percent survivability, and higher scaled pressure and scaled impulse combinations allow fewer survivors. Presenting the curves in this fashion is advantageous since they apply to all

altitudes with different atmospheric pressures and all masses (or sizes) of human bodies. Once one determines the incident overpressure and specific impulse for an explosion, they can be scaled using Equations (4.70) and (4.75). The proper ambient atmospheric pressure to use for the scaling can be acquired from Figure 4.69, which shows how atmospheric pressure decreases with increasing altitude above sea level (Ref. 4.19). The value for body weight used in the scaling is determined by the demographic composition of the particular area under investigation. It is recommended that 11 lb be used for babies, 55 lb for small children, 121 lb for adult women, and 154 lb for adult males. It should be noticed that the smallest bodies in this case are the most susceptible to injury.

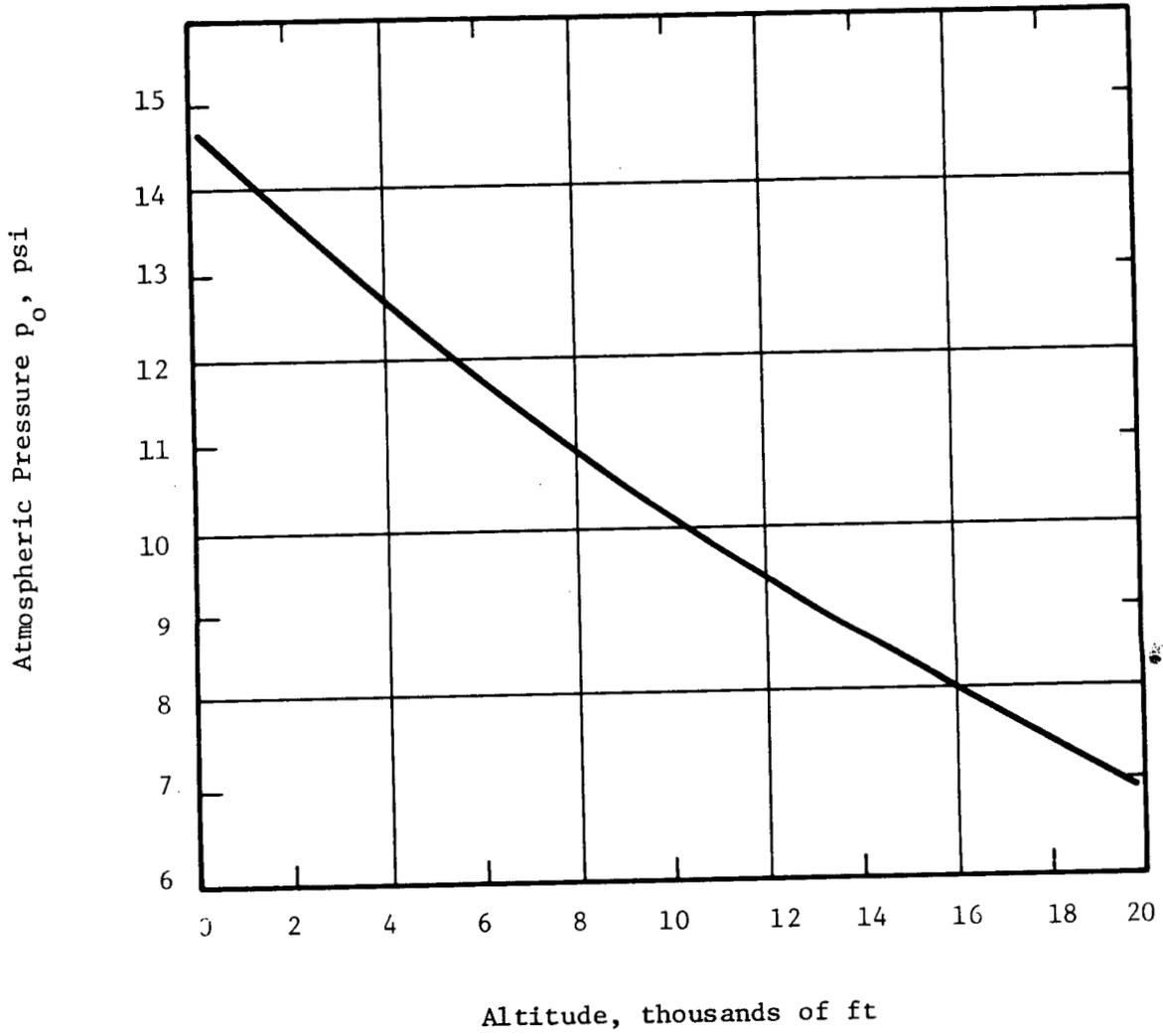


Figure 4.69 Atmospheric Pressure as a Function of Altitude Above Sea Level

EXAMPLE PROBLEM 4.14

PROBLEM - Assess lung damage to humans at an appropriate distance from a given explosive source.

GIVEN: W = explosive charge weight  
R = distance from center of explosive charge  
Altitude (no symbol)  
m = weight of body of human subject

FIND: Probability of survival

<u>SOLUTION:</u>		<u>REFERENCE</u>
1. Determine peak incident overpressure $P_s$ and specific impulse $i_s$ for given charge weight W and distance R		Fig. 4.5
2. Determine ambient atmospheric pressure from altitude		Fig. 4.69
3. Calculate scaled incident overpressure $\bar{P}_s$		Eq. (4.70)
4. Choose weight of the lightest human exposed at distance R		
5. Calculate scaled specific impulse $\bar{i}_s$		Eq. (4.75)
6. Plot $\bar{P}_s$ and $\bar{i}_s$ and determine probability of survival		Fig. 4.68

CALCULATION

GIVEN: W = 100 lb  
R = 100 ft  
Altitude = 4000 ft  
m = 130 lb

FIND: Percent survival

SOLUTION: 1.  $R/W^{1/3} = 100/100^{1/3} = 21.5 \text{ ft/lb}^{1/3}$   
Enter Figure 4.5 and read  $P_s = 1.8 \text{ psi}$   
and  $i_s/W^{1/3} = 2.55 \times 10^{-3} \text{ psi-sec/lb}^{1/3}$   
"Unscale" to determine  $i_s$   
$$\frac{i_s}{W^{1/3}} \cdot W^{1/3} = 2.55 \times 10^{-3} \times 10^{1/3} = 5.49 \times 10^{-3} \text{ psi-sec}$$

2. From Figure 4.69 for 4000 ft altitude,  
 $p_o = 12.6 \text{ psi}$

3. From Equation (4.70),  
 $\bar{P}_s = 1.8/12.5 = 0.144$

4. Given  $m = 130$  lb

5. From Equation (4.75),

$$\bar{i}_s = \frac{i_s}{P_o^{1/2} m^{1/3}} = \frac{5.49 \times 10^{-3}}{12.6^{1/2} \times 130^{1/3}} = 1.08 \times 10^{-3} \frac{\text{psi}^{1/2} \text{ sec}}{\text{lb}^{1/3}}$$

6. From Figure 4.68, enter with  $\bar{P}_s = 0.144$  and  $\bar{i}_s = 1.08 \times 10^{-3}$ . The point lies well below the threshold for lung damage. So, there is no injury and survival is 100%

#### 4.6.2 Tertiary Blast Injury

During whole-body displacement, blast overpressures and impulses interact with the body in such a manner that it is essentially picked up and translated. Tertiary blast damage involves this whole-body displacement and subsequent decelerative impact (Ref. 4.61). Bodily damage can occur during the accelerating phase or during decelerative impact (Ref. 4.68). The extent of injury due to decelerative impact is the more significant (Ref. 4.69), however, and is determined by the velocity change at impact, the time and distance over which deceleration occurs, the type of surface impacted, and the area of the body involved (Ref. 4.61).

Although the head is the most vulnerable portion of the body to mechanical injury during decelerative impact, it is also the best protected (Ref. 4.67). Because of the delicate nature of the head, many may feel that translation damage criteria should be based on skull fracture or concussion. However, since body impact position is likely to be randomly oriented after translation, others may feel that this factor should be taken into account in determining expected amounts of impact damage. In an effort to satisfy proponents of each point of view, both types of impact, essentially head foremost and random body impact orientation, will be considered.

Because of the many parameters involved in decelerative impact, a few assumptions will be made. First of all, translation damage will be assumed to occur during decelerative impact with a hard surface, the most damaging case (Ref. 4.69). Another assumption is that, since impact onto only hard surfaces is being considered, translation damage will depend only on impact velocity. This is, impacting only one type of surface precludes the need for considering change in velocity of the body during impact. This assumption, however, is not entirely valid when one considers that the compressibility of various portions of the body can vary considerably.

White (Refs. 4.61 and 4.62) and Clemenson, et al. (Ref. 4.69), agree that the tentative criteria for tertiary damage (decelerative impact) to the head should be those presented in Table 4.11. White's (Ref. 4.62) recently revised criteria for tertiary damage due to total body impact are summarized in Table 4.12. It is beneficial to note that the mostly "safe" velocity criteria for each type of impact condition are identical.

Baker, et al. (Ref. 4.59) have developed a method for predicting the blast incident overpressure and specific impulse combinations which will translate human bodies and propel them at the critical velocities presented in Tables 4.11 and 4.12. This method and associated prediction curves are reproduced here.

Figure 4.70 contains the pressure-scaled impulse combinations required to produce the velocities for various expected percentages of skull fracture (See Table 4.11) at sea level, while Figure 4.71 contains the pressure-scaled

Table 4.11 Criteria For Tertiary Damage  
 (Decelerative Impact) To The Head  
 (References 4.61, 4.62, and 4.69)

<u>Skull Fracture Tolerance</u>	<u>Related Impact Velocity ft/sec</u>
Mostly "safe"	10
Threshold	13
50 percent	18
Near 100 percent	23

Table 4.12 Criteria For Tertiary Damage  
 Involving Total Body Impact  
 (Reference 4.62)

<u>Total Body Impact Tolerance</u>	<u>Related Impact Velocity ft/sec</u>
Mostly "safe"	10
Lethality threshold	21
Lethality 50 percent	54
Lethality near 100 percent	138

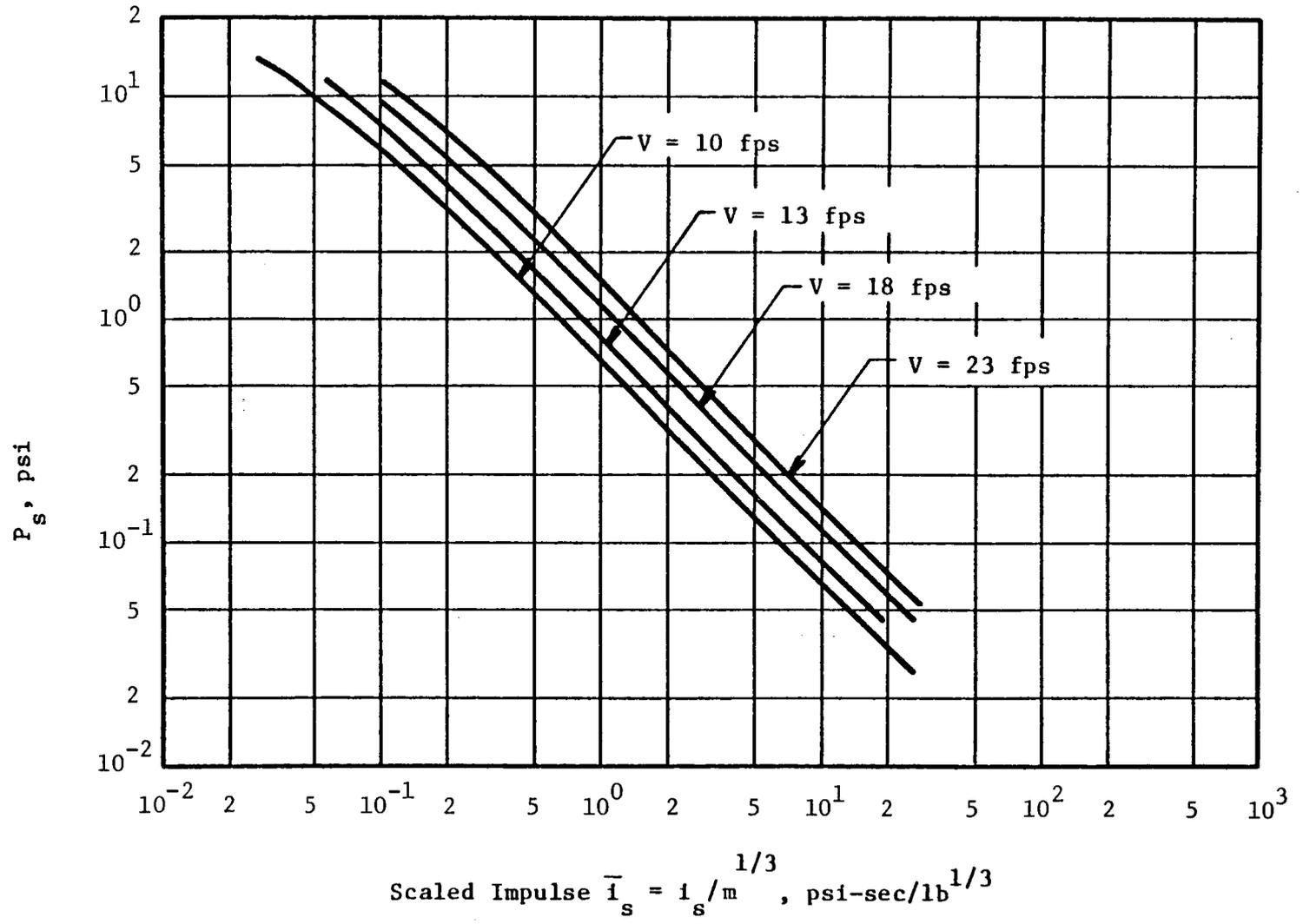


Figure 4.70 Skull Fracture

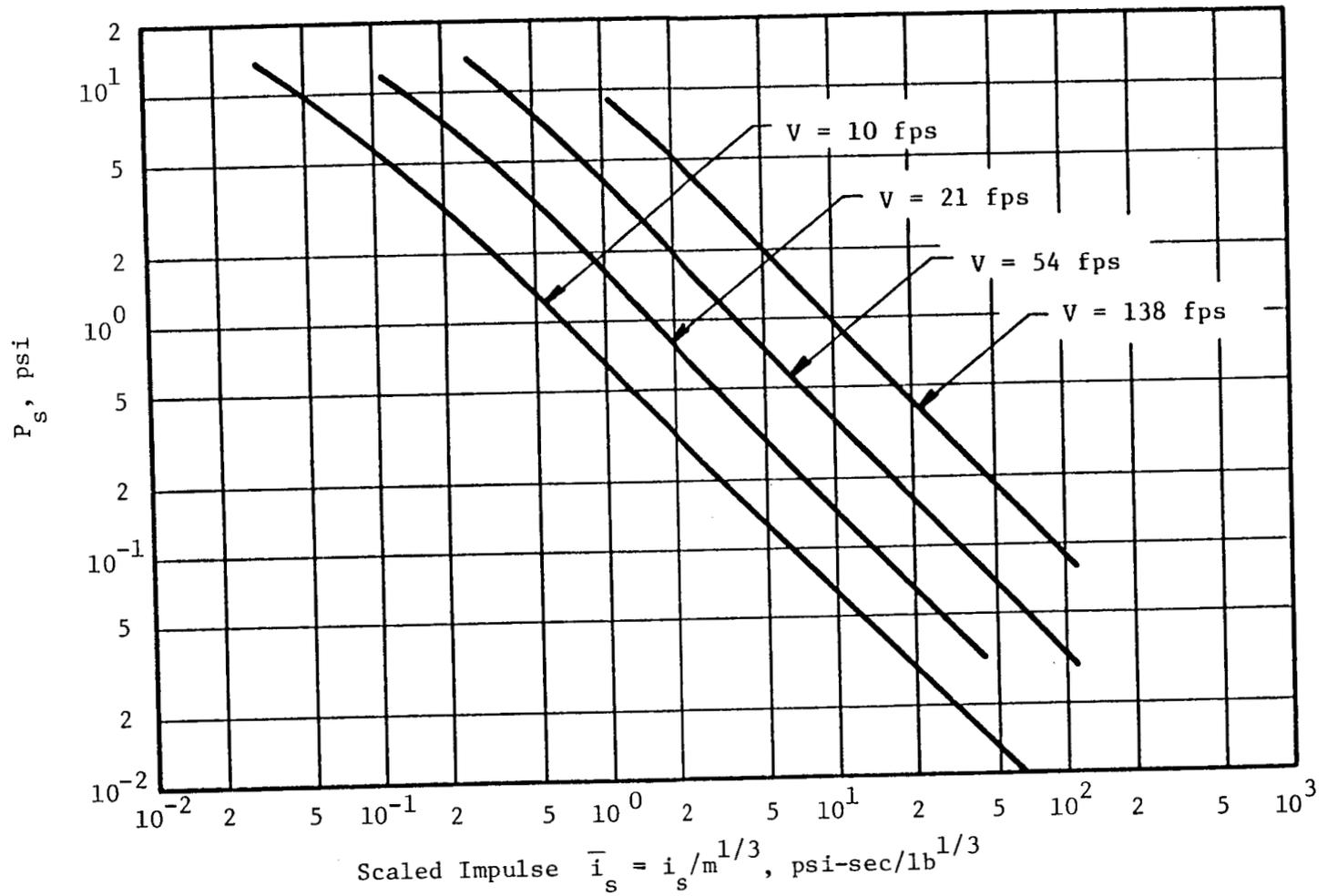


Figure 4.71 Lethality From Whole Body Translation

impulse combinations required to produce the velocities for various expected percentages of lethality from whole body impact (See Table 4.12) at sea level. Curves for other altitudes differ only slightly from the sea level curves.

EXAMPLE PROBLEM 4.15

PROBLEM - Predict possible tertiary blast damage to humans at a specified distance from a given explosive source.

GIVEN: W = explosive weight  
R = distance from center of explosive charge  
m = weight of body of human subject

FIND: Probability of injury

REFERENCE

- SOLUTION:
1. Determine peak incident overpressure  $P_s$  and specific impulse  $i_s$  for given charge weight W and distance R
  2. Determine the lightest representative weight of an exposed human, and calculate  $i_s/m^{1/3}$
  3. Locate  $P_s$  and  $i_s/m^{1/3}$  on graphs for skull fracture and lethality for whole body translation, and read impact velocities
  4. Determine degree of injury for appropriate impact velocities

Fig. 4.5

Fig. 4.70 &  
Fig. 4.71

Table 4.11

CALCULATION

GIVEN: W = 100 lb  
R = 100 ft  
m = 130 lb

FIND: Tertiary blast injury, based on skull fracture and whole body translation

- SOLUTION:
1.  $R/W^{1/3} = 100/100^{1/3} = 21.5 \text{ ft/lb}^{1/3}$   
Enter Figure 4.9 and read  $P_s = 1.8 \text{ psi}$  and  
 $i_s/W^{1/3} = 2.55 \times 10^{-3} \text{ psi-sec/lb}^{1/3}$   
"Unscale" to determine  $i_s$   
 $\frac{i_s}{W^{1/3}} \cdot W^{1/3} = 2.55 \times 10^{-3} \times 100^{1/3} = 1.18 \times 10^{-2} \text{ psi-sec}$
  2. Given m = 130 lb. Calculate  
 $i_s/m^{1/3} = 1.18 \times 10^{-2}/130^{1/3} = 2.33 \times 10^{-3} \text{ psi-sec/lb}^{1/3}$

3. Enter Figure 4.70 with  $P_s = 1.8$  and  $i_s/m^{1/3} = 2.33 \times 10^{-3}$ . This is off the left side of the Figure, but well below the lowest curves for skull fracture. So,  $V \ll 10$  fps. Enter Figure 4.71 with the same numbers. Again,  $V \ll 10$  fps.
4. Referring to Table 4.11 for correlation of velocities with injury, we find that for either the skull fracture or whole body impact criteria, the impact velocities are well below the mostly "safe" velocities. So, no injury would occur.
- NOTE: Had the values for ordinate and abscissa in Figures 4.70 and 4.71 been  $P_s = 1$  psi,  $i_s/m^{1/3} = 1$  psi-sec/lb<sup>1/3</sup>, the velocities for skull fracture velocity would have been  $V = 15$  fps, and for whole body translation  $V = 13$  fps. Skull fracture injury probability would lie between threshold and 50%, while lethality due to whole body translation would lie between mostly "safe" and the threshold for lethality. So, the human would have a relatively high probability of skull fracture, but a low probability of death. Whether this level of injury would or would not be acceptable could only be addressed in separate safety criteria.

#### 4.6.3 Ear Damage Due To Air Blast Exposure

The ear, a sensitive organ system which converts sound waves into nerve impulses, responds to a band of frequencies ranging from 20 Hz to 20,000 Hz. This remarkable organ can respond to energy levels which cause the eardrum to deflect less than the diameter of a single hydrogen molecule (Ref. 4.70). Not being able to respond faithfully to pulses having periods less than 0.3 millisecond, it attempts to do so by making a single large excursion (Ref. 4.70). It is this motion which can cause injury to the ear.

The human ear is divided into the external, middle, and inner ear. The external ear amplifies the overpressure of the sound wave by approximately 20 percent and detects the location of the source of sound (Ref. 4.70). Rupture of the eardrum is a good measure of serious ear damage. Unfortunately, the state-of-the-art for predicting eardrum rupture is not as well developed as that for predicting lung damage from blast waves. A direct relationship, however, has been established between the percentage of ruptured eardrums and maximum overpressure. Hirsch (Ref. 4.67) constructed a graph similar to that shown in Figure 4.72 and concluded that 50 percent of exposed eardrums rupture at an overpressure of 15 psi. White (Ref. 4.61) supports this conclusion for "fast" rising overpressures with durations of 0.003 second to 0.4 second occurring at ambient atmospheric pressure of 14.7 psi. Hirsch (Ref. 4.67), also concluded that threshold eardrum rupture for "fast" rising overpressures occurs at 5 psi, which is also supported by White (Ref. 4.61) for the range of duration and at the atmospheric pressure mentioned above.

At lower overpressures than those required to rupture eardrums, a temporary loss of hearing can occur. Ross, et al. (Ref. 4.70), have produced a graph of peak overpressure versus duration for temporary threshold shift (TTS). Below the limits of the graphs, a majority (75 percent at least) of those exposed are not likely to suffer excessive hearing loss. According to Ross, et al. (Ref. 4.70), their curves should be lowered 10 dB to protect 90 percent of those exposed, lowered 5 dB to allow for a normal angle of incidence of the blast wave, and increased 10 dB to allow for occasional impulses. In sum, to assure protection to 90 percent of those exposed and to allow for normal incidence to the ear (the worst exposure case) of an occasional air blast, their curves should be lowered 5 dB.

Limits for eardrum rupture and temporary threshold shift, as presented above, are dependent on peak incident overpressure and duration. Since specific impulse is dependent upon the duration of the blast wave and since both peak incident overpressure and specific impulse at a specified distance from an explosion can be calculated using methods in this document, it is especially appropriate that pressure-impulse ear damage curves be developed from the pressure-duration curves. Assuming a triangular shape for the blast wave allows for simple calculations which are conservative from an injury standpoint.

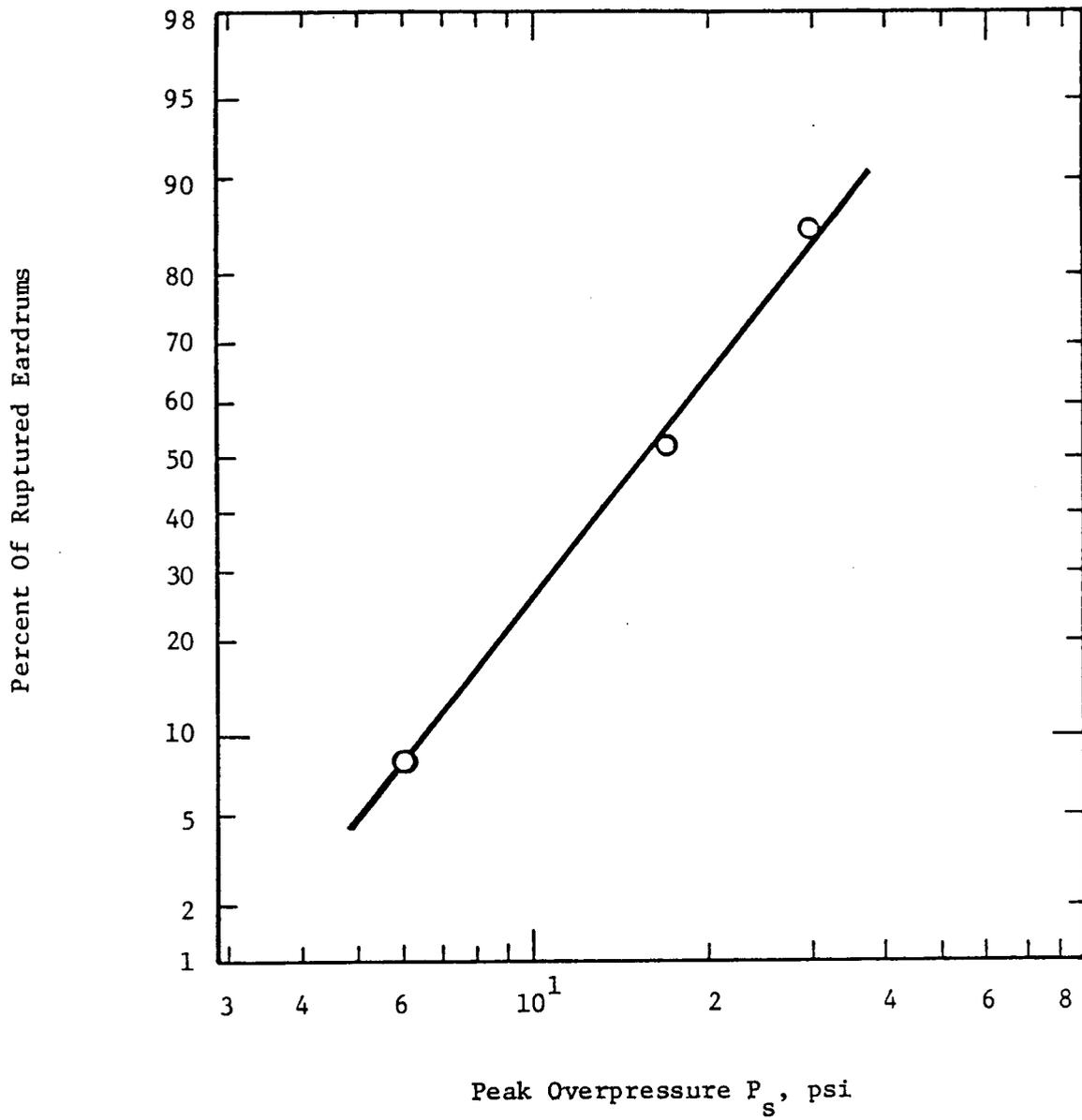


Figure 4.72 Percent Eardrum Rupture as a Function of Overpressure

The ear damage criteria presented in Figure 4.73 were developed from the criteria for eardrum rupture developed by Hirsch (Ref. 4.68) and White (Ref. 4.61) and from the criteria for temporary threshold shift developed by Ross, et al. (Ref. 4.70). Equation (4.72) was used to calculate specific impulse, and temporary threshold shift represents the case where 90 percent of those exposed to a blast wave advancing at normal angle of incidence to the ear are not likely to suffer an excessive degree of hearing loss. The threshold for eardrum rupture curve is the location below which no ruptured ears are expected to occur and the 50 percent of eardrum rupture curve is the location at which 50 percent of ears exposed are expected to rupture.

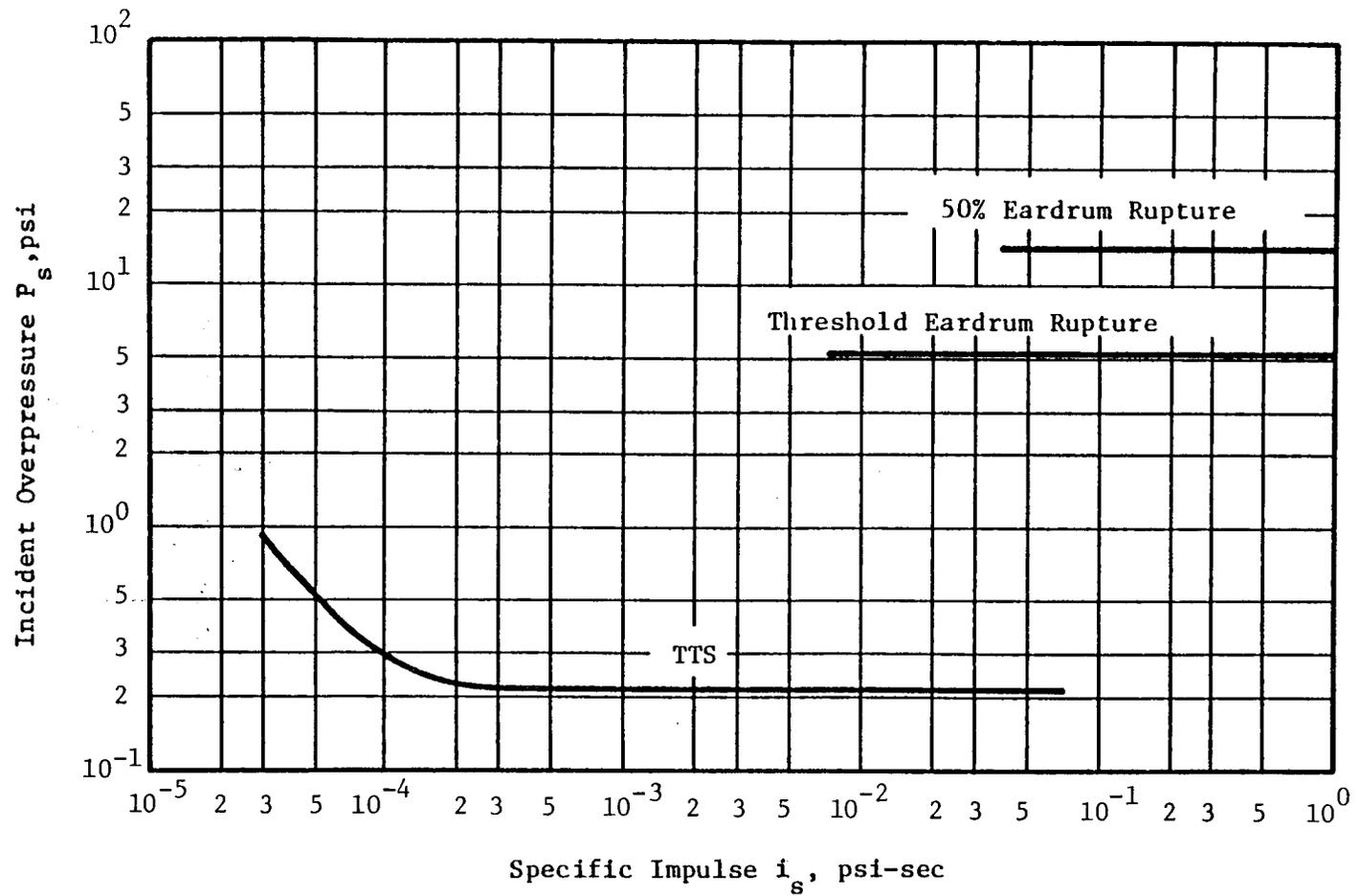


Figure 4.73 Human Ear Damage for Blast Waves Arriving at Normal Angle of Incidence

EXAMPLE PROBLEM 4.16

PROBLEM - Find the probability of ear injury at a given distance from a specified explosive source.

GIVEN: W = explosive charge weight  
R = distance from center of explosive charge

FIND: Probability of ear injury

REFERENCE

SOLUTION: 1. Determine peak incident overpressure  $P_s$  and specific impulse  $i_s$  for given charge weight W and distance R Fig. 4.5  
2. Determine degree of injury by plotting  $P_s$  and  $i_s$  on human ear damage curve Fig. 4.73

CALCULATION

GIVEN: W = 100 lb (free air)  
R = 100 ft

FIND: Level of ear injury

SOLUTION: 1.  $R/W^{1/3} = 100/100^{1/3} = 21.5 \text{ ft/lb}^{1/3}$   
Enter Figure 4.5 and read  $P_s = 1.8 \text{ psi}$   
and  $i_s/W^{1/3} = 2.55 \times 10^{-3} \text{ psi-sec/lb}^{1/3}$   
"Unscale" to obtain  $i_s$   
$$\frac{i_s}{W^{1/3}} \cdot W^{1/3} = 2.55 \times 10^{-3} \times 100^{1/3} = 1.18 \times 10^{-2} \text{ psi-sec}$$

2. Plotting  $P_s$  and  $i_s$  on Figure 4.73, one finds that the point lies well above the curve for TTS, but below the curve for threshold of eardrum rupture. So, humans would suffer temporary hearing loss, but no serious ear injury.  
NOTE: When comparing ear injury, primary blast damage, and tertiary blast damage for the same source, as has been done in Example Problems 4.14, 4.15, and 4.16, one invariably finds that ear injury occurs at a greater distance than the other, more serious, types of blast injury. So, if

safety criteria include an ear damage limit,  
one can be assured that no more serious  
blast injury will occur at the distances  
corresponding to the ear damage limit.