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ESTIMATE OF MAN'S TOLERANCE TO THE DIRECT EFFECTS OF AIR BLAST

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ABSTRACT

Tolerance indices were determined, allowing for the effects of body mass, for thirteen mammalian species using the results of experiments in which animals were exposed near a normally reflecting surface to shocked blast waves whose durations ranged from 0.24 to 400 msec. A general equation was developed for expressing the interrelations between overpressure, duration of the blast wave, body mass, and probability of survival. The species were divided into high- and low-tolerance groups applicable to "large" and "small" mammals, respectively. Since the available evidence indicated that man is more likely to be a member of the high-tolerance group, the tolerance index arbitrarily, but tentatively, assigned to him was the geometric mean of those for the large species. Using criteria developed in experimental studies, the results of the overall analysis were made applicable to free-stream situations in which the long axis of the body is perpendicular or parallel to the direction of propagation of a shocked blast wave.

Research was conducted according to the principles enunciated in the "Guide for Laboratory Animal Facilities and Care." Prepared by the National Academy of Sciences--National Research Council.

PREFACE

During the last fifteen years a continuing research program at the Lovelace Foundation has been concerned with the biological effects of air blast. Especially during more recent years considerable data referrable to several mammalian species have been obtained in investigations of the effects of overpressure per se where the exposure conditions were similar or equivalent; i.e., exposures in which the animals were near a surface which reflected blast waves with fast-rising fronts. Other experiments with fewer animals indicated that the data for reflected blast waves could be applied to free-stream situations under certain conditions.

The data mentioned above, obtained from experiments involving 2097 animals, were used in the present study in an attempt through analysis to achieve a unified concept which would take into account both similarities and differences in the response of various mammalian species to blast waves specified in terms of maximum overpressure and duration. The most important result of the overall approach was the establishment of an analytical framework which was used to predict—at least tentatively—man's response to air-blast overpressures. Another useful result was the evaluation of tolerance indices which later may be causally related to significant biophysical, physiological, and anatomical factors varying between species.

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ESTIMATE OF MAN'S TOLERANCE TO THE DIRECT EFFECTS OF AIR BLAST

1.0 INTRODUCTION

The direct (or primary) effects of air blast are those resulting from exposure of the body to environmental pressure variations accompanying a blast wave. Because of the effects of compressibility, damage—except for local injury from very small nearby charges—occurs where there are differences in tissue density principally in or near the air- or gas-containing organs, the effects on the lungs being particularly important in determining morbidity or mortality. In contrast, the principal indirect effects result from blast-induced translation either of objects which strike the body or of the body itself which may be injured by the acceleration per se or by subsequent impact with other objects; hence, the sites of damage depend largely on chance and the circumstance of exposure.

Considerable information has become available in recent years regarding the tolerance of experimental animals to the direct effects of air blast for a specific exposure situation; viz., the situation with the animal near a flat rigid surface reflecting shocked blast waves at normal incidence. If a unified analysis of these data were possible, animal response as indicated by percent survival could be expressed in terms of (1) maximum reflected overpressure, (2) duration of the wave, (3) body mass of the animal, and (4) individual species tolerance index. Available empirical information would then make it possible to apply the results to certain exposure situations in the free stream; i.e., without a reflecting surface.

It was the primary purpose of this study to make the overall analysis noted above in order to establish an analytical framework which could be used to predict man's tolerance. A secondary purpose was to evaluate tolerance indices which in later studies might be related to physiological or anatomical factors affecting variations in species response.

2.0 EXPERIMENTAL DATA

Most of the experimental data used in this study have appeared in previous publications (see Table 1 for references) but not always in sufficient detail for present purposes. Also, it was necessary to make certain refinements, described later, in the reported high-explosive parameters in order to achieve a unified analysis. The mortality data in all cases are applicable to the 24-hour period following the blast experience.

The shock-tube data, labeled ST in Table 1, were obtained with the left side of the animal against the end-plate that closes the tube except for the monkey which was facing, but against, the end-plate. The difference in tolerance, if any, caused by this variation in orientation is not known. The monkey and larger species were held with harness and straps while the smaller species were restrained in specially designed metal cages with 90 percent open area. Maximum overpressures and durations listed in Table 1 are those measured with pressure transducers placed near the end-plate.

Except in a few instances as noted later, the high-explosive data were obtained with all animals prone on a concrete pad and the charge placed overhead. The rodents, cats, and rabbits were held on the concrete pad with nylon string and tape. All other species were restrained in harness. The only exception to the prone position was that for 9 of the 12 sheep in Group 128, Table 1. In this case the animals were suspended upright with the 1-lb charge placed at the level of the chest in front of or behind them. By comparing the results for these subjects to those for the other experiments (Groups 129 to 132) with 1-lb charges when the sheep were prone and the charge overhead, the biological response was found to be not significantly influenced by the presence of a reflecting surface, a circumstance that is not the case with "long"-duration blast waves for which lethality occurs at much lower overpressures.

In all the experiments represented by Groups 128 to 132, injury was found, in contrast to damage following exposure to lower overpressures of longer durations, to be more nearly localized to the portion of the lung nearest the charge. In fact, animals exposed at the end-plate of a shock tube typically received somewhat more damage in the lung opposite the oncoming blast wave.[21] These differences in response will be discussed later in more detail.

Overpressures and durations for the high-explosive experiments were measured at or near the surface of the concrete pad except for the experiments with the suspended sheep mentioned above. In this case, blast parameters referrable to a reflecting surface visualized as being against the animal opposite the charge were obtained from published data for Pentolite.[14]

For several reasons accurate measurements of duration are difficult to obtain from the measured pressure-time records. Since the overall analysis to be made required at least consistent duration values, smoothed data published for Pentolite[14] were used to determine high-explosive durations (listed in Table 1) by assuming for a given charge weight that Pentolite releases 10 percent more energy than TNT, Comp. B, or RDX.

In some of the earlier experiments, the sensitive element of the pressure transducer was 0.75 inch above the concrete pad (Table 1). To make these measurements consistent with the other data, information reported by Schlueter et al.[23] was used to determine maximum reflected overpressures at the surface of the pad. The resulting corrections were found to be significant, especially for the smaller charges.

3.0 ANALYTICAL PROCEDURES AND RESULTS

A relation pointed out years ago by Schardin[22] is still instructive; namely, that mammalian response to air blast is more nearly dependent on overpressure impulse ($\int P\,dt$) if the durations are "short" or overpressure per se if they are "long." It was natural to relate the "long" and "short" to the response time, or natural period, of the mammalian thorax since the lungs are the principal target organs.[1,2,4,24]

A relationship between maximum overpressure, P, and duration of the positive phase, T, satisfying both conditions stated above, can be expressed as

$$P = P^{*} \left(1 + aT^{-b}\right) \tag{1}$$

where P^{*}, a, and b are constants to be evaluated from experimental data. Note that as T becomes large aT^{-b} approaches zero and P approaches P^{*}, the overpressure criterion for "long" duration waves. On the other hand, for small values of T the term aT^{-b} becomes large compared to one (1) and Equation (1) can be written

$$P\, T^{b} \approx P^{*} a \tag{2}$$

which approximates the condition of constant impulse if b is near unity. The constant b cannot be expected to be exactly unity since the shapes of explosive-produced blast waves change with maximum overpressure. It will be demonstrated later that Equation (1) provides a satisfactory expression for the tolerance data over the entire range of durations associated with the experiments.

In a previous study[2] it was shown by dimensional analysis that the significance of a particular blast-wave duration can be related to the ambient pressure, p_o, and also to the mass, m, of the experimental mammal. These concepts were used in the present study to scale all experimental durations, t_+, to durations, T, applicable to a 70-kg mammal and to an ambient pressure of 14.7 psi; i.e.,

$$T = t_{+} \left(70/m\right)^{1/3} \left(p_o/14.7\right)^{1/2} \tag{3}$$

where m is measured in kg, and p_o in psi.

The study cited above, as well as experimental studies,[6,8] produced an approximate relationship between ambient pressure and maximum overpressure for a given biological response. For the purpose of the present study this can be expressed as

$$P = p_r \left(14.7/p_o\right) \tag{4}$$

where P is the maximum reflected overpressure applicable to an ambient pressure of 14.7 psi and p_r is the maximum reflected overpressure applicable to an ambient pressure of p_o expressed in psi.

The quantity P^{*} in Equation (1) is the long-duration overpressure producing a given, but unspecified, biological response. P^{*} can be made specifically applicable to various levels of lethality by the following transformation:

$$P^{*} = P_{sw}\, e^{c(y-5)} \tag{5}$$

where y is mortality in probit units, c is the reciprocal of the probit slope, and P_{sw} is the square-wave (or long-duration) overpressure resulting in 50 percent mortality. Note that the form of Equation (5) results from the usual assumption that the probit of mortality is proportional to the logarithm of overpressure for a given duration (cf Reference 17).

The equation used in the regression analysis was derived from Equations (5) and (1).

$$P = P_{sw} e^{c(y-5)} (1 + a T^{-b}) \tag{6}$$

where P and T are scaled experimental overpressure and duration defined by Equations (4) and (3), respectively. Initial estimates were made for a, b, and c, applicable to all species, and a P_{sw} value for each of the 13 species. By varying the estimates in repeated trials, it was possible to determine parameter values which yielded a minimum value of chi-square as defined by Finney.[12] Examination of the chi-square value so obtained showed that Equation (6) did not adequately represent the data, the probability being approximately 0.62 percent that the deviations noted were due to chance. A detailed examination showed that the guinea-pig data were the largest contributors to the large chi-square value. When these data were dropped and the process repeated, the chi-square test indicated an acceptable probability of 25 percent that the scatter was due to chance.

Values of the constants a and b from the latter analysis are 6.76 and 1.064, respectively. Although the other parameters were also evaluated, it was decided to re-evaluate them with the usual parallel-probit analysis[12] making use of the already evaluated a and b and the concept of equivalent square-wave overpressure defined in Equation (1):

$$P^{*} = P / (1 + 6.76\, T^{-1.064}). \tag{7}$$

Using the data for all species except the guinea pig, the parallel-probit analysis gave a value for c (reciprocal probit slope) of 0.1788. The F-test used to test for parallelism indicated that the probability of scatter as great as that noted was 35 percent, provided the true probit lines were parallel.

This analysis also produced P_{sw} values, defined in Equation (5), for each mammalian species. The chi-square test indicated that the parallel-probit analysis was sound since the probability was 15 percent that the observed scatter in the data was due to chance.* Individually, the chi-square probabilities ranged from 8.4 percent for the mouse to 92.6 percent for the cat, all acceptable at the five percent level.

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* The previous minimum chi-square analysis yielded a probability of 25 percent. The reason for this apparent discrepancy is that the probit analysis is based on maximum likelihood, although chi square is used to test the fit relative to the data.[12]

Results of the parallel-probit analysis are illustrated in Figure 1 for the sheep. For comparison, the results of an individual probit analysis are also shown on the same chart. The parallel analysis resulted in narrower confidence bands in the lower and higher mortality regions. Note that the high-explosive point plotted at 16.7 percent mortality, representing the data for Group 128 (Table 1), is in good agreement with the derived probit lines. As mentioned in Section 2, data for 9 of the 12 sheep in this group were obtained without a reflecting surface.

The results of a probit analysis for the guinea pig alone are plotted in Figure 2. Note that the composite slope for the other species, shown for comparison, is considerably flatter than that for the guinea pig. The value of c (reciprocal slope) found for the guinea pig (0.08499) was significantly different from that for the other species (0.1788) at the 99.9 percent confidence level. The chi-square test for the guinea-pig analysis indicated a probability of only 1.3 percent that the observed deviations were due to chance. The reason for these anomalous results is not known at this time.

The square-wave overpressures resulting in 50 percent mortality, P_{sw}'s, evaluated in the parallel-probit analysis for 12 mammalian species can be considered to be indices of blast tolerance which are independent of body mass. The 13 species (including the guinea pig) were divided into two groups according to their blast tolerances as indicated by the P_{sw} values. These values, listed in Figure 3, ranged from 50.0 to 71.9 psi for the high tolerance group consisting of the larger animals and from 30.8 to 36.9 psi for the low tolerance group consisting of the smaller animals.

The survival curves shown in Figure 3 are directly applicable to an ambient pressure of 14.7 psi and to a mammal with a body mass of 70 kg and a P_{sw} blast tolerance of 61.5 psi, the geometric mean of those for the large species. Note that the equation given in the figure is of the same form as Equation (6) except that the mortality probit, y, was replaced with the survival probit, z, (y-5) being the same as (5-z).

The overall analysis, results of which were used to plot the curves in Figure 3, was made with the data for the individual groups listed in Table 1. The observed survival rates for these groups cannot easily be compared with the derived curves in Figure 3 since the curves are specifically applicable to only five levels of survival. To make comparison easier, 50-percent survival overpressures, P_{50}'s, were evaluated by the usual parallel-probit analysis for each set of groups in each species array with approximately the same durations; i.e., the same explosive charge weight or the same shock-tube arrangement. These points were plotted in Figure 3 using the overpressure and duration scaling indicated on the coordinates of the chart except that p_r was replaced by P_{50} and t_+ by the geometric mean of the experimental durations.

Note that the overpressure scaling mentioned above contains a factor, $61.5/P_{sw}$, which accounts for differences in species tolerances making it possible to compare all points to the 50 percent survival curve. This comparison indicates that the points generally scatter about the curve with no definite trend discernible. Because of the increased influence of duration inaccuracies, the short-duration points are scattered more than the long-duration ones. The short-duration shock-tube points tend to be relatively lower than the adjacent long-duration high-explosive points. This could be caused by a difference in the shapes of blast waves generated by the two sources, the shock-tube waves having a larger impulse for a given overpressure and duration.

Guinea-pig data are plotted in Figure 3 for purposes of comparison even though they were not used in the overall analysis. Note that the four guinea-pig points are in good agreement with the 50-percent survival curve although the probit slopes, reflected in the separation of the survival curves, were shown to be significantly different.

4.0 ESTIMATE OF MAN'S TOLERANCE

To which of the blast-tolerance groups formed by the experimental animals is man likely to belong? Previous estimates place him in the high-tolerance group.[1, 2, 9, 13, 16, 18, 20, 26, 27] Assuming that man is a member of this group but lacking further evidence, his tolerance was arbitrarily but tentatively taken to be the geometric mean of those for the members of this group; i.e., P_{sw} = 61.5 psi (see Figure 3).

Examination of the species tolerance indices, P_{sw}'s, in relation to certain lung parameters lends credence to the assumption stated above. The lung volume and mass data reported by Crosfill and Widdicombe[5] were found to be useful for this purpose since data were obtained with the same experimental techniques for seven of the species used in the present study. These authors also reported similar data for man, obtained, however, by different techniques.

These data are shown in Figure 4 as plots of P_{sw} versus both average lung density and average lung volume per unit body mass for the mouse, rat, guinea pig, rabbit, cat, dog, monkey, and man. Although a satisfactory explanation for the apparent correlations has not been formulated at this time, these plots indicate an undeniable tendency for blast tolerance to decrease with increasing lung density and to increase with increasing normalized lung volume.

The survival data presented in Figure 3 are strictly applicable to situations where the thorax of the subject is near a flat surface against which a sharp-rising blast wave reflects at normal incidence, the blast parameters being measured at the reflecting surface. However, some experimental data[17, 18, 29] obtained with guinea pigs and sheep suggest methods for relating exposures near a reflecting surface to certain types of exposures in the free stream, the blast parameters in the latter case being measured in the vicinity of the thorax. Even though the supporting data are meager, the rationale of the resulting criteria seems reasonable. The first criterion, applying to free-stream exposures where the long axis of the body is aligned with the direction of propagation of the blast wave (Figure 5), is that approximately equivalent damage will result if the incident (side-on) overpressure in the free-stream case is the same as the reflected pressure in the instance of a reflecting surface. The second criterion, applying to exposure where the long axis of the body is perpendicular to the blast winds (Figure 6), is that the biological response will be about the same as with a reflecting surface provided that the incident overpressure plus the dynamic pressure for the free-stream exposure is the same as the reflected pressure when a reflecting surface is present. Both criteria are applicable to fast-rising free-stream and reflected blast waves of the same duration.

The criteria for the two free-stream situations described above are plotted in Figs. 5 and 6 in terms of the incident overpressure and duration. It should be noted that these charts are applicable to 14.7-psi ambient pressure and to a 70-kg mammal whose P_{sw} blast tolerance is 61.5 psi, assumed to be man. Scaling to situations involving different ambient pressures, body masses, or blast tolerances can be accomplished with procedures similar to those indicated in Figure 3. Also shown on these charts are curves for threshold lung damage. The criterion[17,18] used in computing these curves is that for a given duration lung damage begins to occur at one-fifth the 50-percent survival overpressure.

The curves presented in Figure 7 are the same as those in Figure 3 for the reflecting situation except that incident instead of reflected overpressure is plotted on the ordinate. Also a curve for threshold lung damage was added.

To make the survival curves predicted for man (Figures 5, 6, and 7) more readily usable, the data were interpreted in terms of surface bursts of TNT as shown in Figures 8, 9, and 10. Pentolite data compiled by Goodman[14] were used assuming that 1.0 lb of Pentolite is equivalent to 1.1 lb of TNT and that the ground reflection factor is 1.8. The ordinates on the right side of these charts indicate the nuclear yields producing approximately the same blast waves as those produced by the corresponding TNT charges.

The curves in Figure 8 are applicable to free-stream situations where the long axis of the body is directed toward the explosive charge. Threshold lung damage is predicted for a 1-lb charge placed about 2 ft from the thorax; however, with this orientation the head or legs would be much nearer the charge and would undoubtedly receive severe damage. This obvious limitation in the applicability of the survival curves is obscured in Figure 5 where the same data are plotted in terms of overpressure and duration.

5.0 DISCUSSION

In a previous study[1] man's tolerance to air-blast overpressures was estimated making use of most of the data used in the present study for the large species. At that time, however, data were not available for scaled durations of less than 2 msec. The present overpressure estimates compared to the previous ones are 0 to 19 percent lower for durations between 2 and 2.9 msec, 0 to 17 percent higher for durations between 2.9 and 100 msec, and less than 3.1 percent higher for durations greater than 100 msec. In the previous study, the maximum overpressures obtained in the high explosive experiments with the dog and goat were not adjusted to account for the position of the gauge being 3/4 inch above the concrete pad. That this was done in the present study probably accounts for the tolerance estimates for the immediate durations being somewhat higher than those presented previously (see Section 2).

The gross response of the thorax to air blast has been described as an implosion process.[28] Measured and computed intrathoracic overpressures[1,2] suggest that the chest wall is accelerated inward during the first phase of the blast experience, the momentum so gained being dissipated as high gaseous pressures build up in the lungs due to volume reduction.* The intrathoracic pressure records indicate that subsequent oscillations are highly damped. What characteristics other than size make one mammalian species respond differently from another to the blast experience? A model study[1] indicated that increases in the mass or area of the rib cage enhance the response to long duration waves while increases in lung volume or damping factor (tissue and air resistance) depress the response. The same study suggested that changes in the effective area of the airways or the stiffness of the rib cage has little effect on the total response.

The comparative data presented in Figure 4 are consistent with the above predictions in that the species with the larger lung volumes relative to body mass tend to have higher blast tolerance. The same chart also suggests that average lung density may in some way affect blast tolerance, the species with the lower densities having the higher tolerances. It is questionable whether this is a causal or a casual relationship. Further studies will undoubtedly not only reveal other significant factors affecting blast tolerance but also will demonstrate their interrelationships.

An interesting and somewhat surprising result of this study is that, for the available experimental data, body mass was the only animal parameter necessary to relate the species air-blast response times to each other; i.e., duration scaling was stated in terms of body mass and not, for example, of lung volume and body mass. From theoretical considerations[1,2] animals of the same body mass but different lung volumes should have different response times, the one with the smaller volume responding faster. However, as illustrated in Figure 4, animals with the smaller lung volumes have lower blast tolerances. Because the air contained in the lungs acts as a non-linear spring, the magnitude of the blast load also influences the response time—the smaller the blast load the longer the response time.[1] Thus, because of these opposing effects, it may be that the animals with the relatively small lungs had about the same scaled (by body mass) response times as those whose lungs are larger in relation to their body masses.

The experiments with the sheep exposed to the 1-lb explosive charges (see Section 2) deserve further comment. For the suspended animals in Group 128, the charge was placed 1.17 and 2.25 ft from the nearest and most distant surface of the thorax, respectively. The scaled incident overpressure at the near surface is 647 psi with an associated peak dynamic pressure of 1430 psi, resulting in a total load of 2077 psi according to the overpressure-plus-dynamic-pressure concept presented in Section 4. Thus, the total pressure on the near surface was considerably greater than 1260 psi which would have been the reflected overpressure had a flat surface been placed against the animal opposite the charge. It should be mentioned that the initial loading of the near surface was actually greater than 2077 psi because of partial reflection of the incident wave against the thorax, this enduring until flow was established around the animal.

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* The time required for this process is called "response time."

The preceding paragraph helps to explain why the absence of a reflecting surface did not influence mortality when the sheep were exposed to relatively high overpressures of short duration. However, additional comment should be made in regard to the localized lung damage observed subjacent to the thoracic cage nearest the charge.

First, it is necessary to consider the velocity of sound within the lungs. Clemedson and Jönsson[3] measured the propagation velocities of pressure pulses in excised and inflated rabbit and calf lungs. Their experimental velocities, ranging from 15 to 30 m/sec, are in good agreement with simple theory for sound propagation in bubbly solutions of air and water (see, e.g., Reference 11) assuming that lung tissues have physical properties similar to those of water. These remarkably low propagation velocities in the lungs can be thought of as resulting from the tissue-air continuum's having a relatively large compressibility and density owing to the presence of air and tissue, respectively.

From the foregoing, it seems reasonable that a localized load of high intensity and short duration would accelerate a portion of the thoracic cage to velocities exceeding that of sound within the lungs. Thus, much of the impact energy would be absorbed locally before it could be propagated as a pressure wave to more distant portions of the lungs. The usual fast-rising shocks by which energy is efficiently transported in water alone are not observed in water-air mixtures, particularly when the bubbles are as small as alveoli; i.e., about 0.25 to 0.3 mm in diameter.[25] One reason for this is effective energy dissipation because during oscillation more heat is conducted from the compressed air bubble to the water heat sink than returns to the bubble during expansion.[10, 15] A significant difference, however, between bubbly water and the air-containing lungs is that tissue, not being liquid, would tend to tear and rupture upon distortion whereas the water would not.

The experimental blast parameters used in this study are those occurring at a reflecting surface located near the thorax. The overpressures measured at this location, however, were not necessarily the significant ones in producing damage to the thorax. This has been pointed out for the case of the sheep exposed to blast waves of high overpressure and short duration produced by 1-lb charges. Because of the rapid decay of these short-duration waves, the most severe load was felt by the thoracic surface nearest the charge, the average load for the entire thorax being somewhat less. It should be mentioned that the spatial length of these blast waves was of the same order as the width of the animal; thus, for the experiments where a reflecting surface was present, the full dynamic pressure impulse could be felt by the leading thoracic surface before the reflected wave could return to neutralize it.

The blast waves which were temporally and spatially longer than those discussed above did not decay as rapidly with distance. Thus, with increasing duration the maximum load occurred on those portions of the thoracic cage nearest the reflecting surface, the average load being somewhat less.

The blast waves of still longer durations experienced negligible decay while engulfing the animal, first with the incident overpressure (plus the dynamic pressure on the leading surface) and then with the reflected overpressure. This loading was probably more uniform than those occurring with any of the waves of shorter duration; however, due to step-wise loading, the lung more distant from the end-plate generally received a little less damage than the other.[21]

In summary, the blast loads measured by the pressure gauges compared to the effective, or average, loads on the thorax were low, high, and about the same for exposure to short-, intermediate-, and long-duration blast waves, respectively. These observations are in general agreement with a previously published[1] criterion for primary blast damage based on overpressure impulse occurring within a critical time; i.e., according to this criterion the 50-percent survival curve in Figure 3 is (a) 0- to 30-percent low for durations less than 2.8 msec, (b) 0- to 15-percent high for durations between 2.8 and 100 msec, and (c) correct to within one percent for durations greater than 100 msec.

The rationale of the "partial" impulse criterion mentioned above is that the response time (called critical time) of a mammal to shocked blast waves depends principally on body mass and that the impulse felt by the thoracic wall within the critical time determines the magnitude of the initial response which, for exposures to classical waves, is also the greatest. Thus, this simplified concept is based on the effective load on the thorax which is not necessarily that registered by a pressure gauge.

TABLE 1. MORTALITY DATA FOR ANIMALS EXPOSED NEAR A REFLECTING SURFACE TO AIR BLAST

(Ambient Pressure: 12 psi)

N: group number

m: animal mass, kg.

W: charge weight, lb. (1/32 lb., RDX; 1/4 lb., Comp. B; 1, 8, and 64 lb., TNT except where noted). ST indicates shock tube.

p_r: maximum reflected overpressure, psi. Overpressures which were measured 3/4 inch above the reflecting surface are in parentheses. Adjacent values are overpressures occurring at the reflecting surface (see text).

t: duration of the positive overpressure phase, msec, measured for the shock tube experiments and scaled for the high explosive experiments (see text).

R: ratio of animals dying within 24 hours to those exposed.

Species	N	m	W	p_r	t	R	Ref.
Mouse	1	.0238	1/32	(27.7) 44.8	0.441	7/32	19
	2			(32.9) 55.8	0.403	26/48	
	3			(37.9) 67.0	0.375	27/34	
	4			(41.8) 76.1	0.356	17/20	
	5	.0238	1/4	(27.4) 36.9	0.951	3/10	19
	6			(30.0) 40.9	0.913	10/20	
	7			(39.2) 54.8	0.813	19/20	
	8	.0238	1	(21.0) 24.5	1.72	1/20	19
	9			(24.0) 28.6	1.64	4/20	
	10			(27.3) 33.4	1.56	38/60	
	11			(28.5) 35.0	1.54	18/20	
	12	.0207	ST	19.2	354	2/40	19
	13			21.6	354	8/40	
	14			26.4	354	17/40	
	15			30.0	354	34/40	
	16			32.9	354	32/40	
Hamster	17	.089	ST	25.2	354	2/20	17
	18			27.2	354	12/30	
	19			31.4	354	23/30	
	20			33.4	354	26/30	

TABLE 1. (Contd.)

Species	N	m	W	P_r	t	R	Ref.
Rat	21	.200	1/32	(53.1) 103.5	0.310	3/13	19
	22			(65.8) 135.3	0.274	5/12	
	23			(74.1) 157.0	0.256	8/13	
	24	.200	1/4	(39.4) 55.1	0.813	3/20	19
	25			(44.0) 62.1	0.775	7/20	
	26			(46.6) 66.1	0.756	5/10	
	27			(48.5) 69.1	0.740	7/10	
	28	.200	1	(34.2) 42.5	1.43	3/20	19
	29			(42.5) 53.5	1.31	19/30	
	30			(52.7) 67.1	1.19	26/30	
	31	.200	8	(33.2) 38.0	3.00	4/20	19
	32			(37.6) 43.3	2.85	8/10	
	33			(38.0) 43.8	2.84	7/10	
	34	.200	ST	27.0	354	6/40	17
	35			31.4	354	21/40	
	36			32.6	354	28/40	
	37			35.0	354	29/30	
Guinea Pig	38	.547	1/4	(45.6) 64.6	0.762	3/12	19
	39			(47.8) 68.1	0.743	4/8	
	40			(58.8) 84.9	0.674	13/15	
	41	.547	1	(29.1) 35.8	1.52	0/10	19
	42			(34.8) 43.3	1.42	1/10	
	43			(39.8) 49.9	1.35	30/40	
	44	.547	8	(32.2) 36.8	3.01	21/42	19
	45			(34.1) 39.0	2.95	17/20	
	46			(36.0) 41.4	2.88	18/20	
	47	.655	ST	21.0	354	0/30	17
	48			24.3	354	5/30	
	49			25.4	354	13/30	
	50			27.5	354	28/30	
Rabbit	51	1.90	1/4	(63.9) 92.4	0.662	3/9	19
	52	1.90	1	(64.4) 82.5	1.09	2/4	19
	53			(70.0) 89.8	1.05	3/4	
	54			(77.6) 99.1	1.00	9/10	
	55			(50.9) 64.8	1.20	6/14	
	56			(55.0) 70.1	1.17	4/8	
	57			(62.5) 80.0	1.10	8/9	
	58	1.90	8	(32.2) 36.8	3.02	1/10	19
	59			(34.3) 39.3	2.94	2/10	

TABLE 1. (Contd.)

Species	N	m	W	P_r	t	R	Ref.
Rabbit, (contd.)	60	1.90	8	(37.6) 43.3	2.84	18/40	19
	61			(40.4) 46.7	2.74	7/10	
	62	1.90	64	(29.3) 31.6	6.36	0/8	19
	63			(35.5) 38.8	5.92	4/8	
	64			(36.3) 39.8	5.84	16/20	
	65	3.7	ST	19.2	354	0/8	17
	66			21.8	354	1/8	
	67			22.6	354	3/8	
	68			25.7	354	6/8	
	69			32.5	354	7/8	
Cat	70	2.88	ST	34.0	380	0/8	17
	71	2.58		36.6	372	1/8	
	72	2.26		40.6	360	3/8	
	73	1.98		43.9	374	4/8	
	74	2.61		46.8	358	5/8	
	75	2.55		49.8	376	7/8	
Monkey (Stump Tail)	76	5.8	64	103.5	3.94	1/4	18
	77	6.0		111.8	3.80	2/4	
	78	5.4		139.0	3.44	4/4	
	79	5.1	ST	47.3	106	0/3	21
	80	5.4		55.3	123	3/5	
	81	5.6		61.1	118	3/4	
	82	4.5		70.8	118	1/1	
Dog	83	17.6	8	(109) 122	1.82	1/8	17
	84	13.7		(202) 229	1.34	7/9	
	85	14.4		(240) 275	1.22	9/12	
	86	15.3	64	(73.0) 79.0	4.44	1/11	17
	87	16.8		(81.9) 87.7	4.24	2/6	
	88	15.4		(88.8) 94.3	4.08	3/6	
	89	17.0		(95.6) 100	4.00	4/6	
	90	18.3	ST	59.5	15.8	5/9	17
	91	16.8		53.3	15.2	5/9	
	92	16.4		50.0	14.0	2/9	
	93	16.5		43.4	14.3	1/9	
	94	18.3		54.5	20.5	4/5	
	95	18.6		51.4	20.8	4/6	
	96	17.2		48.8	22.6	2/4	
	97	19.7		40.8	21.6	1/5	
	98	18.4		38.1	20.2	1/8	
	99	18.0		46.2	33.6	4/10	

TABLE 1. (Contd.)

Species	N	m	W	P_r	τ	R	Ref.
Dog (contd.)	100	15.9	ST	59.4	55.0	1/1	17
	101	16.1		48.7	55.6	3/7	
	102	16.6		43.4	52.6	1/9	
	103	17.2		38.2	53.8	0/4	
	104	16.3	ST	50.7	80.0	2/3	17
	105	18.7		47.3	80.3	2/6	
	106	18.1		42.5	78.0	1/7	
	107	14.5	ST	53.0	400	9/10	17
	108	15.4		48.1	400	6/10	
	109	15.2		44.1	400	1/10	
	110	15.3		39.2	400	0/5	
Goat	111	24.7	8	(256) 295	1.18	6/12	17
	112	26.3	64	(98.7) 104	3.92	1/5	17
	113	20.8		(106.1) 111	3.80	3/5	
	114	21.1		(111.9) 118	3.72	3/5	
	115	25.0	ST	68.2	17.6	5/5	17
	116	22.9		62.6	17.4	5/6	
	117	22.8		57.6	17.2	2/4	
	118	22.0		54.2	16.0	1/5	
	119	21.1	ST	60.8	39.6	6/7	17
	120	21.5		58.6	38.0	5/7	
	121	21.2		55.4	39.8	4/8	
	122	23.1		47.6	37.5	1/6	
	123	20.1	ST	52.2	62.0	3/10	17
	124	20.3	ST	59.3	400	4/5	17
	125	16.8		56.9	400	3/5	
	126	20.3		51.4	400	4/10	
	127	22.5		44.9	400	2/10	
Sheep	128	52.6	1*	126[illegible]	0.288	2/12	21
	129			1680	0.246	3/3	
	130			1330	0.308	2/5	
	131			963	0.369	0/2	
	132			571	0.490	0/3	
	133	49.9	8	440	0.962	1/4	21
	134	54.0	64	113	3.78	0/12	18
	135	55.3		138	3.45	0/24	
	136	51.6	64	159	3.22	27/57	18
	137	59.2		197	2.90	4/8	

* 1 lb Pentolite.

TABLE 1. (Contd.)

Species	N	m	W	p_z	t	R	Ref.
Sheep, (contd.)	138	51.8		234	2.65	4/4	18
	139	48.9	ST	47.2	216	0/5	18
	140	54.3		49.6	211	2/10	
	141	53.1		52.0	212	3/10	
	142	54.8		54.1	210	6/10	
	143	53.8		57.0	212	3/4	
Swine	144	55.6	64	157	3.24	[illegible]/16	18
Burro	145	156	64	180	3.03	0/2	21
	146	167		199	2.88	0/2	
	147	202		203	2.84	0/1	
	148	179		337	2.21	1/1	
Steer	149	181	ST	37.6	161	0/4	7
	150	176		42.6	184	5/10	
	151	175		44.9	176	3/5	
	152	183		46.8	195	5/6	
	153	200		49.6	215	2/2	

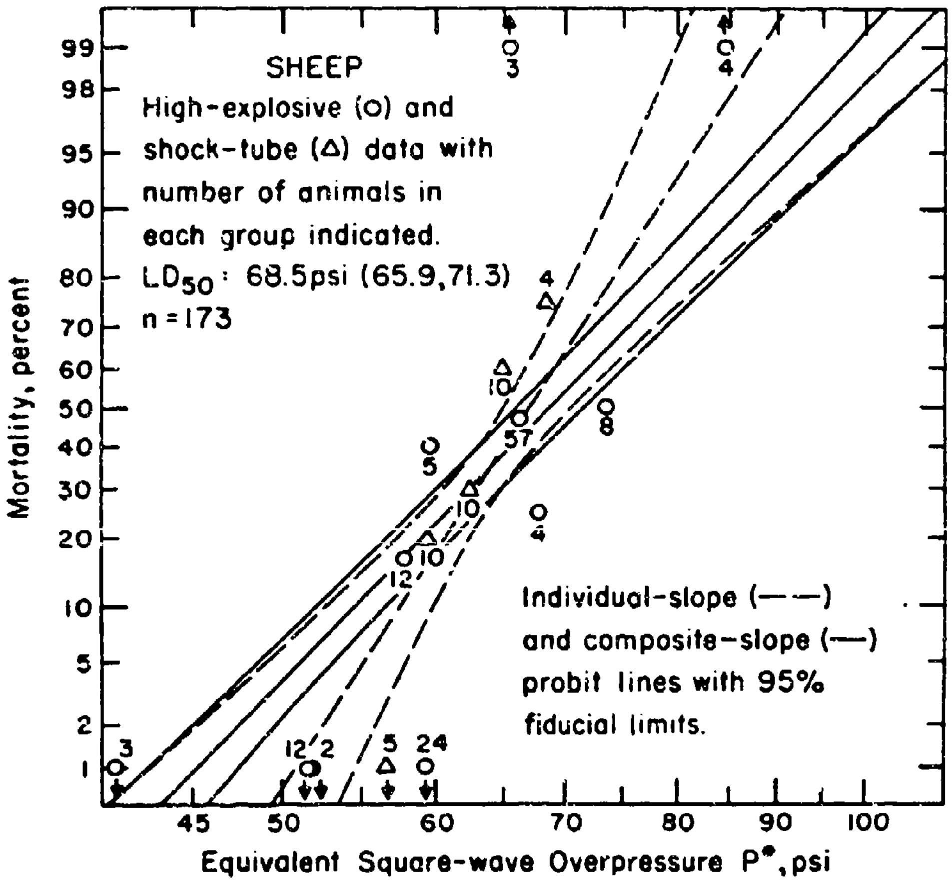


Figure 1 Results of the parallel-probit analysis for the sheep in terms of equivalent square-wave overpressure, defined in Equation 7. Results of an individual analysis for the sheep are shown for comparison.

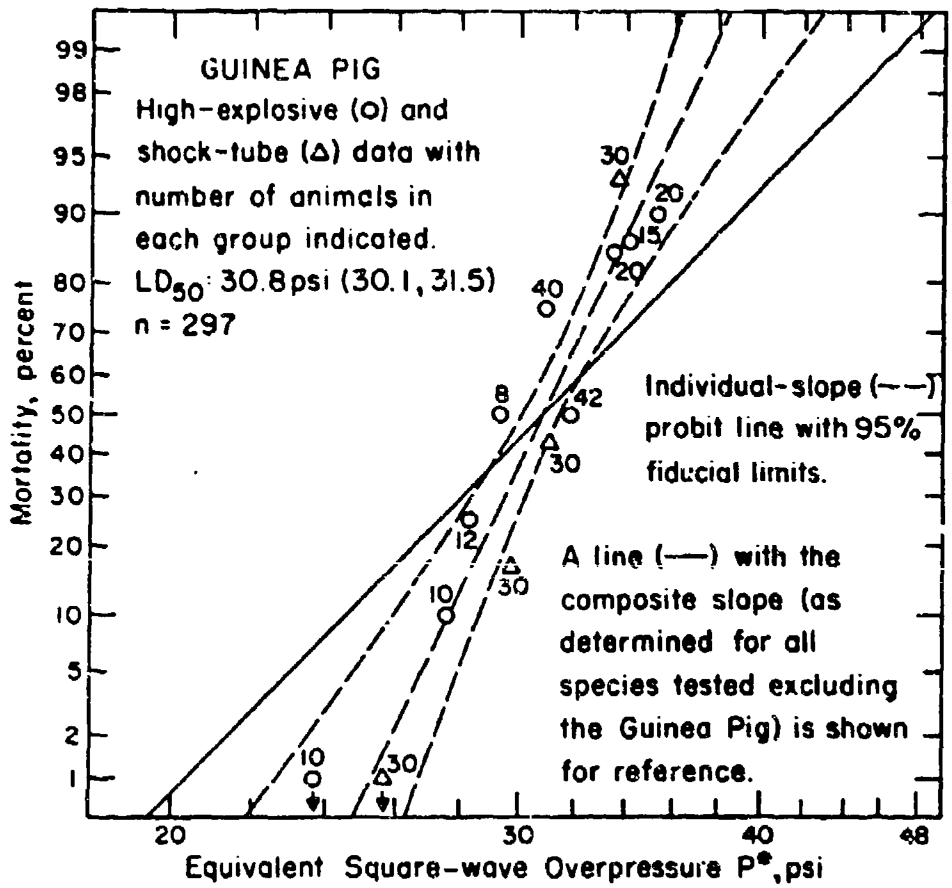


Figure 2 Results of the probit analysis for the guinea pig in terms of equivalent square-wave overpressure, defined in Equation 7. The composite slope from the parallel-probit analysis for the other 12 species is shown for comparison.

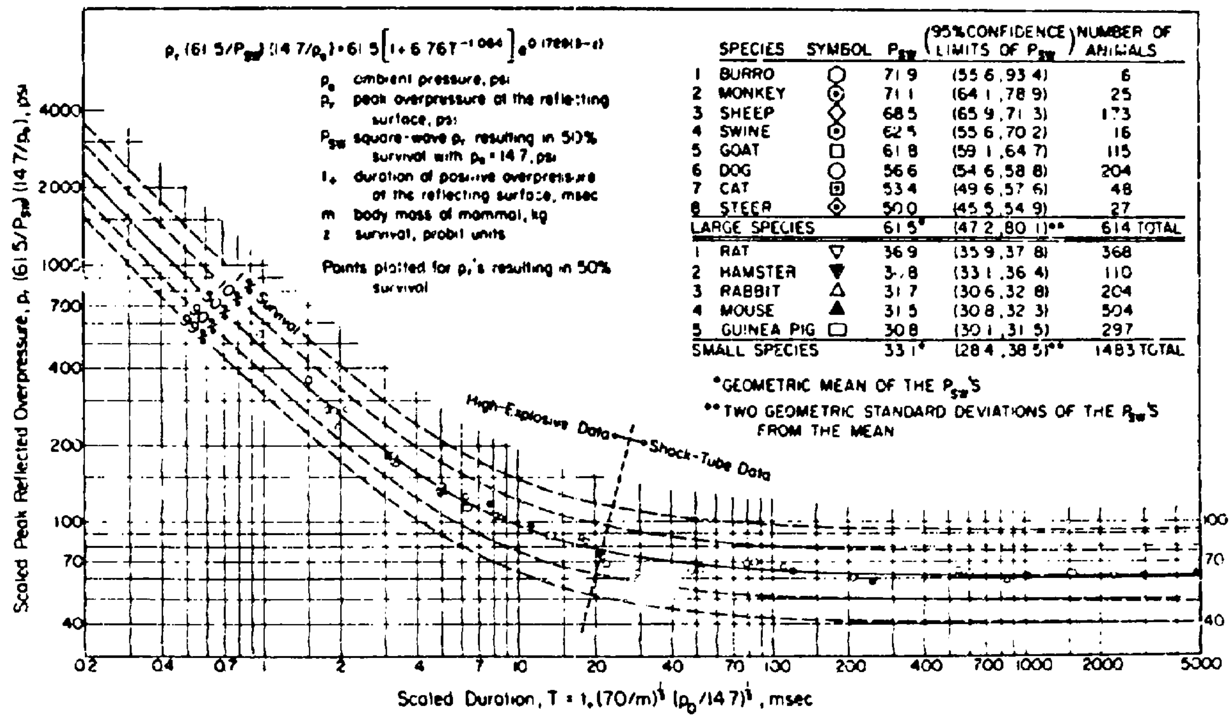
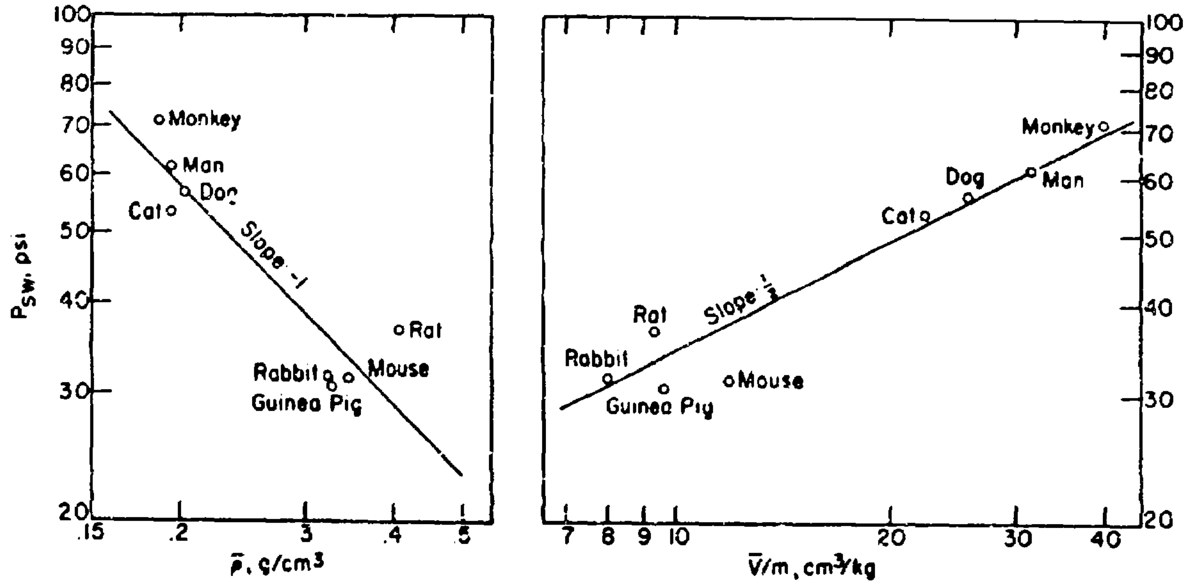


Figure 3 Survival curves, (24-hour) applicable to sharp-rising blast waves, derived from the analysis of data for 12 mammalian species (excluding guinea pig). See text for explanation of plotted points.



P_{sw}: square-wave overpressure resulting in 50% survival, see Figure 3

$\bar{\rho}$: avg density of lungs $= M/(\bar{V}+v)$

M: mass of lungs

$\bar{V}$: avg gaseous volume of lungs $= FRC + \frac{1}{2}TV$

FRC: functional residual capacity

TV: tidal volume

v: volume of lung tissue

m: body mass

Figure 4 Square-wave overpressure resulting in 50-percent survival (P_{sw}) as functions of average lung density and average lung volume per unit body mass for eight mammalian species. Lung data from Reference 6.

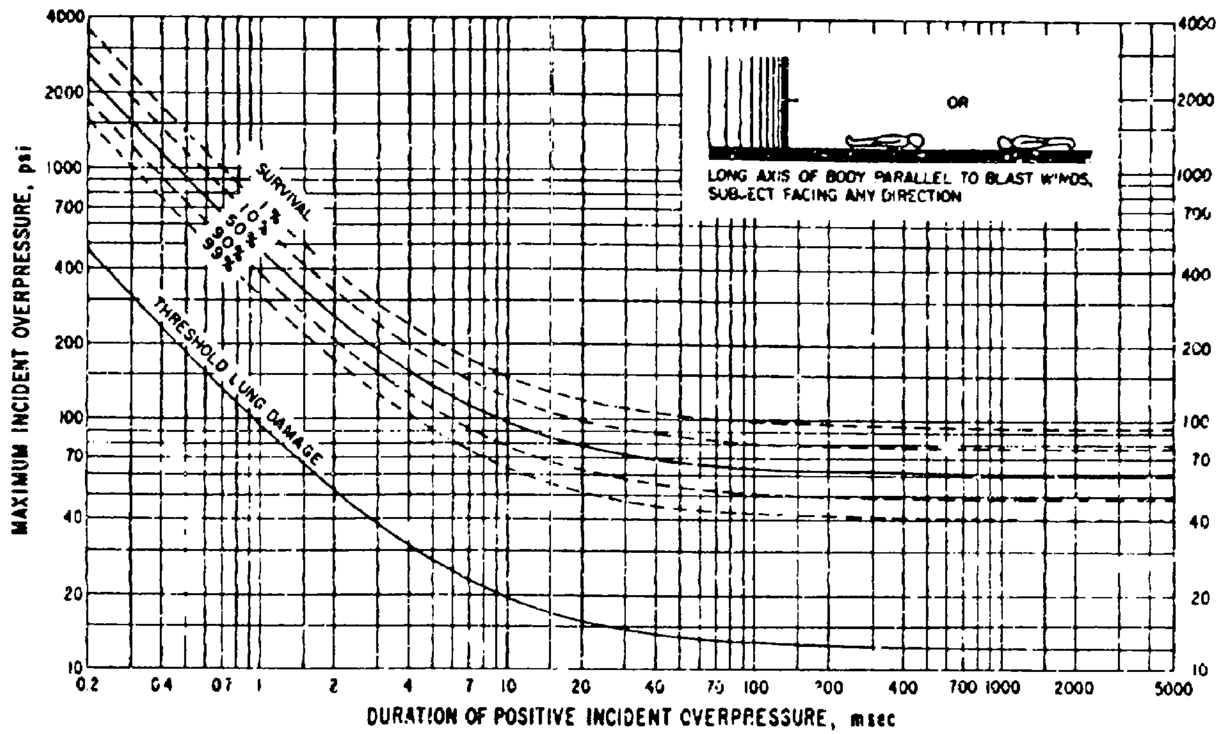


Figure 5 Survival curves predicted for 70-kg man applicable to free-stream situations where the long axis of the body is parallel to the direction of propagation of the shocked blast wave.

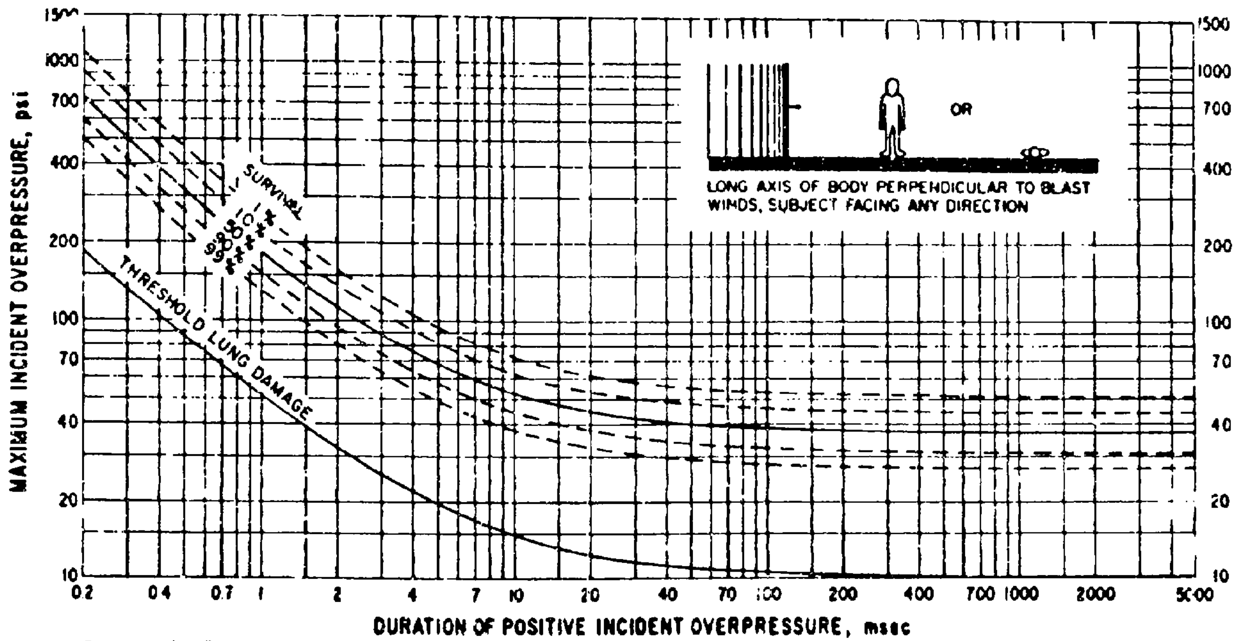


Figure 6 Survival curves predicted for 70-kg man applicable to free-stream situations where the long axis of the body is perpendicular to the direction of propagation of the shocked blast wave.

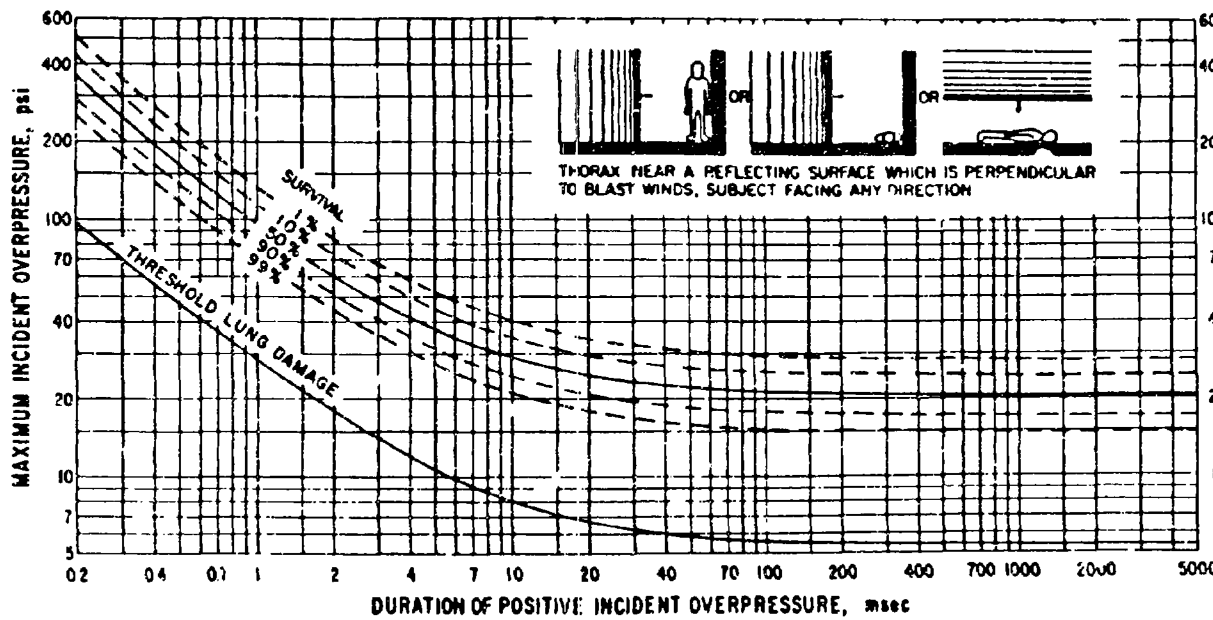


Figure 7 Survival curves predicted for 70-kg man applicable to blast situations where the thorax is near a surface against which a shocked blast wave reflects at normal incidence.

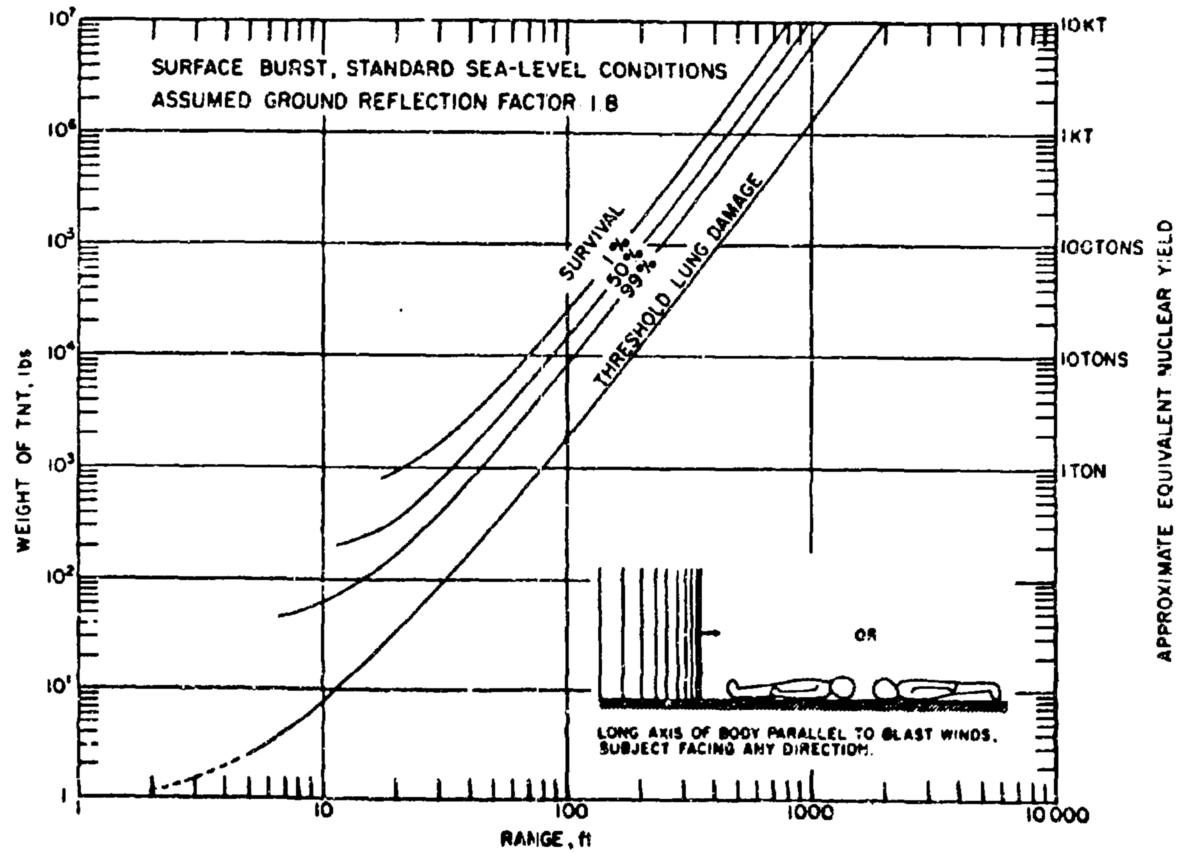


Figure 8 Predicted survival curves for man exposed in the free stream to surface bursts of TNT where the long axis of the body is parallel to the blast winds.

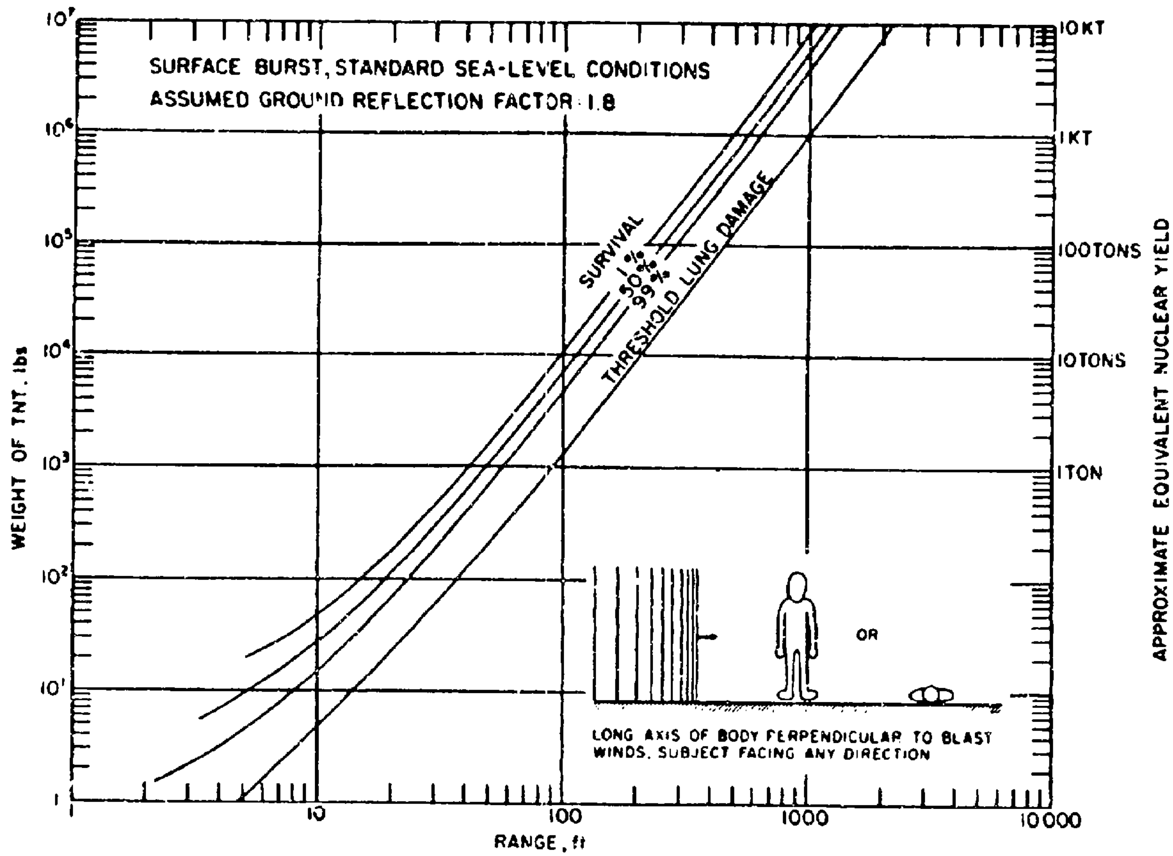


Figure 9 Predicted survival curves for man exposed in the free stream to surface bursts of TNT where the long axis of the body is perpendicular to the blast winds.

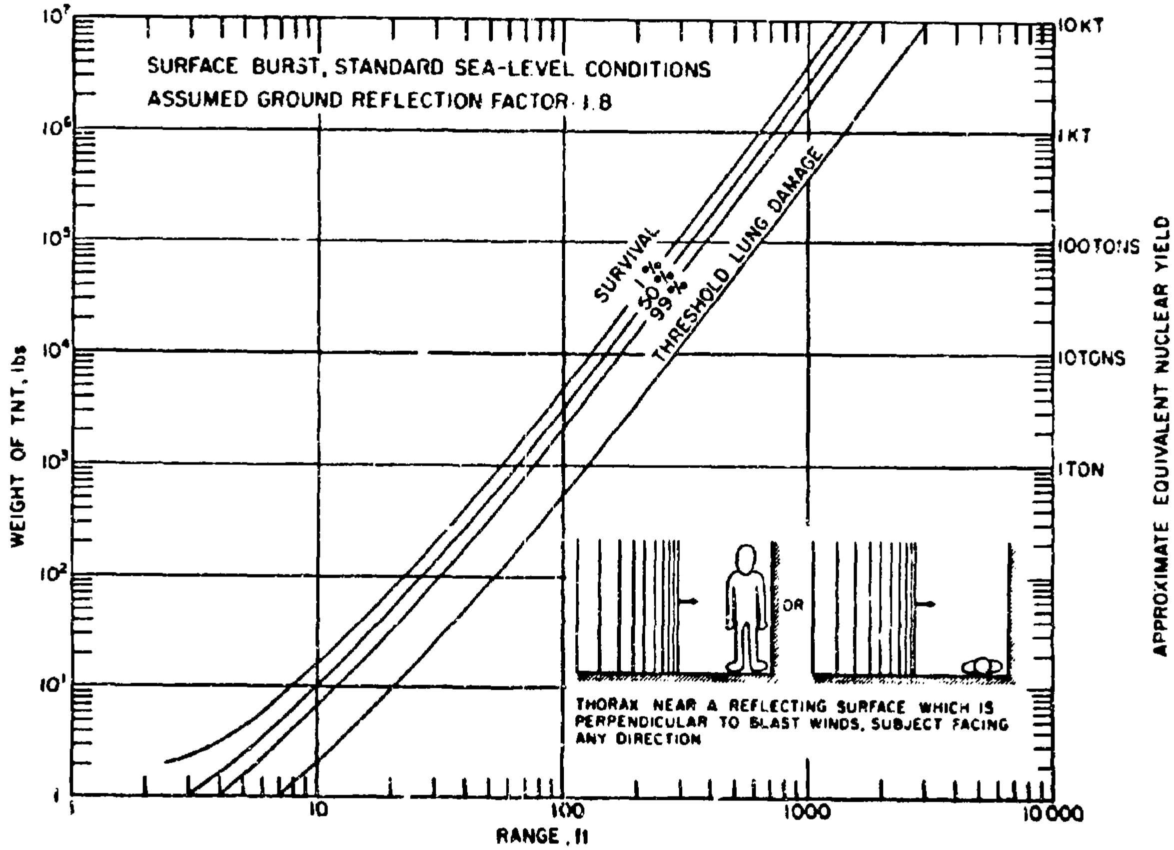


Figure 10 Predicted survival curves for man exposed to surface bursts of TNT where the thorax is near a flat rigid surface reflecting the blast wave at normal incidence.

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13. ABSTRACT

Tolerance indices were determined, allowing for the effects of body mass, for thirteen mammalian species using the results of experiments in which animals were exposed near a normally reflecting surface to shocked blast waves whose durations ranged from 0.21 to 100 msec. A general equation was developed for expressing the interrelations between overpressure, duration of the blast wave, body mass, and probability of survival. The species were divided into high- and low-tolerance groups applicable to "large" and "small" mammals, respectively. Since the available evidence indicated that man is more likely to be a member of the high-tolerance group, the tolerance index arbitrarily, but tentatively, assigned to him was the geometric mean of those for the large species. Using criteria developed in experimental studies, the results of the overall analysis were made applicable to free-stream situations in which the long axis of the body is perpendicular or parallel to the direction of propagation of a shocked blast wave.

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