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BLAST PHENOMENA FROM EXPLOSIONS  
AT THE WATER SURFACE

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Introduction

The principal objective of this study was to evaluate the blast and shock phenomena (in air and underwater) resulting from a pure surface explosion (i.e. the situation where the charge is half in and half out of the water).

The particular case of an explosion at an air-liquid (water, in most cases) interface is considered in this paper because this case is easier to handle both analytically and experimentally than an explosion at an air-solid interface, and thus permits one to compare more readily analytical and experimental results. Moreover, it should be noted that solids under sufficiently strong impulsive loads are known to behave much as liquids. The general results of the air-liquid interface case can be utilized for any air-solid case by substituting the appropriate material constants to represent the liquid properties of the solid under consideration. The problem of predicting surface burst phenomena involves particular difficulties when compared with the so-called free-space cases in which the explosion occurs entirely within a given surrounding medium. The most serious difficulty arises from the fact that the general characteristics of the shock waves vary depending on the nature or the type of the explosion, since the majority of the features of the shock waves are controlled by the initial stages, where the characteristics of the individual explosion predominate. This situation makes it difficult to establish any simple scaling rule independent of the individual nature of the explosives used. For this reason it is usually difficult to deduce anything of a general nature from the results of individual tests or step-by-step numerical solutions starting from specified initial input conditions. A less serious difficulty is found in the magnitude of the density ratio of the two interface media involved. Although this ratio for air to water is much less than 1, it is not small enough to warrant neglecting it. Thus, the motions in the different media cannot be treated separately, as in the case of air to ground.

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Aside from existing literature on the air-ground cases, only a few previous studies on the air-water case are available for either experimental or theoretical investigations (references 1 through 9). All these data are based on rather small chemical explosions, and the relation of these results to nuclear burst cases is very uncertain, especially for this particular configuration (i.e. a spherical charge half submerged in water).

This situation thus implies a definite need for a thorough study of the problem, especially for nuclear burst cases. It is essential to study the initial and later stages separately, so that the proper approaches can be sought for handling each of these different stages, whose characteristic features are depicted in fig. 1.

As mentioned earlier, there may be no general solution that will represent all the initial stages caused by different kinds of explosions, such as chemical, nuclear, electric spark, etc., so that they must be studied individually. On the other hand, some of the important characteristics of the flow fields in the later stages can be expressed in a general term regardless of the nature of the explosions, mainly because only a small interaction exists between the flow fields in water and those in air regions above the water; thus they can be formulated separately in the following manner. A linear acoustic approximation is used to satisfy the water environment, while a modified free airblast approximation is used to express the flow field in air. This model leads to a set of air and water shock pressure formulas, which contain some unknown parameters and functions to be determined from the characteristics of the initial stages, depending on the type of explosive.

Two different types of initial stages were considered: a point source model of a finite amount of mechanical energy released instantaneously at a point on the interface assuming this to be realistic for the wide varieties of nuclear explosions; and a general chemical explosion of bare, spherical HE.

These two cases were utilized for determination of the unknown parameters and functions appearing in the pressure formulas in the later stages. The pressure values given by the formulas thus obtained for the HE cases were compared with the test data from the explosion of forty 10-pound spherical TNT charges conducted simultaneously with the theoretical investigation. The comparisons of the theoretical values with experimental data and with test data available from charge weights as high as 10,000 pounds show good agreement.

#### Solution of Later Stage

##### General characteristics of the flow based on acoustic theory

Assume here linear acoustic properties throughout the entire space. This assumption is obviously not valid near the explosion source, especially in the air environment. Nevertheless this serves to give an overall insight into the understandings of the problem

which can thus lead to the development of modifications necessary to obtain more realistic solutions.

As illustrated in fig. 2, designate  $p(r,z,t)$  and  $p'(r,z,t)$  as the water and air overpressures at the time  $t$ . Let  $r$  and  $z$  be the cylindrical coordinates;  $p_0$ ,  $\rho_0$ , and  $c_0$  are the pressure, the density, and the sound velocity in the undisturbed water region, and  $\bar{p}_0$ ,  $\bar{\rho}_0$ , and  $\bar{c}_0$  are the corresponding values in air.

General solutions for  $p$  and  $p'$ , expressed in the Laplace-Bessel integral forms, are fitted together at the interface to satisfy the boundary conditions, and then are simplified, by utilizing the small value of the density ratio  $\epsilon^2$  ( $\epsilon^2 \equiv \bar{\rho}_0/\rho_0$ ), to yield

$$p(r,z,t) = \frac{z}{q} F_0 \left( t - \frac{q}{c_0} \right) H \left( t - \frac{q}{c_0} \right) + p_a \quad (1)$$

$$p'(r,z,t) = \frac{1}{q} \bar{p}_0 W_0 \left( t - \frac{q}{\bar{c}_0} \right) H \left( t - \frac{q}{\bar{c}_0} \right) \quad (2)$$

where  $q = \sqrt{r^2 + z^2}$ ,  $F_0$  and  $W_0$  are the input functions related to the singularities of  $p - p'$  and  $\partial/\partial t(v' - v)$  at the center. Here  $v$  and  $v'$  are the  $z$  components of the velocities in the water and air regions, respectively. The input functions  $F_0$  and  $W_0$  are given as

$$\left. \begin{aligned} F_0(t) &\equiv \int_0^\infty (p' - p)_{z=0} r dr \\ W_0(t) &\equiv \int_0^\infty \frac{\partial}{\partial t} (v' - v)_{z=0} r dr \end{aligned} \right\} \quad (3)$$

$H$  is the Heaviside step function, and  $p_a$  represents the term corresponding to the water pressure induced by the air pressure  $p'$  given by Equation 2. Equations 1 and 2 exhibit the following important general characteristics of the flow field. First, the airblast field  $p'$  is represented by a spherical wave from a point source; second, the water shock  $p$  consists of two parts: one caused by a doublet source and the second one,  $p_a$ , induced by the air pressure. While these qualitative descriptions of the flow field are generally true, since they are based primarily on the small value of  $\epsilon$ , it is only necessary to modify Equations 1 and 2 so that the resulting formulas can be used.

#### Modification of the formulas

First, Equation 2 for the air pressure  $p'$  should be replaced by the equivalent free airblast characteristics caused by an explosion in free air with an equivalent charge weight  $W_{ef}$  which is larger than the actual charge weight  $W$ , and the ratio  $\beta$  defined by

$$\beta \equiv \left( \frac{W}{W_{ef}} \right)^{\frac{1}{3}} \quad (4)$$

Here  $\beta$  is a parameter that depends on the nature of the explosion. Second, the airblast field is not exactly in spherical symmetry but should be distorted due to the interaction effect with the water shock field. Since this distortion is rather small, this can be incorporated in the formula by introducing a parameter  $S$ , which will be called the "Skewness factor." With use of these parameters  $\beta$  and  $S$ , the characteristics of the air pressure  $p'$  such as its peak pressure  $P(r,z)$  and its duration  $D(r,z)$  at  $(r,z)$  are determined from the corresponding free-air peak pressure  $P_f(\lambda_e)$  and the duration  $D_f(\lambda_e)$  at an equivalent reduced distance  $\lambda_e$  as

$$P(r,z) = \left( \frac{1 + S \cos \theta}{1 + S} \right)^2 P_f(\lambda_e) \quad (5)$$

$$D(r,z) = \beta D_f(\lambda_e) \quad (6)$$

where  $\tan \theta = \frac{r}{z}$  ( $0 \leq \theta \leq \frac{\pi}{2}$ )

$$\lambda_e = \beta q W^{\frac{1}{3}} \frac{1 + S}{1 + S \cos \theta} \quad (7)$$

Using this airblast pressure on the interface as an input, the air-induced pressure term  $p_a$  can be estimated numerically by utilizing the scheme given in reference 10; here alternatively the following approximation formula is developed by introducing various minor assumptions

$$p_a(r,z,t) = \frac{U_o}{m'_o c_o} \frac{1}{q} \left( \frac{z}{q} \right)^v \bar{\rho}_o W_o (t - \bar{t}) H(t - \bar{t}) \quad (8)$$

where  $U_o$  is the initial airblast velocity,  $m'_o$  is its initial decay rate,  $v$  is a parameter whose value is about 0.1, and  $\bar{t}(\equiv \bar{t}(r,z))$  is the arrival time of the wave at a position  $(r,z)$ . The resulting pressure  $p(r,z,t)$  consists of two waves represented by the two terms in Equation 1 complemented by Equation 8. In principle, the second wave induced by the airblast propagates ahead of the direct wave of the first term. But the difference is very small for most of the cases (is zero for  $r = 0$ ) and can be noticeable only in the region close to the surface, where the pressure-time histories of test data indeed show two peaks. It is also noticed that the first term is proportional to  $z \cdot q^{-3}$  while the second is roughly proportional to  $q^{-1}$ . Thus the pressure is dominated by the second term with increasing distance  $q$ . But the retaining of the first term is indispensable to represent the importance of the direct

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effects near the source. Now, the input functions  $F_o(t)$  and  $W_o(t)$  can be estimated approximately as

$$\left. \begin{aligned} F_o(t) &= \left( P_s R_s - P'_s R'_s \right)_{r=0} \cdot a \\ \bar{p}_o W_o(t) &= \left( m' P'_s - \epsilon^2 m P_s \right)_{r=0} \cdot a \end{aligned} \right\} \quad (9)$$

where  $P_s$  and  $R_s$  are the water shock front pressure and the shock front position,  $P'_s$  and  $R'_s$  are the corresponding values for the air shock front,  $m$  and  $m'$  are the decay rates of the water and air shock velocities, and  $a$  is the effective radius of the spread of these inputs.

Further details of the pressure formulas depend on the nature of an explosion through the determination of those constants and functions introduced above.

#### Initial Stage and Pressure Formulas

##### Bare, spherical chemical explosive

Consider here the case of the spherical chemical explosive whose center is positioned at the water surface. The magnitude of  $a$  in this case can simply be

$$a = a_o \equiv \text{"the charge radius"}$$

and one may postulate that

$$\left. \begin{aligned} \left( P_s R_s - P'_s R'_s \right)_{r=0} &= \left[ \left( P_s \right)_{r=a_o} - \left( P'_s \right)_{r=a_o} \right] a_o \\ \left( m' P'_s - \epsilon^2 m P_s \right)_{r=0} &= \left( m' P'_s \right)_{r=a_o} - \epsilon^2 \left( m P_s \right)_{r=a_o} \end{aligned} \right\} \quad (10)$$

Now those pressure values at  $r = a_o$  can be computed using the free airblast and free-water shock data in the following manner

$$\left. \begin{aligned} \left( P_s \right)_{r=a_o} &= P_{so} e^{-t/D_{so}} \\ \left( P'_s \right)_{r=a_o} &= P'_{so} e^{-t/D'_{so}} \end{aligned} \right\} \quad (11)$$

where  $P_{so}$  and  $D_{so}$  are, respectively, the peak overpressure and the duration of the free-water shock at the charge surface, and  $P'_{so}$  and  $D'_{so}$  are the corresponding values for the free airblast. In practice, further simplifications can be introduced because of the fact that  $P_{so} \gg P'_{so}$  and  $P'_{so} \gg \epsilon^2 P'_{so}$ , and one will get finally from Equations 9, 10, and 11

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$$\left. \begin{aligned} F_o(t) &= P_{so} a_o^2 e^{-t/D_{so}} \\ \bar{p}_o W_o(t) &= m_o' P_{so}' a_o e^{-t/D_{so}'} \end{aligned} \right\} \quad (12)$$

Substituting Equation 12 into Equations 1 and 8, and utilizing the free air and free-water shock values at the charge surface (references 11 and 12), one obtains the following formula for the water shock:

$$p(\lambda_r, \lambda_z, \tau) = 8.4 \times 10^3 \frac{\lambda_z}{\lambda^3} e^{-3.9(\tau-\tau')} H(\tau-\tau') + 1.1 \times 10^4 \frac{1}{\lambda} \left(\frac{\lambda_z}{\lambda}\right)^{0.1} e^{-26\tau} H(\tau) \quad (\text{psi}) \quad (13)$$

where

$$\lambda = qW^{\frac{1}{3}}, \lambda_r = rW^{\frac{1}{3}}, \lambda_z = zW^{\frac{1}{3}} \quad \left(\text{ft-lb}^{\frac{1}{3}}\right)$$

$$\tau = (t - \tilde{t})W^{\frac{1}{3}}, \tau' = (q/c_o - \tilde{\tau})W^{\frac{1}{3}} \quad \left(\text{msec-lb}^{\frac{1}{3}}\right)$$

Regarding the parameters  $\beta$  and  $S$  in the airblast formulas (Equations 5 and 6), the value of  $\beta$  can be determined from the energy consideration ( $\beta = 0.87$  in this case). The parameter  $S$  is more or less related to the overall geometry of the shock wave, and there is no clear way to estimate its magnitude beyond the fact that it is small. Thus  $S = 0.15$  was found to give a better fit to the test data, although its variation is not sensitive to the resulting pressure values.

Those pressure formulas derived in the case represented by Equations 5, 6, and 7 with  $\beta = 0.87$ ,  $S = 0.15$  for the airblast, and Equation 13 for the water shock are plotted in figs. 3-5 and compared with various test data (references 1 through 7, 13, and 14). The good agreement between the theoretical values and the test data in these figures establishes the usefulness of these formulas for spherical HE charges. This agreement also indicates the overall validity of the various assumptions introduced in the process of analysis in the previous section. This fact is important since this gives some assurance of reliability for the general formulas given by Equations 5 through 9, thereby establishing the validity of the formulas in the next section for the nuclear explosion cases, for which any direct verification is not feasible.

#### Point source model

With particular attention to the case of stronger

explosions, consider here their initial stages, as described by a similarity solution, which can be derived as a result of the following three major assumptions.

First, a point source input is assumed in the sense that a finite amount of mechanical energy is released instantaneously at a point on the air-water interface.

Second, the pressures at the shock fronts (in air and water) are assumed to be much higher than the ambient pressure in the undisturbed region, so that the latter quantity is negligible.

Last, it is necessary for the similarity relation to assume that both air and water behave as polytropic substances, or in other words, the product of (pressure)  $\times$  (density) $^{-\gamma}$  is a function of entropy only, where the exponent  $\gamma$  takes different values for different media. The validity of using this assumption in the airblast region has been well established. However, its use for the water environment in connection with the second assumption above should be regarded with caution. This fact is important to recognize when taking into account the difference between the initial stages in weak and intense explosions.

In any case, the assumptions above lead to a similarity of flow field and reduce the basic system of equations to a simpler system by use of similarity variables, and furthermore, the similarity makes it possible to determine a definite energy partitioning ratio of the airblast and water shock in terms of the released energy, which is a constant in the solution considered herein.

By utilizing the small value of  $\epsilon$ , a successive approximation scheme for the solution of the similarity equations was developed and the system of equations for the first approximation solution was found numerically. This provides an almost spherically symmetric solution (reference 15) for the airblast region with its distortion in the order of  $\epsilon$ , and a very oblate water shock front, which is almost a plane wave parallel and close to the intersection surface. This solution was used to compute the energy ratio, which gives  $\beta = 0.79$  and  $S = 4 \times 10^{-3}$ .

The input functions  $F_0$  and  $W_0$  of Equation 9 are found (for this approximation) from

$$F_0(t) = P'_s(R'_s)R'_s{}^2$$

$$\bar{\rho}_0 W_0(t) = \frac{3}{2} P'_s(R'_s)R'_s$$

Since the function  $R'_s(t)$  as well as the pressure  $P'_s(R'_s)$  are available from the free airblast data, these can be utilized here.

#### Conclusions

General pressure formulas for the region not so close to the explosion source were derived and their output calculations were compared with HE test data; the comparison showed very good

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agreement except for a small region on each side of the interface, wherein both measurements and formulas appear less reliable. A point source model was also developed to furnish the necessary initial conditions to the general formulas for nuclear explosion cases.

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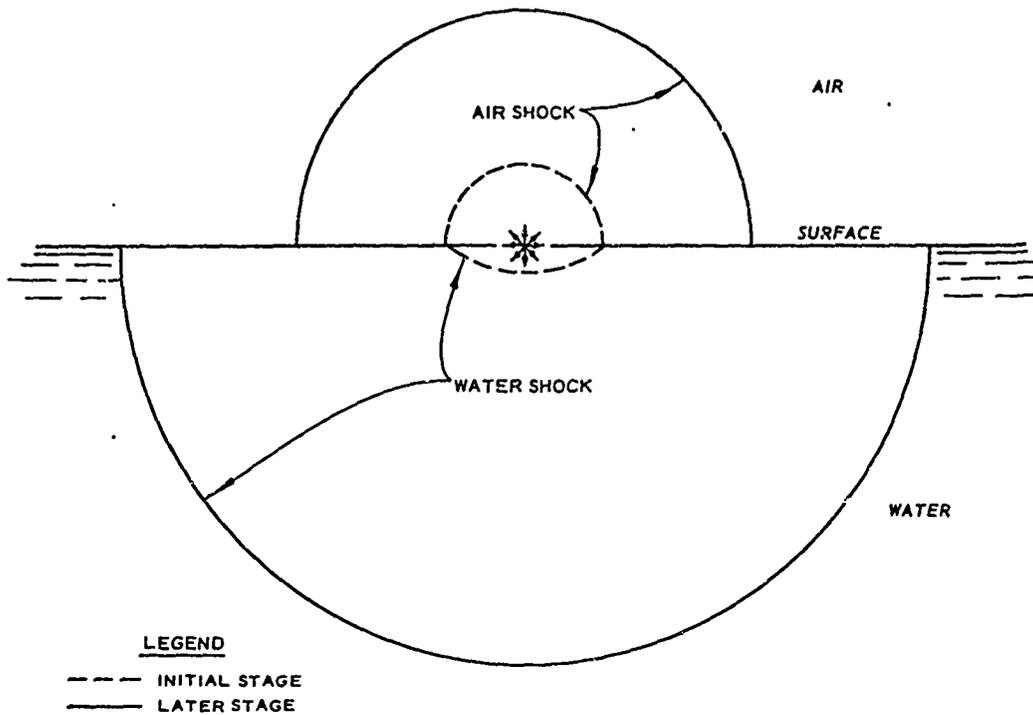


Fig. 1. Characteristics of initial and later stages resulting from explosion at water surface (charge half submerged)

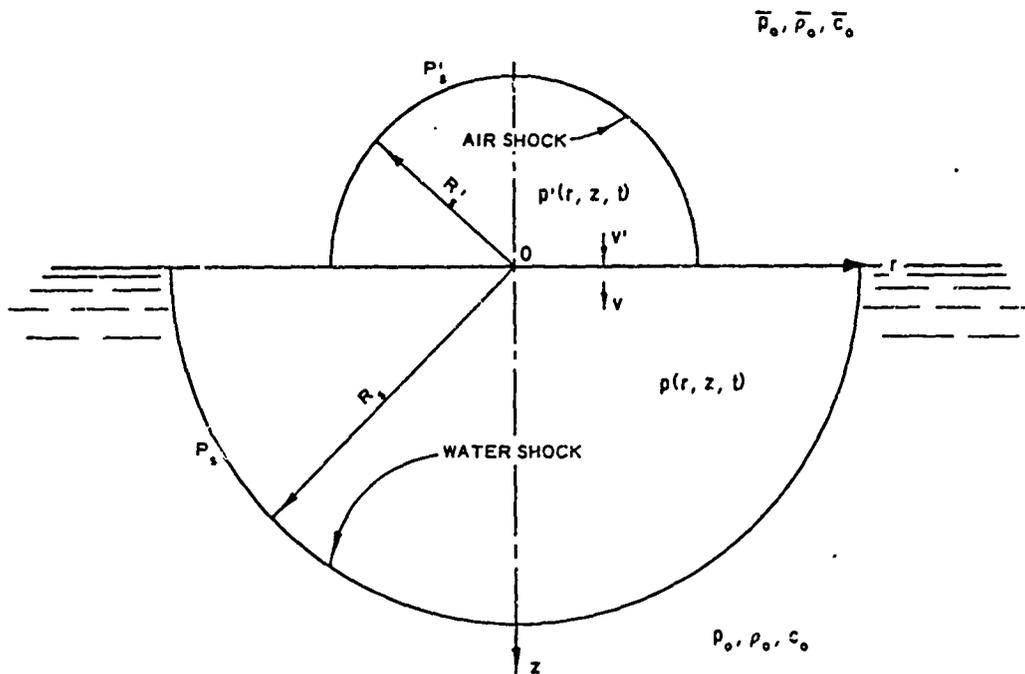


Fig. 2. Illustration of coordinate system and notation

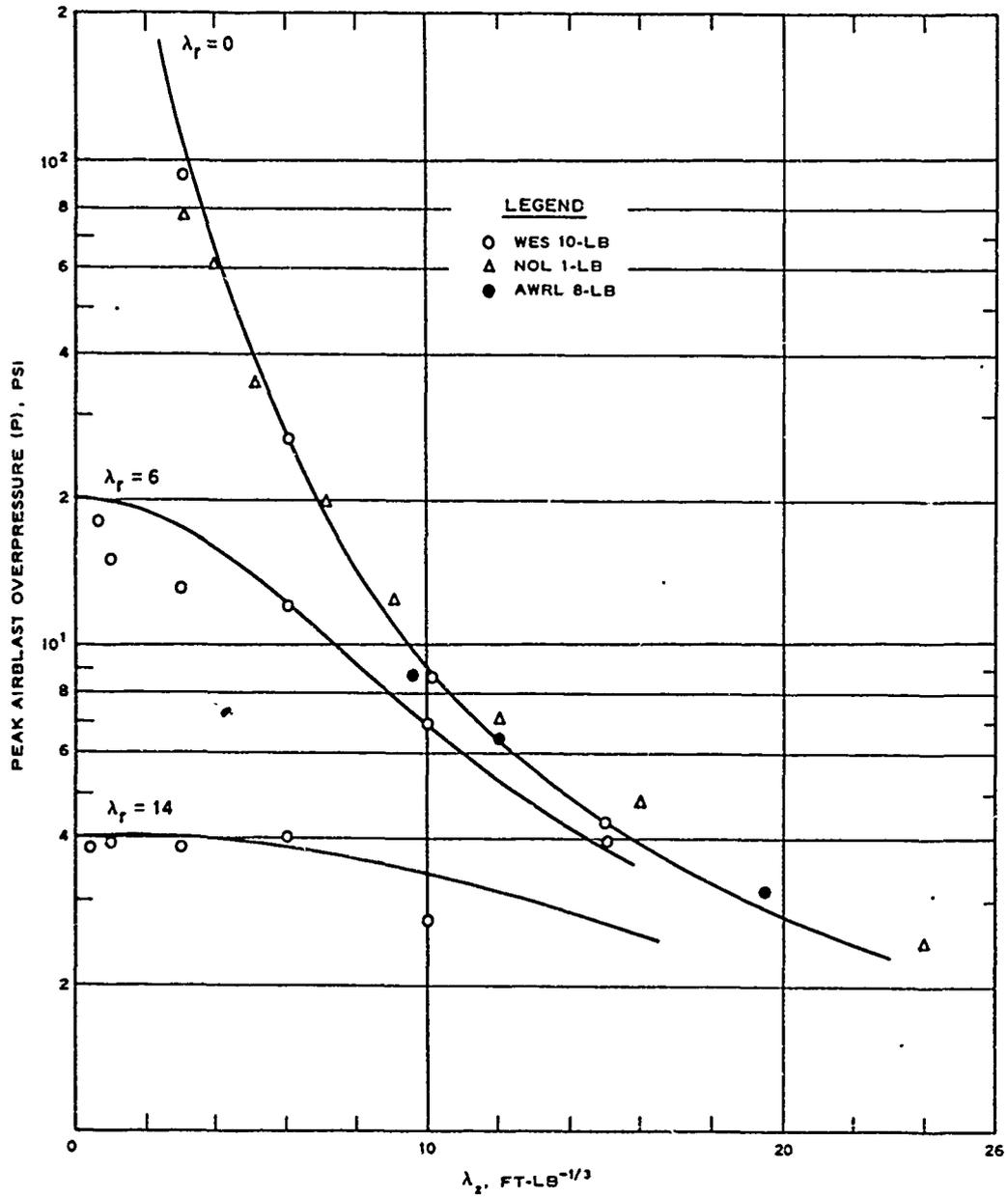


Fig. 3. Peak airblast overpressures from Equation 5 compared with test data;  $\lambda_r = 0, 6, \text{ and } 14 \text{ ft-lb}^{1/3}$

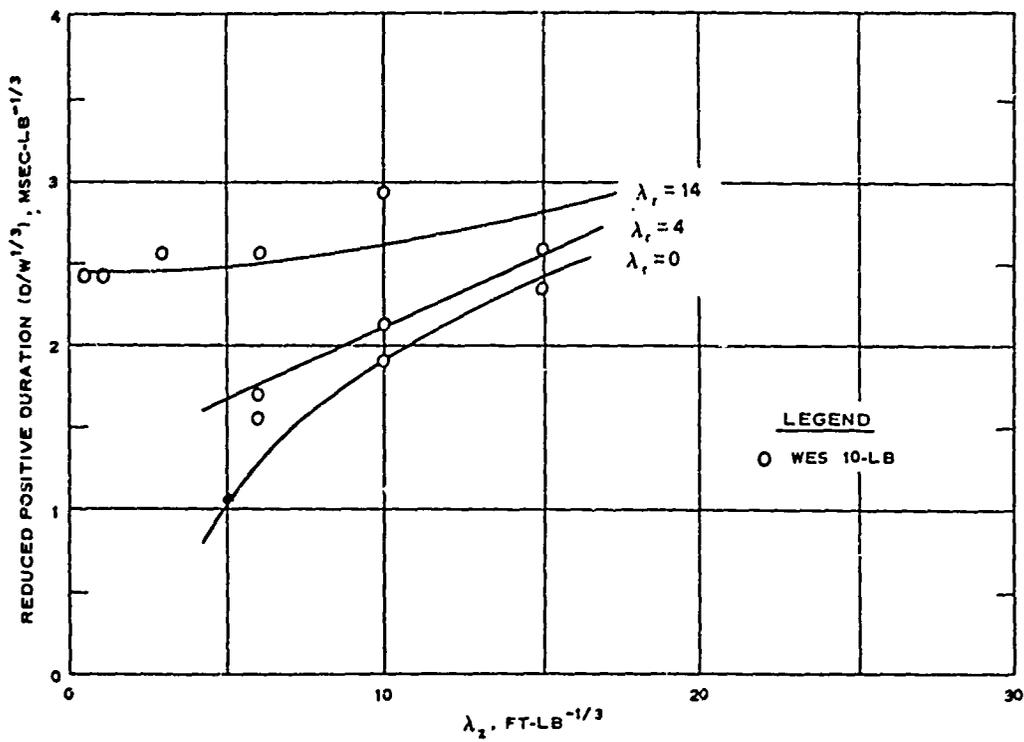


Fig. 4. Reduced positive duration from Equation 6 compared with test data;  $\lambda_r = 0, 4, \text{ and } 14 \text{ ft-lb}^{-1/3}$

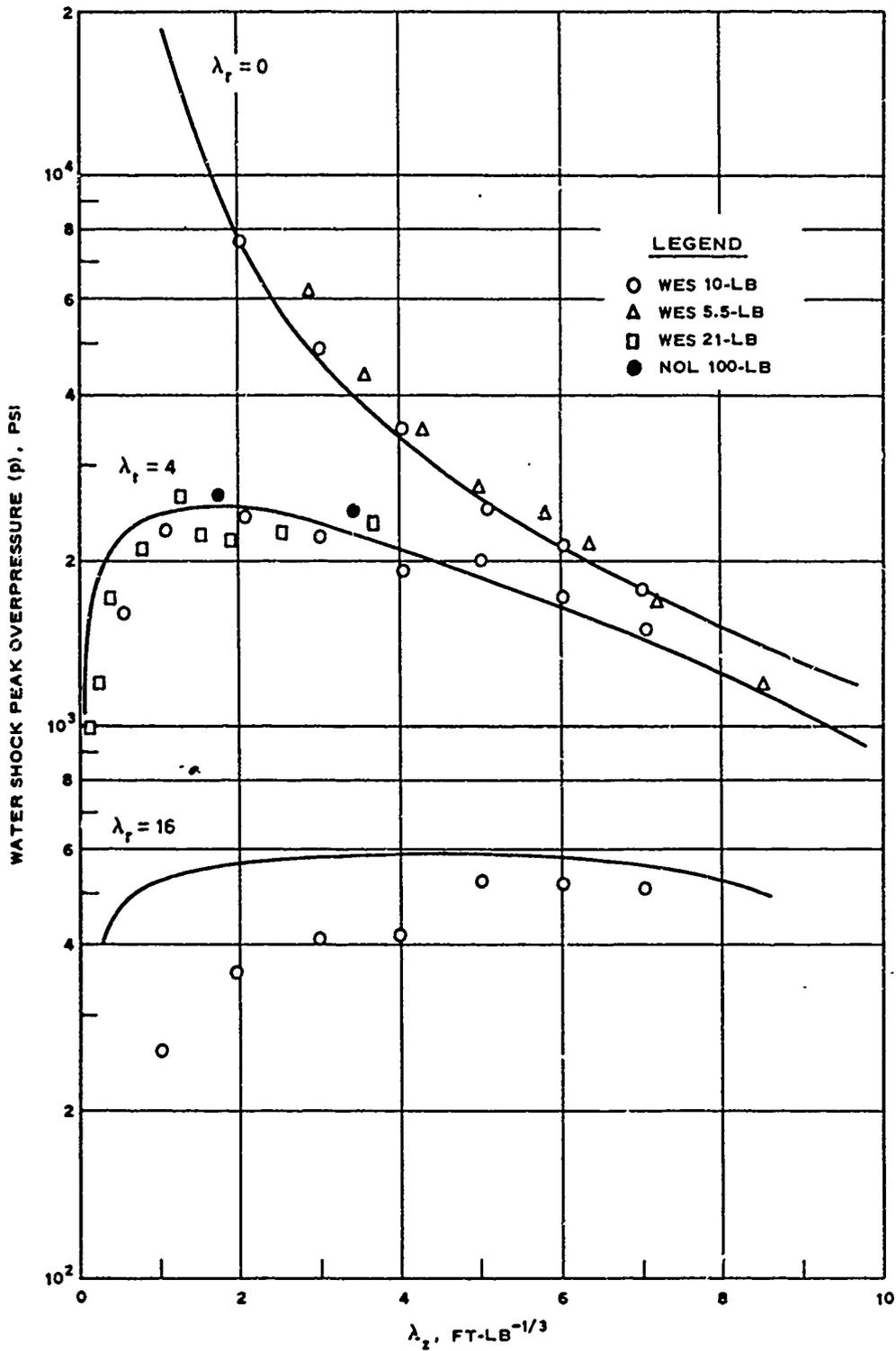


Fig. 5. Water shock peak overpressure from Equation 13 compared with test data;  $\lambda_r = 0, 4, \text{ and } 16 \text{ ft-lb}^{-1/3}$

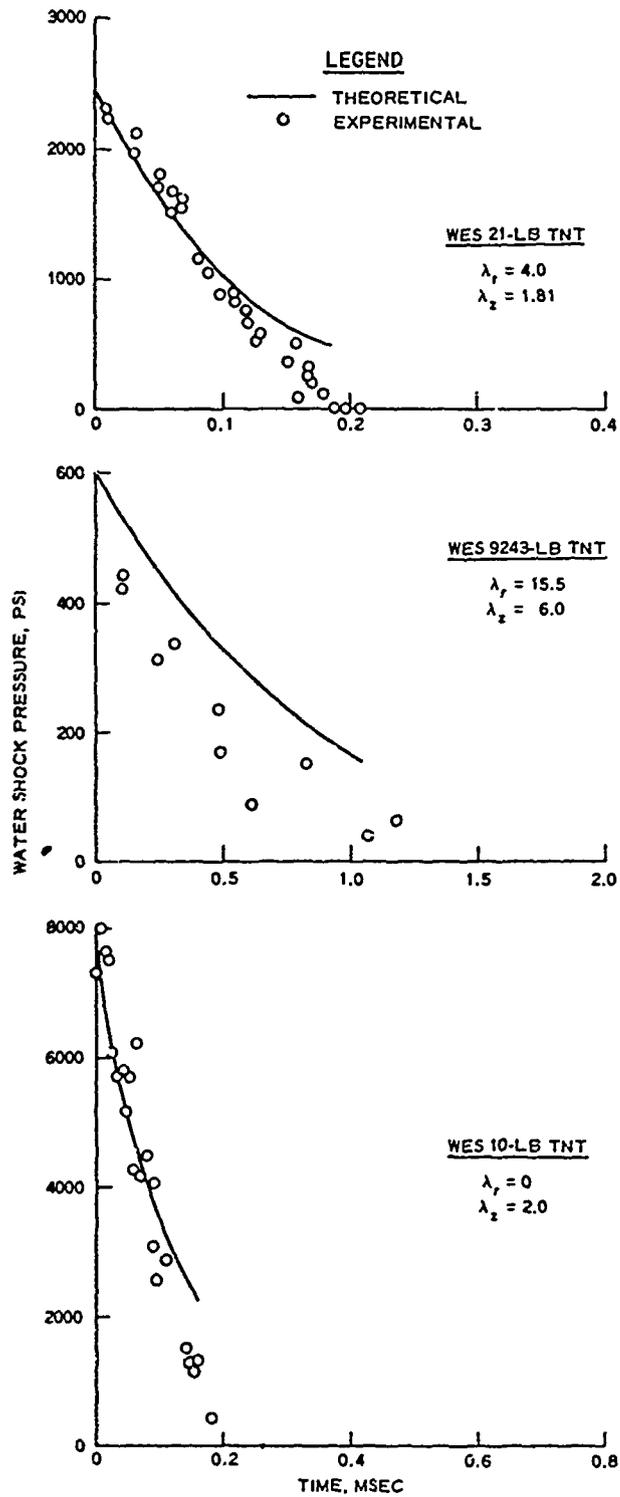


Fig. 6. Water shock pressure time history from Equation 13 compared with test data