WYLE LABORATORIES - RESEARCH STAFF
REPORT WR 66-3

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By

F. V. Bracco

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SUMMARY

This paper is about the problem of determining the air shock parameters close to liquid propellant explosions. The proper system of equations is presented together with the logic of a numerical approach, to solve them. To prove the practical importance of a rigorous approach, the magnitude of the near-field pressure is estimated and justified. For the rigorous solution, either the equation of state of the products of the explosion or the detonation velocity as a function of the loading density (or oxidizer to fuel ratio) must be known. The estimated solution has been based on the assumption that the initial air shock velocity is approximately equal to the detonation velocity and has also considered the influence of the explosive mass to energy ratio. In any case the maximum energy release should be determined through an experimental approach. For the proper analysis of the close-field of liquid propellant explosions, it is concluded that the chemistry of the process should be included, that the proper set of equations is numerically solvable, that the shock transmission model should be improved, that the TNT equivalency system is physically incorrect and that predicted blast pressures based on the use of the TNT equivalency system are overconservative. Finally, it is also concluded that the proper theoretical approach is of comparable significance to the definition of the maximum close-field blast pressures as the proper knowledge of the maximum total energy release.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

a	Speed of Sound
b,c,d	Equation of State Constants
c_p	Specific Heat at Constant Pressure
e	Internal Energy per Unit of Weight
E	Internal Energy per Equivalent Mole
E'	Explosion Energy
H	Energy Released per Equivalent Mole
m_i	Number of Moles of Product "i" per equivalent Mole of Reactant
M	Weight of the Equivalent Mole (12.032 for 1:5 LH_2 - LO_2 Mixture)
N	Total Number of Moles of the Gaseous Products
p	Pressure
Q	Energy Released per Unit of Weight
R	Universal Gas Constant; Distance from the Center of the Explosion
R_i	Gas Constant of Product "i"
t	Time variable
T	Temperature
u	Particle Velocity
V	Shock Velocity
WT	TNT Equivalent Weight
γ	Specific Heats Ratio
λ	Reduced Distance
ρ	Density

1.0 INTRODUCTION

Although it is generally agreed that close to a liquid propellant explosion site, the peak overpressure is less than the corresponding peak overpressure from a TNT explosion of equal energy, neither a defined theory nor sufficient experimental data are presently published for the computation of the actual numerical values of the peak overpressure and of the other air shock parameters close to a liquid propellant rocket explosion. Lacking such theory or data, TNT charts are often used for the close-field with the result that design blast loads are overly conservative in this region.

The problem of the air blast parameters close to the explosion site is of great practical interest to aerospace industries and government agencies engaged in defining safety measures around propellant storage areas and rocket testing and launching sites. In particular, manned capsules, nuclear material containers, launching and testing pads, and support bunkers represent some of the structures influenced by close-field explosion criteria.

In the approach presently used to determine the air shock parameters from liquid propellant rocket explosions, TNT blast design charts are used and entered with a TNT charge weight which is a percentage of the propellant weight. These percentages have been established experimentally by far-field measurements. Presently, it is felt that this procedure leads to good predictions for the "close-field" and that the uncertainty about the total energy released is "more important" than possible effects due to the "differences" between liquid propellants and TNT. Nevertheless, no quantification of practical value to the designer who has to consider the possibility of a blast is found for the terms: "Far-field", "close-field". "conservative", "more important", and "differences".

The close-field is defined in this paper as the region within which both the chemical properties, and the energy of the charge influence the air shock parameters. In contrast the far-field is the region where the energy of the charge is the only influencing parameter. In defining the close-field, consideration has been given to: explosive mass to energy ratio, initial air shock velocity, and rate of energy release.

From analytical studies of explosions from $LH_2 - LO_2$ and RP-1 - LO_2 liquid rockets, it has been possible to calculate tentative values of initial air shock peak overpressures, close field peak overpressures, and corresponding radii. The initial peak overpressure is estimated to be 40 to 80 atmospheres versus the 450 to 550 atmospheres for conventional solid explosives. A 5.10^6 lb TNT equivalent rocket explosion would have a close field radius of about 1000 feet. Between 600 and 300 feet from such an explosion, the peak overpressure is 2 to 5 times lower than the corresponding peak overpressure from the TNT explosion of equal total energy.

Admittedly, the total energy released is a major element in determining blast overpressures, but in the close-field, our specific prediction for the peak overpressure for liquid propellants is equivalent to a reduction by a factor of 2 to 5 in the total energy and therefore is of comparable significance to the definition of close field blast pressures as the definition of the total energy released.

The paper is essentially divided into two parts. In the first part the governing equations are presented together with the outline of a numerical system for their solution. In the second part an estimate for the peak over pressure in the close-field is given and justified.

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2.0 THE PROPER THEORETICAL APPROACH

The explosion problems have been studied for a long time through numerical calculations essentially because the assumptions which must be made to reach closed form solutions are too restrictive (15). However, both for the numerical and for the analytical approach, flow equations, chemical equilibrium equations, initial conditions and boundary conditions are needed (15). Generally, the flow equations are some form of the Navier-Stokes equations (15). The initial conditions are the conditions of the explosive and of the air before the explosion. The shock front conditions can be considered as boundary conditions (15). The attention will be focused on the shock front conditions because what is said for them can be extended to the flow equations and because the problem of the transmission of the detonation shock into air, which belongs to the boundary conditions, is of particular interest.

In particular, the equations and the conditions to determine the detonation shock in a $LH_2 - LO_2$ mixture will be presented. Then the equations for the air shock will be given but it will be shown that for the determination of the air shock one additional condition is needed. Then it will be seen how this additional condition is set by the transmission phenomena at the boundary between $LH_2 - LO_2$ explosive and air.

The problem of the transmission of a shock from an inert medium into another inert medium has been satisfactorily solved (6). However, the problem of the transmission of a shock from a chemically reactive medium into an inert one does not seem to have been properly considered. There is a critical difference in the expansion wave observed in an inert medium compared to that observed in a chemically reactive one. In the first case the expansion wave may be considered as an isentropic process. But in the chemically reactive case the temperature change due to the passage of the expansion wave causes a change in the local chemical composition, and thus a change in the local energy of the flow. Since the expansion wave acts as an energy generator (or absorber), the isentropic equations are not applicable. It is possible that the complex chemical processes could lead to the same energy level at the differing temperatures either side of the expansion wave. In such a case the isentropic equations would apply and the reactive gas would be apparently inert. But in the large majority of the practical cases different energy levels correspond to different temperatures and the isentropic equations are not applicable.

Figure (1) helps to define the symbols which will be used. Although the following equations are for a 1:5 LH_2 - LO_2 mixture, the approach is valid for any propellant.

2.1 The Detonation Shock

This problem is independent of the transmission problem, and it is solved using the shock and the thermochemical equilibrium equations. The following equations determine the detonation shock of a 1:5 LH_2 - LO_2 mixture:

Mass Conservation

$$\rho_3 V_3 = \rho_4 (V_3 - u_4) \tag{1}$$

Momentum Conservation

$$p_4 - p_3 = \rho_3 V_3 u_4 \tag{2}$$

Energy Conservation

$$\frac{E - H}{M} = \frac{1}{2} (p_4 + p_3) (1/\rho_3 - 1/\rho_4) \tag{3}$$

Equation of State

$$p_4 = \frac{N}{M} \rho_4 (RT_4 + b p_4 + c p_4^2 + d p_4^3) \tag{4}$$

Process Equations

Chemical Reaction Equation

$$H_2 O_{0.626} \rightarrow m_1 H_2O + m_2 OH + m_3 H_2 + m_4 O_2 + m_5 H + m_6 O \tag{5a}$$

Mass Conservation

$$2.0 = 2 K_1 m_5^2 m_6 (p_4/N)^2 + K_2 m_5 m_6 (p_4/N) + 2K_3 m_5^2 (p_4/N) + m_5 \tag{5b}$$

Mass Conservation

$$0.626 = K_1 m_5^2 m_6 (p_4/N)^2 + K_2 m_5 m_6 (p_4/N) + K_4 m_6^2 (p_4/N) + m_6 \tag{5c}$$

Thermochemical Equilibrium Equations

$$m_1 = K_1 m_5^2 m_6 (p_4/N)^2 \; ; \quad m_2 = K_2 m_5 m_6 (p_4/N) \tag{5d}$$

$$m_3 = K_3 m_5^2 (p_4/N) \; ; \quad m_4 = K_4 m_6^2 (p_4/N) \tag{5e}$$

Definitions

$$E = \sum_{i=1}^{6} m_i E_i - (2 E_H + 0.626 E_0) \tag{5f}$$

$$H = \sum_{i=1}^{6} m_i H_i - (2 H_H + 0.626 E_0) \tag{5g}$$

$$N = \sum_{i=1}^{6} m_i$$

Process Assumption

$$-\frac{dp_4}{d\left(\frac{1}{\rho_4}\right)} = -\left(\frac{\partial p_4}{\partial \frac{1}{\rho_4}}\right)_H = (p_4 - p_3) \Big/ (1/\rho_3 - 1/\rho_4) \qquad (5i)$$

In the above system of equations, ρ_3, p_3 (and T_3) are known, u_4, p_4, ρ_4, and T_4 must be determined while some of the other variables (V_3, b , c , and d) might be known and the remaining will have to be calculated. Accordingly the following three cases will be considered:

> V_3, b, c, and d are known; b, c, and d are known and V_3 is unknown; and finally V_3 is known as a function of the fuel-to-oxidizer ratio while b, c, and d, are unknown.

Assume first that both detonation velocity and equation of state of the products of the explosion are known (V_3, b, c, and d). Pressure and temperature (p_4 and T_4) are then guessed and equations 5b and 5c solved for m_5 and m_6 (the equilibrium constants, K_i, are tabulated as functions of the temperature only (2, 11, 13)). Equations (5d), (5e), (5f), (5g), and (5h) are then solved for m_1, m_2, m_3, m_4, E, H, and N (the internal energies, E_i, and the heats of formation, H_i, are again tabulated as functions of the temperature only (2, 11, 13)). In equations (1), (2), (3), and (4) the unknowns are now u_4, p_4, ρ_4 and T_4 of which p_4 and T_4 have already been guessed. If the four equations are not compatible, a new guess for p_4 and T_4 must be made and the process repeated. To avoid having to guess both pressure and temperature (p_4 and T_4), P.B. Carter (13) assumes that the process is at constant volume and replaces p_4 with $N\rho_4 RT_4/M$ where ρ_4 is assumed known, while H. Jones and A.R. Miller in their calculations for TNT explosions (2) rearranged the process equations and considered the detonation pressure tending to infinity thus eliminating it from the system. To apply this approach to the $LH_2 - LO_2$ case it would be necessary to rearrange equations (5b) and (5c) and to take the limit for p_4 tending to infinity. It is believed that the restrictions imposed by both P.B. Carter and H. Jones and A.R. Miller can be removed if the calculations are made by a modern high-speed digital computer.

Assume now that the detonation velocity is not known, while the equation of state of the products of the explosion is still known (b, c, and d). The condition necessary for the

stability of the detonation velocity and for a constant heat release at the detonation front, expressed by the Jouquet condition (5i) can be used and the problem is still solvable (2).

Finally, if the equation of state of the products of the explosion is not known, but a series of detonation velocities versus fuel-to-oxidizer ratio iis known, the equation of state can be approximately determined by first guessing the values of a, b, and c; then calculating the detonation velocities for the different fuel-to-oxidizer ratios, checking them versus the experimental values and then modifying a, b, and c to repeat the process if necessary (2).

A limitation to the accuracy of any of the above systems to solve the detonation shock problems, is the fact that equations (5a) through (5e) are derived by using the perfect gas equation of state for the products of the explosion (11, 13).

2.2 The Transmitted Shock

For the transmitted shock we can write the usual normal shock relationships which determine all the variables related to the transmitted shock provided one of them is calculated from an additional condition. Namely we have:

Mass Conservation

$$\rho_1 V_1 = \rho_2 (V_1 - u_2) \tag{6}$$

Momentum Conservation

$$p_2 - p_1 = \rho_1 V_1 u_2 \tag{7}$$

Energy Conservation

$$\frac{1}{2} V_1^2 + c_p T_1 = \frac{1}{2} (V_1 - u_2)^2 + c_p T_2 \tag{8}$$

(This equation is valid only for a perfect gas, adiabatic process)

Equation of State

$$p_2 = R_2 T_2 \rho_2 \tag{9}$$

Thus it is seen that in the above system p_1, ρ_1 and T_1 are known and V_1, p_2, ρ_2, T_2 and u_2 can be calculated provided that one of them is known.

2.3 The Expansion Wave

At this point only one air-shock variable must be calculated for the complete problem to

be solved. Thus the equations for the expansion wave must be sufficient to determine the expansion variables and the air shock parameter which still is needed. The assumptions that are made for the expansion wave must be compatible with the equations of state and of chemical energy release of the explosion products, namely equations (3) and (4), since the expansion wave moves through the detonation products. The following derivation of the expansion equation is the classic one apparently due to Riemann.

For an isentropic flow we have:

Mass Conservation

$$\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + \rho \frac{\partial u}{\partial x} = 0$$

Momentum Conservation

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{a^2}{\rho} \frac{\partial \rho}{\partial x} = 0$$

If the first of these equations is multiplied by a/ρ and then the two are added or subtracted, the result is the following pair of equations:

$$\frac{\partial u}{\partial t} \pm \frac{a}{\rho} \frac{\partial \rho}{\partial t} + (u \pm a) \frac{\partial u}{\partial x} \pm (u \pm a) \frac{a}{\rho} \frac{\partial \rho}{\partial x} = 0$$

which may be written

$$\frac{\partial (u \pm f(\rho))}{\partial t} + (u \pm a) \frac{\partial (u \pm f(\rho))}{\partial x} = 0$$

also

$$\frac{D}{Dt} \left[u \pm f(\rho) \right] = 0$$

having defined $f(\rho) = \int (a/\rho)\, d\rho$ + constant. Thus one obtains:

$$u \pm f(\rho) = \text{constant}$$

along curves in the t, x plane given by $x_t = u \pm a$. These curves are the characteristics of the flow. The above defines u for a medium initally at rest and undergoing a diffusion through which the density changes from ρ' to ρ''. Thus u is given by:

$$u = \pm \int_{\rho'}^{\rho''} a \frac{d\rho}{\rho} + \text{constant}$$

In our case the medium is actually in motion with the particle velocity u_4 and the density changes from ρ_4 to ρ_5. Thus for our case we have

$$u_5 = u_4 + \int_{\rho_4}^{\rho_5} a \frac{d\rho}{\rho}$$

So far only mass and momentum equations have been used. We can still use the energy equation, state equation, and some assumptions about nature of the transformation. If we assumed that the explosion gases are perfect ones, and that the expansion is an isentropic one, we would have the following system of equations:

Mass and Momentum Conservation

$$u_5 = u_4 + \frac{2}{\gamma_4 - 1}\left(\gamma_4 R_4 T_4\right)^{1/2}\left[1 - \left(\frac{T_5}{T_4}\right)^{1/2}\right]$$

Equation of State

$$p_5 = R_4 \rho_5 T_5$$

Process Assumptions

$$\rho_4 / \rho_5 = \left(T_4 / T_5\right)^{\frac{1}{\gamma_4 - 1}}$$

$$p_5 = p_2 \quad ; \quad u_5 = u_2$$

Where there would be five equations and the five following unknowns: p_5, ρ_5, T_5, u_5, and u_2 or p_2. Thus the transmission problem would be determined since both the expansion wave and one of the air shock parameters (u_2 or p_2) could be calculated. The above approach is the one generally followed (6) in spite of the fact that the assumption of an isentropic expansion is in contradiction with the nature of the chemical reaction

expressed by equations (4) and (5). Applying the proper energy and state equations, the five equations to be used in this case for the expansion wave and the transmission problem are the following:

Mass and Momentum Conservations

$$u_5 = u_4 + \int_{\rho_4}^{\rho_5} \left[\frac{dp}{d\rho}\right]^{1/2} \frac{d\rho}{\rho} \qquad (10)$$

Energy Conservation

$$dE - dH = Mp\ d\left(\frac{1}{\rho}\right) \qquad (11)$$

Equation of State

$$p = \frac{N}{M}\rho\ (RT + bp + cp^2 + dp^3) \qquad (12)$$

Process Assumptions

$$p_5 = p_2\ ;\ u_5 = u_2 \qquad (13)$$

To conclude this section on the proper theoretical approach to determine the air shock parameters close to a liquid propellant explosion, it is proper to say that the above system is in essence the one used by H. Jones, A.R. Miller (2), G. Taylor (3) and H.L. Brode (7) for the calculation of the TNT explosion in air. The complete set of equations is summarized in Figure 2. In figure (3) a possible logical scheme for a numerical integration to take into account the chemical reaction while moving the shock front is sketched. This scheme allows the use of available computer programs. Both computer programs to calculate the motion of shocks in inert gases (Hydrodynamic Codes), and computer programs to calculate chemical reactions (Chemical Codes) are presently available. A new computer program to consider hydrodynamic motion and chemical reaction at the same time would certainly be preferable but would also require a longer time.

3.0 AN ESTIMATE FOR THE CLOSE-FIELD PEAK OVERPRESSURE

The explosion elements, which influence the air shock parameters most, are: explosion energy, explosive mass to energy ratio, rate of energy release and initial air shock velocity. It is evident that the explosion energy is a major element. Unfortunately, only a few theoretical observations of limited usefulness can be made about the amount of

energy possibly released in a rocket explosion. Although attempts to predict the energy release on theoretical considerations have been made, it is generally accepted that realistic results can be defined only from the statistical analysis of experimental data. Some considerations will be made on the influence of the explosive mass to energy ratio and of the initial air shock velocity.

3.1 The Explosive Mass to Energy Ratio

In Taylor's similarity solution for strong shocks (3), the mass of the explosive with respect to the mass of air within the shock is neglected. Taylor pointed out that his results should be independent of the nature of the explosive when the mass of air within the shock is considerably larger than the initial mass of the explosive. Prior to this, Taylor and then Bethe (1), noticed that it takes a considerable time for the energy to transfer from a concentrated explosive charge to the surrounding air, owing to the great difference in density between these two media. Thus,during all this period, the pressure in the air shock is less than it would be for a point source explosion liberating the same energy. The same argument can be repeated in comparing explosions of concentrated charges like TNT with explosions of propellants because the rate of energy release in propellant explosions is much smaller than the corresponding rate in TNT explosions. Finally, Brode (5), found that solutions for a point source explosion and for two hot isothermal spheres with starting overpressures of 2002 and 121 At., respectively, and equal densities inside and out, become equal when the air engulfed by the shock front is equal to, or larger than, 10 times the initial mass of the hot gases. From all the above considerations it follows that the definitions of the far field must respect the "10 times the initial mass of explosive" criterion since, by definition, the far-field is the region where the blase parameters are independent of the type of explosion and dependent only on the total energy released.

When the "10 times initial mass" concept is applied to a TNT surface explosion, the outer radius of the close-field or inner radius of the far-field is found as follows:

$$10.\ WT = \frac{2}{3} \cdot \pi \cdot (C.F.R.)^3_{TNT}\ \rho_0$$

$$(C.F.R.)_{TNT} = (15 \cdot WT / (\pi \cdot \rho_0))^{1/3}$$

where $(C.F.R.)_{TNT}$ stands for "close-field radius for TNT" and WT stands for "weight" of the TNT charge". The reduced distance, $\lambda_{surface}$, for $(C.F.R.)_{TNT}$, can now be determined using its definition:

$$\lambda_{surface} = \frac{R}{(E'/P_0)^{1/3}} = 0.112 \cdot \frac{R}{(WT)^{1/3}}$$

and setting:

$$R = (C.F.R.)_{TNT}$$

it is found:

$$\lambda_{surface} = 0.112 \cdot (15 / (\pi \cdot \rho_0))^{1/3} = 0.445$$

Entering Figure 6 with this value of $\lambda_{surface}$ and reading on the "TNT" calculated and measured curve", the peak overpressure at which the TNT close-field ends and the far-field begins, is found to be 4.46 At.

The "10 times the initial mass" concept can now be extended to $LH_2 - LO_2$ explosions. Usually the mixture ratio for $LH_2 - LO_2$ is 1:5 while the stoichiometric mixture ratio is 1:8. The stoichiometric heat of combustion is 51,000 Btu/lb. Since the usual mixture ratio is not stoichiometric, 40,000 Btu/lb. is assumed to be the maximum heat of combustion. Thus, 6 lb. of $LH_2 - LO_2$ should yield 40,000 Btu. However, the specification recommended in Reference (14), is that 60 per cent of the weight of the propellant shall be the weight of the equivalent TNT explosive. Since 1 lb. of TNT releases 1,940 Btu, 6 lb. of $LH_2 - LO_2$ would yield (0.6 x 6) x 1,940 = 7,000 Btu when they explode. Since 6 lb. of $LH_2 - LO_2$ release 7,000 Btu instead of 40,000 Btu, either only part of the 6 lb. actually explode and the remaining will burn, or all 6 lb. actually explode with low efficiency. Specifically, either only 6 x 7,000 Btu/40,000 Btu = 1.05 lb. of propellant explode with 100 per cent chemical efficiency and 4.95 lb. will burn or all of the 6 lb. of propellant explode with a chemical efficiency of 7,000 Btu/40,000 Btu = 17.5 per cent, or anything between 1.05 and 6 lb. actually explode with a chemical efficiency varying between 100 and 17.5 per cent.

The extremes of chemical efficiencies have to be excluded. Moreover, the per cent of propellant which does not take active part in the explosion, still shares the energy released thus reducing the actual energy conveyed to the air shock at the beginning of its propagation. Thus, 5 lb. for $LH_2 - LO_2$ appears to be a reasonable choice for the weight of propellant taking active part in the explosions. The factor of 5 for $LH_2 - LO_2$ is then used to define the peak overpressure at the outer limit of its close-field. Thus, for

$$LH_2 - LO_2: \lambda_{surface} = (5)^{1/3} \cdot (0.445) = 0.76$$

Following the same approach (16), a factor of 3 was estimated for RP-1-LO_2 mixture. Thus for:

$$RP\text{-}1\text{-}LO_2: \lambda_{surface} = (3)^{1/3} \cdot (0.445) = 0.642$$

from which the peak overpressures are found to be 1.5 At. for $LH_2 - LO_2$ and 2.0 At. for $RP\text{-}1\text{-}LO_2$. The above does not take into account the rate at which energy is released. The importance of this is illustrated by the limit case of normal combustion in which the energy is released so slowly that it can be distributed into the surrounding air by convection, conduction, and radiation. In this case, no shock would be generated. Since the rate of energy release for propellants is actually smaller than for solid charges, a longer time is needed for the same energy to be transferred from the products of liquid propellant explosions into air than from the products of solid charge explosions. For this reason the estimated maximum values of the overpressures for which TNT charts can be used in predicting air blast parameters from explosions of the above propellants are further lowered from 1.5 At. and 2.0 At. to 1.0 At.

3.2 The Initial Air Shock Velocity

As pointed out by Rudlin (4), there is some disagreement between present theoretical predictions and experimental measurements of initial shock velocity from solid charges. It was pointed out that the theoretical predictions are often based on the assumption that the reacting gages are perfect isentropic gases and, that this assumption is unrealistic. The result of these predictions is that the initial air shock velocity is generally considerably different from the detonation velocity.

Experimental results tend to show that such a difference does not exist (9, 10). Figure (4) shows no discrenable change in the slope of the distance - time curve describing the motion of the shock from a gaseous mixture into air. Figure (5) shows the same trend for the motion of the shock from a solid charge into air. These data are considered to be sufficient to justify the assumption that the initial air shock velocity is approximately equal to the detonation velocity of the exploding material when estimates for the close-field air shock parameters are of interest.

Unfortunately, a rather extensive search revealed only one set of experimental data (8) for the detonation velocity of a $LH_2 - LO_2$ mixture (2.3 km/sec.), and one for the detonation velocity of a $RP\text{-}1\text{-}LO_2$ mixture (2.2 km/sec.). According to the proposed assumption, using the above detonation velocities, the initial air shock pressure would be 54 and 50 At., respectively. Available data on detonation velocities of gaseous mixtures support the hypothesis of liquid mixtures detonation velocities in the 2 to 3 km/sec. range.

Knowing the initial air shock pressure and the range within which this pressure will be smaller than that from a TNT explosion of equal energy; that is, knowing the peak overpressures at which the close-fields end, an estimate can be made of the probable range of surface peak overpressures from liquid propellant rocket explosions. This range is given in Figure (6). This range is an estimated one; present plans are that accurate calculations

for it will be performed. However, even the estimated range is believed to give a better approximation than the one reached through a TNT equivalency assumption. The experimental data of Figure (6) are from Reference (12) and they tend to bear out the initial rough estimate. These data are from 300 lb. RP-1-LO_2 charges and their actual TNT equivalencies at 1.0 At. overpressure range between 8 and 32 per cent.

Notice the following three points about Figure (6);

1. The estimated range of overpressure was originally for LH_2 - LO_2 mixtures while the experimental results are for RP-1-LO_2 mixtures. However, the estimated range applies equally well to RP-1-LO_2 mixtures since their detonation velocities are within the same range (2-3000 m/sec.).

2. The experimental data have been made to superimpose at 1.0 At. peak overpressure. The choice of 1.0 At. peak overpressure has been previously justified. The reason for superimposing data at 1.0 At. peak overpressure is that the rate of decay of overpressure with distance rather than the total energy release is of interest in this figure. This means Figure (6) does not attempt to estimate the maximum energy which might be released, but only the maximum overpressure once that the maximum energy has been determined experimentally.

3. Notice that the estimated peak overpressure at a given distance from a liquid charge is considerately less than the corresponding peak overpressure at the same distance from a TNT charge of the same total energy. In turn, this implies that the positive phase duration and impulse are higher for a liquid charge than for a TNT charge.

In Figure (7) the curve, crossing the family of constant TNT curves, is the upper line of the estimated range of Figure (6). In this figure the decrease of the TNT equivalent with increasing pressure is again emphasized. Thus, for example, to find the distance at which a maximum overpressure of 100 psi could be measured, a half of the maximum far-field TNT equivalent can be assumed. Thus for this order of pressures, considering the chemistry of the explosion is equivalent to reducing the maximum TNT equivalent to a half without changing any safety factor.

When the above considerations are applied to a possible explosion of a Saturn V, it is found that the local peak overpressure is two to five times lower than predicted from TNT charts in a range of distances where manned capsules, nuclear material containers and support bunkers are actually located (Figure 8).

4.0 CONCLUSIONS

In the present work the influence of the nature of the explosive on the close-field air shock parameters, has been emphasized. The critical point of the initial air shock velocity has been stressed. A specific system to calculate the air shock parameters close to the

explosion site has been outlined.

The author is presently engaged in applying some aspects of the presented approach and regrets that the acquisition of more specific results, which he hoped to have ready for this presentation, had been delayed. Hence, the presented results must be considered as preliminary.

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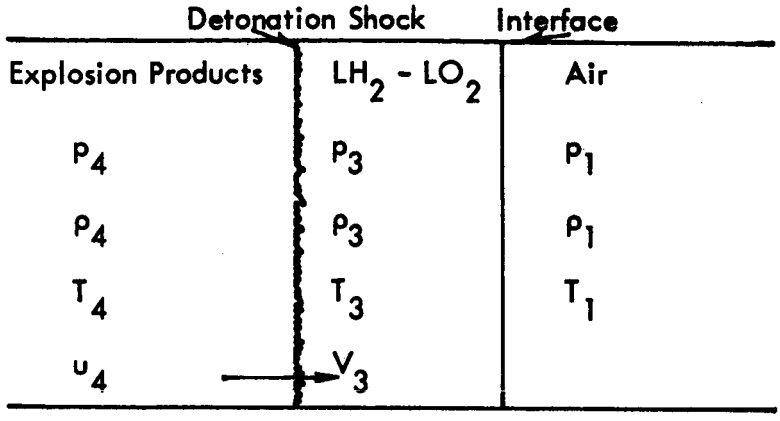
CONDITIONS IMMEDIATELY BEFORE THE DETONATION SHOCK REACHES THE INTERFACE



CONDITIONS IMMEDIATELY AFTER THE DETONATION SHOCK REACHES THE INTERFACE

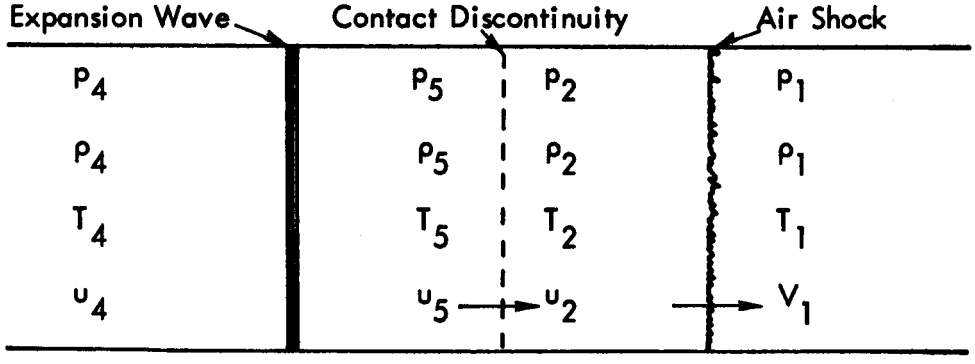


Figure 1. The Transmission of a Detonation Shock Into an Inert Medium.

EQUATIONS

For the Detonation Products	Shocked Air
Conservation of Mass	Conservation of Mass
Conservation of Momentum	Conservation of Momentum
Conservation of Energy	Conservation of Energy
Chemical Reaction Equations	
Thermochemical Equilibrium Equations	Adiabatic Process Assumption
Atomic Species Conservation Equations	
Equation of State	Equation of State

BOUNDARY CONDITIONS

At The Detonation Front	Rankine-Hugoniot Equations Jouguet Condition
At The Charge Air Interface	Expanded Detonation Pressure = Shocked Air Pressure Expanded Detonation Particle Velocity = Shocked Air Particle Velocity Rieman Expansion-Wave Equation
At The Air Shock Front	Rankine - Hugoniot Equations

INITIAL CONDITIONS

Initial Conditions of Charge and Air

Figure 2. Explosion Equations and Conditions.

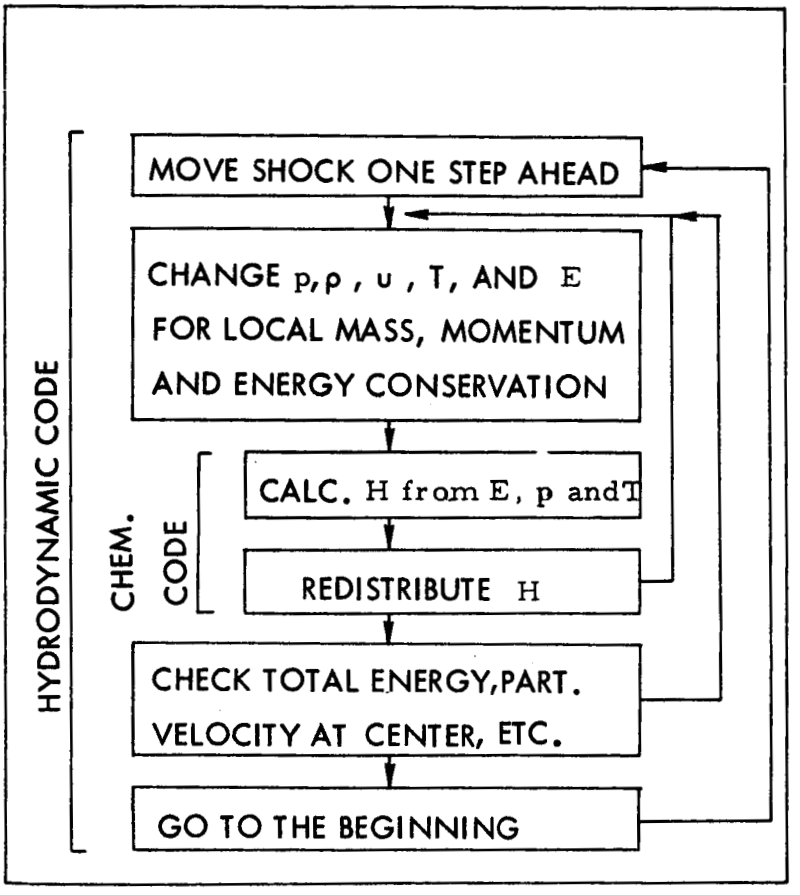


Figure 3. Numerical Computation of Explosion Parameters, Both in Explosive and in Air.

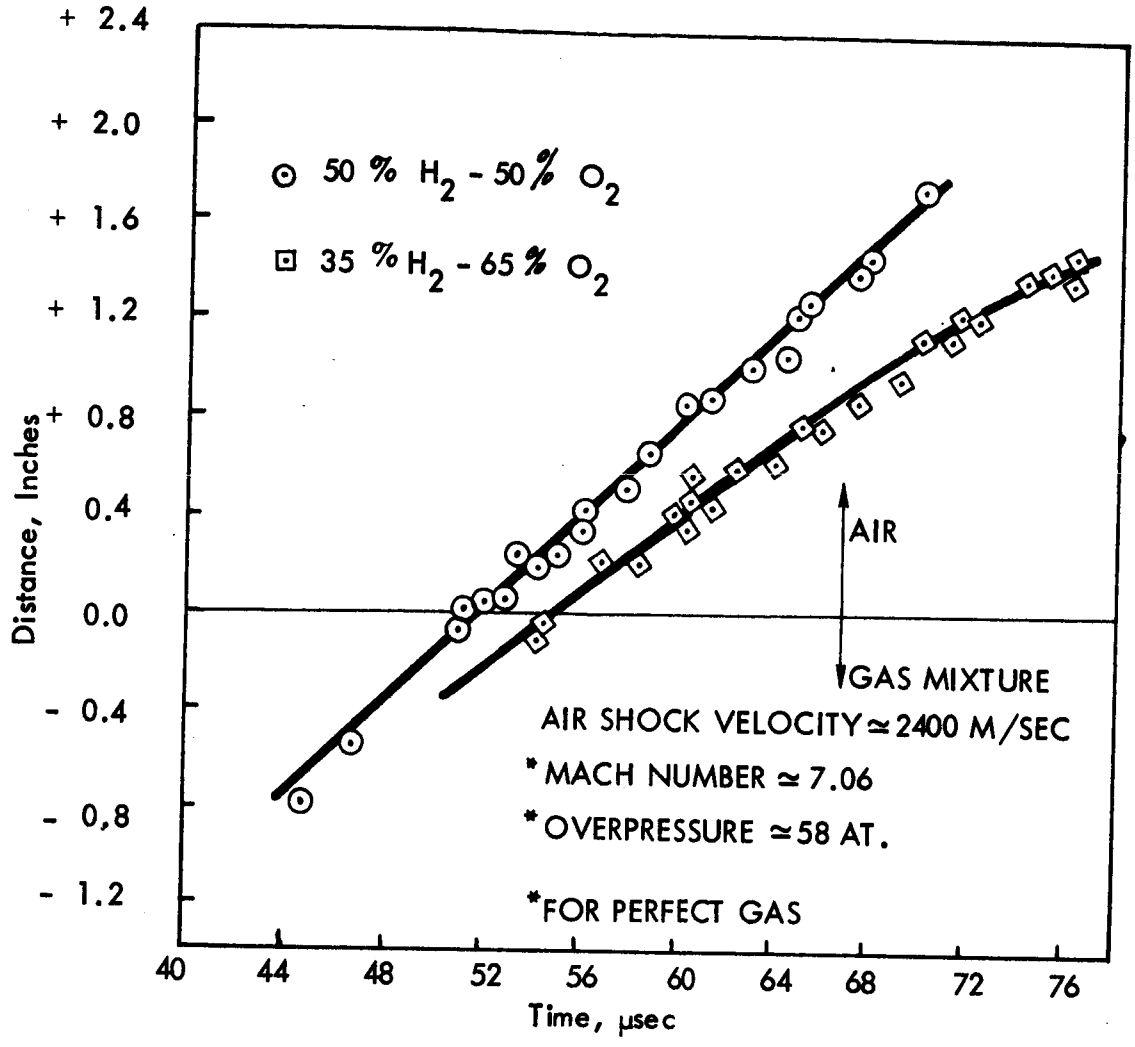


Figure 4. Gaseous Charge - Air Transmission Velocity.

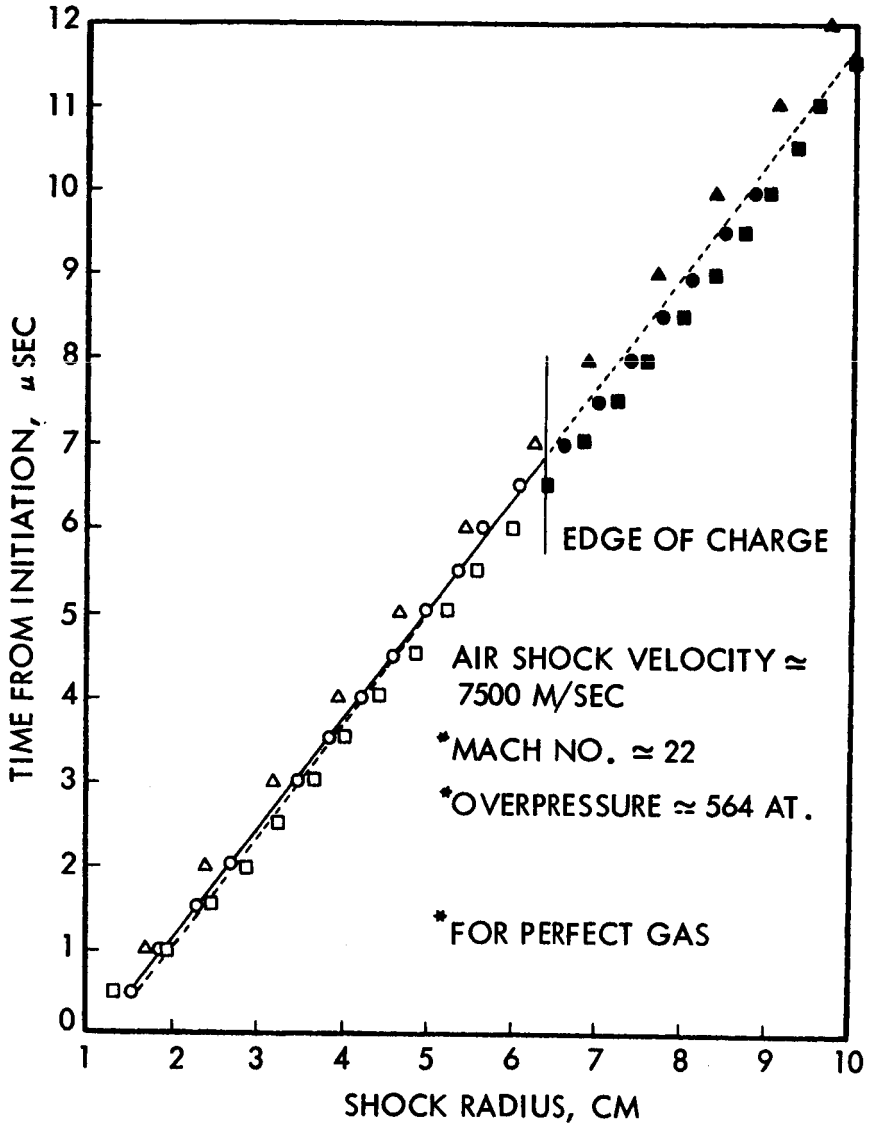


Figure 5. Solid Charge - Air Transmission Velocity.

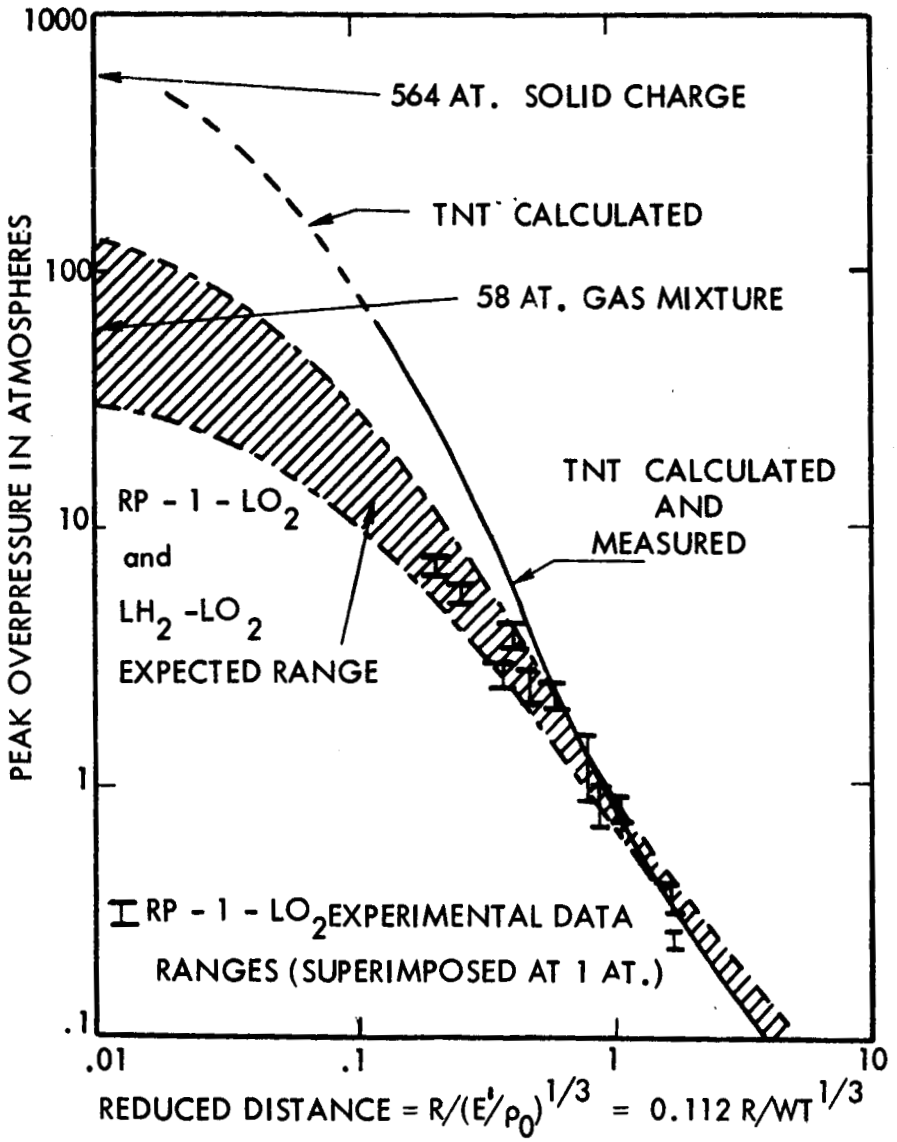


Figure 6. Close-Field Peak Overpressure (Estimated Range).

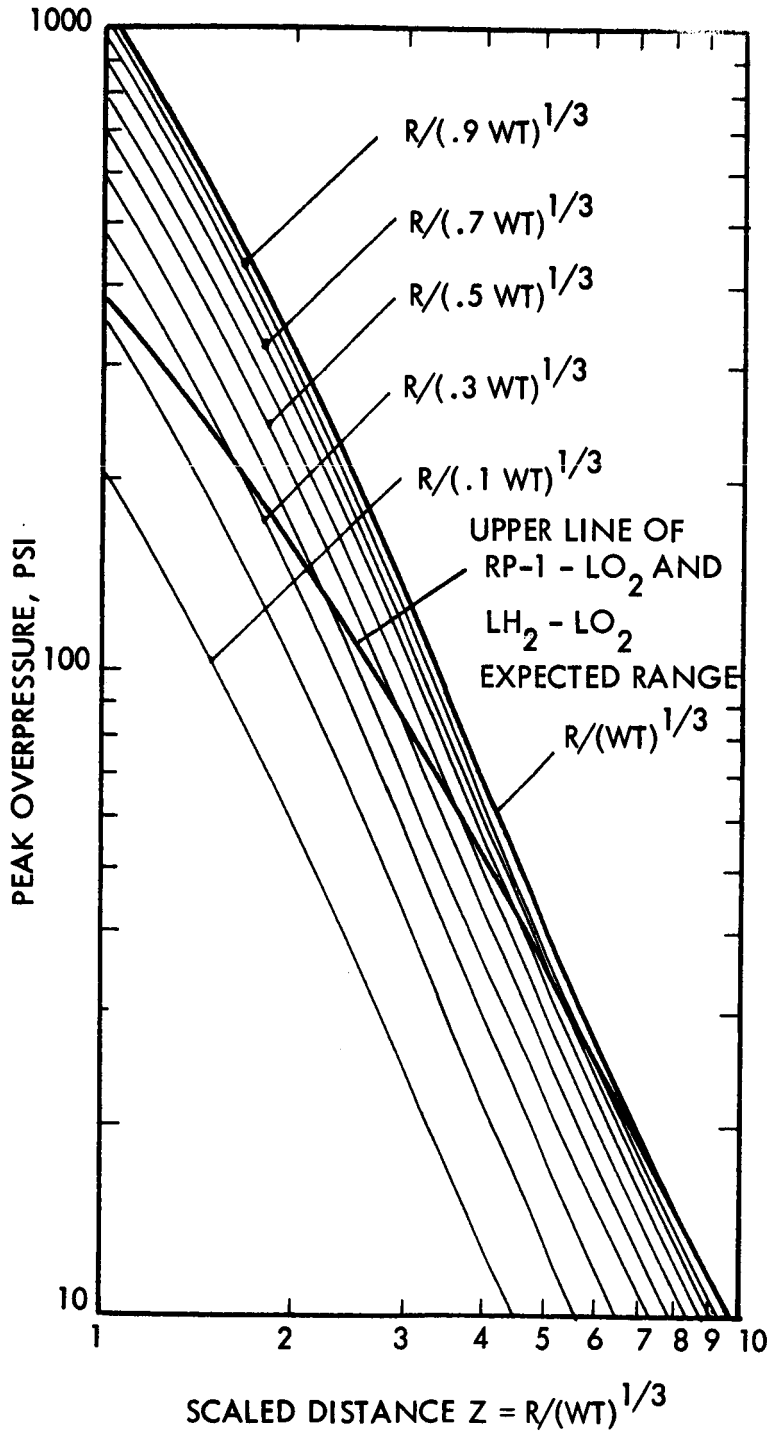


Figure 7. Decrease of the TNT Equivalent in the Close-Field.

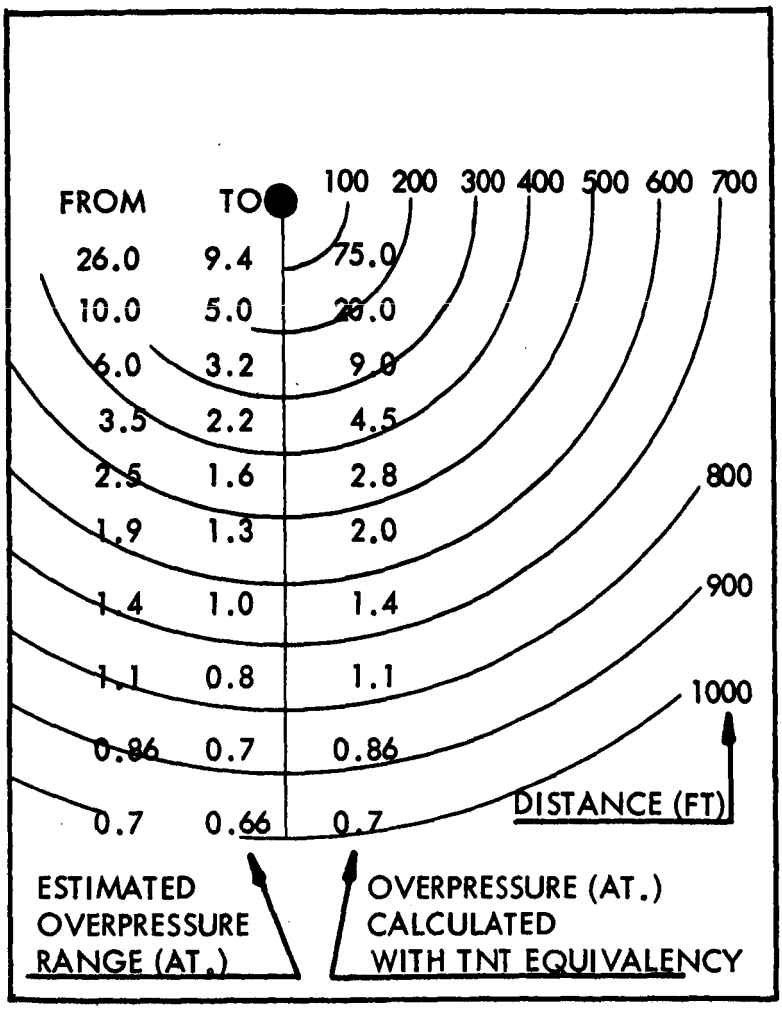


Figure 8. Saturn V Close-Field Peak Overpressure Assuming a Far-Field TNT Equivalent of 1 Million Pounds.