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ON THE SCALING OF PRESSURES FROM NUCLEAR EXPLOSIONS WITH SOME OBSERVATIONS ON THE VALIDITY OF THE POINT-SOURCE SOLUTION

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ON THE SCALING OF PRESSURES FROM NUCLEAR EXPLOSIONS WITH SOME OBSERVATIONS ON THE VALIDITY OF THE POINT-SOURCE SOLUTION

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ABSTRACT: This report discusses the scaling of pressure-distance curves for a particular model of a nuclear explosion using an ideal-gas equation of state. A family of non-dimensional curves is presented which allows scaling to different ambient conditions for a given energy source. These curves also make possible scaling close-in to the initial fireball. In addition, it is shown that the theoretical point-source solution for an ideal gas agrees with the computed solutions, except at close-in distances and at shock strengths below 50. It is shown that neither of these ideal-gas solutions agrees as well with experiment as does a real-gas solution.

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ON THE SCALING OF PRESSURES FROM NUCLEAR EXPLOSIONS WITH SOME OBSERVATIONS ON THE VALIDITY OF THE POINT-SOURCE SOLUTION

Certain concepts in explosion investigations have been especially valuable because they make generalizations or extensions possible. Two such concepts are Sachs scaling and the point-source solution. Sachs scaling permits extension of one set of explosion results for a given situation to new situations. The point-source explosion model produces an analytic solution (as opposed to the numerical solutions necessary for solution of the usual hydrodynamic equations) which makes examination and generalizations of the behavior of the explosion parameters possible.

The authors of this report examine these two concepts and, by comparison with numerical results of the hydrodynamic equations, suggest the limitations that must be placed upon use of scaling and of point-source solutions for blast from nuclear explosions.

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J. A. DARE
Captain, USN
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C. J. ARONSON
By direction

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1. INTRODUCTION

Scaling procedures have long been used to extend the range of applicability of both numerical calculations and experimental observations. In particular, "Sachs scaling"[1] has been very useful in the treatment of blast problems, both for high explosives and for nuclear weapons. However, it is well known that Sachs scaling has limitations in the region close to the energy source, since the only property of the source taken into account is the total energy release. This has the consequence that in a rigorous application of Sachs scaling the parameters describing the energy source cannot be varied at will. For example, it will be shown that when an explosion is Sachs scaled to different ambient conditions, it is required that the parameters describing the source be changed correspondingly. This is not the usual experimental situation, where it is generally desired to change the ambient conditions without changing the source.

In this report we shall discuss the scaling of pressure-distance curves for a particular model of a nuclear explosion using an ideal gas equation of state. A family of non-dimensional curves will be presented which allows scaling to different ambient conditions for a given energy source. These curves also make it possible to apply scaling close-in to the initial fireball.

In addition, it will be shown that the theoretical point source solution[2-5] for a shock of infinite strength in an ideal gas agrees with our computed solution (which does not assume a point source) over a wide range of scaled distance. However, neither the theoretical point-source solution nor our computed ideal-gas solution agrees with experimental data as well as do real-gas solutions.

2. DISCUSSION

2.1 Nuclear Explosion Model

A nuclear explosion in air is an extremely complex phenomenon, and many simplifying assumptions are necessary before it is possible to attempt any sort of analytic treatment. One approach is to assume that the explosion deposits an amount of radiative energy within a sphere of air in such a way that the temperature and pressure are increased in this sphere while the density remains at the ambient value. This heated sphere of air, at uniform temperature and pressure, then expands, creating a shock which propagates into the atmosphere.

Some further simplifications allow the numerical computation of the subsequent time evolution by means of a one-dimensional hydrodynamic computer code. This code considers only pure hydrodynamics, using an artificial viscosity to spread the shock over a few spatial zones. Such a numerical calculation has been carried out for a 1-kiloton explosion at sea level, using a real-gas equation of state for air.[8] The computed results for the airshock agree to within 5 per cent with experimental results,[6] for nuclear explosions, which shows that the model is useful for sea-level phenomena.

At this stage, it is natural to ask whether this type of calculation may be scaled to different ambient pressures. It turns out that a useful method of scaling does exist if the air is treated as an ideal gas. The method which we describe in the next section is a generalization of Sachs scaling for an ideal gas and allows scaling close-in to the fireball.

2.2 Scaling of Nuclear Explosions

Consider an ideal gas in which an amount of internal energy E is uniformly distributed throughout a sphere of radius a. The density and pressure in the ambient atmosphere (outside the energized sphere) are taken to be ρ_0 and p_0, respectively. The density within the sphere is taken to be ρ_0, and the particle velocity is initially zero everywhere. The origin of coordinates is taken at the center of the sphere, and r measures the radial distance from this origin. Then the following quantities are sufficient to describe the phenomena: a, E, p_0, ρ_0, r, t, γ, where t = time, and γ = ratio of specific heats for the ideal gas. We may form the set of dimensionless quantities:

$$\lambda = r/(E/p_0)^{1/3}$$

$$\tau = \frac{t p_0^{5/6}}{E^{1/3}\ \rho_0^{1/2}} \tag{1}$$

$$\zeta = a/(E/p_0)^{1/3}$$

(Note that, because of the ideal gas assumption, we have $\gamma = \frac{p_0}{\rho_0\ e_0} + 1$, where e_0 = internal energy per unit mass for ambient atmosphere.) It is not difficult to show that any other dimensionless parameters which may be formed from the available quantities a, E, p_0, ρ_0, r, t, γ must be functions of λ, τ, ζ, and γ. We may thus take this set of dimensionless parameters as a fundamental set for the description of the solution to our problem. λ and τ are the dimensionless independent variables, while ζ and γ are dimensionless constants.

Any dependent variable which describes some aspect of the evolution of the physical system can be non-dimensionalized and expressed in terms of our fundamental set. For instance, if p_s is the pressure at the shock front, we may put

$$\Pi = \frac{p_s}{p_0} = F_1\ (\lambda,\ \tau,\ \zeta,\ \gamma) \tag{2}$$

where F_1 is an unknown function which can only be obtained by solving the partial differential equations describing the problem. Similarly, the shock path equation must be representable in the form

$$F_2\ (\lambda,\ \tau,\ \zeta,\ \gamma) = 0 \tag{3}$$

We may obtain a dimensionless pressure-distance curve (pressure at the shock front as a function of shock position) by eliminating τ between (2) and (3). The result is an expression of the form

$$\Pi = F_3\ (\lambda,\ \zeta,\ \gamma) \tag{4}$$

If the function F_3 (λ, ζ, γ) could be somehow determined, a set of dimensionless pressure-distance curves could be generated, each curve being a plot of equation (4) for different values of ζ and γ. Each curve could then be used to predict shock pressure as a function of shock radius, subject to certain restrictions. That is, a given curve, labeled by $\zeta = \zeta_0$ and $\gamma = \gamma_0$, would not yield pressure versus distance for any arbitrary combination of γ, initial radius, ambient pressure, and explosion energy. It could be used only for values of a, E, p_0, ρ_0, ϵ_0 which satisfy $\frac{a}{(E/p_0)^{1/3}} = \zeta_0$ and $\frac{p_0}{\rho_0 \epsilon_0} + 1 = \gamma_0$.

This gives rise to the situation mentioned in the introduction, where it was stated that the scaling process requires that the parameters describing the source be changed when the phenomenon is scaled to different ambient conditions. Thus, suppose that we have available only a single Π versus λ curve, obtained from equation (4) by letting $\gamma = 1.4$ and letting ζ have some specific value, say ζ_0. Then $\zeta_0 = \left(\frac{E}{p_0}\right)^{-1/3} a$, and if we wish to scale to a new ambient pressure, say p_0', then we can use the same curve only if we also change E and/or a in such a way that $\left(\frac{E'}{p_0'}\right)^{-1/3} a'$ is still equal to ζ_0. This restriction can be avoided if a set of curves is available for which the associated values of ζ cover the desired range.

2.3 Dimensionless Pressure-Distance Curves

Such a set of curves has been generated using a one-dimensional hydrodynamic code[7] on an IBM-7090. This code solves the partial differential equations of gas dynamics using finite difference methods, and has been applied to the problem described above for various values of initial fireball radius and ambient pressure. From the complete solutions thus obtained, non-dimensional curves for the shock pressure versus shock radius have been constructed. These curves are plotted in Figures 1 and 2, which show the high pressure region ($\Pi > 100$), and low pressure region ($\Pi < 100$), respectively (see Appendix A). In Figure 1, the shock strength, Π, is plotted against λ, while in Figure 2, the overpressure, $\Pi - 1$ is plotted against λ; this distinction is made for reasons of clarity in plotting the low pressure region. The ambient atmosphere was assumed to be an ideal gas with $\gamma = 1.4$, so that the curves are plots of equation (4), for various values of ζ, and with $\gamma = 1.4$. (In particular, the curve for $\zeta = 0.0123$ was obtained from a calculation of a 1-kt nuclear explosion at sea level. For this case, the initial radius of the fireball was chosen to be a = 4.251 meters.)

It can be seen from Figure 1 that each curve joins onto a single main curve at approximately two fireball radii. A result of this fact is that, as far as distances greater than two fireball radii are concerned, only a single curve is necessary to scale any given pressure-distance calculation to some other ambient pressure. In this range, the curve is independent of the dimensionless variable* ζ, and the scaling used is what

* Actually, this is not strictly true, because of the fact that the second and subsequent shocks join the main shock at times which depend on the initial fireball radius. However, these appear only as minor perturbations to the main pressure-distance curve.

is ordinarily known as Sachs scaling. On the other hand, for scaling the close-in pressure-distance curve to other ambient pressures, it is first necessary to locate the proper dimensionless curve by calculating the appropriate value of ζ. This seems reasonable in view of the fact that at small distances the phenomena of energy transfer to the ambient air and the subsequent shock formation are certainly influenced by the initial fireball size. Therefore, we would not expect the scaling to be independent of a in this region.

It is evident from Figure 1 that the main curve is the envelope of the family of different ζ curves. (The complete main curve can be constructed by including the extrapolated portion, shown on the figure as a dashed line.) This main curve can also be considered to be a limiting curve which is approached by the ζ curve as $\zeta \to 0$. Since $\zeta \to 0$ may be achieved by letting $a \to 0$, while keeping E and p_0 constant, it is then clear that the main curve can be regarded as the pressure-distance curve for a point source of energy E in an atmosphere of ambient pressure p_0.

This interpretation of the main curve can be verified as follows. It can be shown from Figure 1 that, for $\Pi > 100$, the main curve is represented very well by the analytical formula

$$\Pi = 0.158 \lambda^{-3} \tag{5}$$

The problem of a point source explosion for a shock of infinite strength has been solved analytically by similarity methods[2,3,4] For the range of values in Figure 1, the shock strengths are quite high ($10^2 < \Pi < 10^5$), so that it seems reasonable to check equation (5) against these analytical results. The similarity theory yields for the pressure-distance curve the expression[4]

$$p = \frac{8}{25 (\gamma + 1) \alpha} E/r^3 \tag{6}$$

where α is a dimensionless quantity which depends only on γ. This quantity has been evaluated by Sedov[5] for $\gamma = 1.4$, and the result is $\alpha = 0.851$. Thus equation (6) takes the form

$$p = 0.1567 E/r^3 \tag{7}$$

If equation (5) is converted to dimensioned variables, p_0 cancels out and the expression becomes

$$p = 0.158 \, E/r^3 \qquad (8)$$

Comparing (7) and (8), we see that the correspondence between the computed and analytic result is excellent. Thus, for $\Pi > 100$, the main curve is identical with the point source, infinite shock strength, pressure-distance curve.

For lower shock strengths, we can expect that the main curve will deviate from the analytic pressure-distance curve given by (7). This is because (7) is derived under the assumption of infinite shock strength, so that the similarity solution is no longer correct when the shock pressure becomes sufficiently small. In fact, referring to Figure 2, we see that the two curves begin to deviate at $\Pi \cong 50$.

2.4 Comparison with Real-Gas Calculations and Experiment

In the previous sections, we have discussed pressure scaling for a particular model of a nuclear explosion. In this model, an ideal-gas equation of state was used for air, with $\gamma = 1.4$. Since it is known[8] that computations of this model with a real-gas equation of state agree closely (at sea level) with experiment, it is of interest to compare the ideal-gas result with the real-gas result. Figure 3 presents a comparison of these two treatments for the particular case of a 1-kiloton explosion at sea-level conditions. The ideal-gas result, for $\gamma = 1.4$, is obtained from Figures 1 and 2, using $\zeta = 0.0123$. (As we have seen, this curve coincides with the infinite-shock-strength, point-source solution for an ideal gas at distances greater than two fireball radii, and at shock strengths greater than 50.) An ideal-gas result has also been computed for $\gamma = 1.2$, which is a rough limit for γ at high pressures. The comparison then shows that the real-gas calculation agrees with experiment much better than does either of the ideal-gas calculations. In fact, it is clear that the ideal-gas calculation will not correspond with experiment for any value of γ, since the slopes of the ideal-gas curves differ considerably from the experimental and real-gas slopes.

It would therefore be logical to attempt to devise a scaling technique (analogous to the one previously described) for the same model of a nuclear explosion, but with the real-gas equation of state. Unfortunately, more sophisticated equations of state introduce new dimensional quantities which complicate the analysis considerably.

3. CONCLUDING REMARKS

In this report, we have reviewed the use of dimensional analysis to scale pressure-distance curves for a particular model of a nuclear explosion. The following conclusions may be stated:

3.1 It is possible to scale pressure-distance curves for the ideal gas by means of a family of non-dimensional Π versus λ curves, each curve corresponding to a particular value of ζ.

3.2 For distances larger than twice the fireball radius all of the ζ curves coincide, so that in this range only one non-dimensional curve is necessary.

3.3 Within two fireball radii one must first find the proper dimensionless curve to use by determining the relevant value* of the parameter ζ.

3.4 The envelope of the family of ζ-curves coincides with the point-source curve except for distances less than two fireball radii and for shock strengths less than 50.

3.5 All of the calculations described above apply for an ideal gas. A computer calculation made for a 1-kt explosion at sea level conditions, using a real-gas equation of state, gives better agreement with experiment than either the point-source solution or the ζ-curve solution.

* Any reasonable physical situation will usually have a value of ζ between zero and 0.05. Even conventional explosives have ζ values in this range: for pentolite at sea level, $\zeta = 0.014$. The particular explosion model discussed in this report, however, does not apply to high explosives, e.g., see reference 8.

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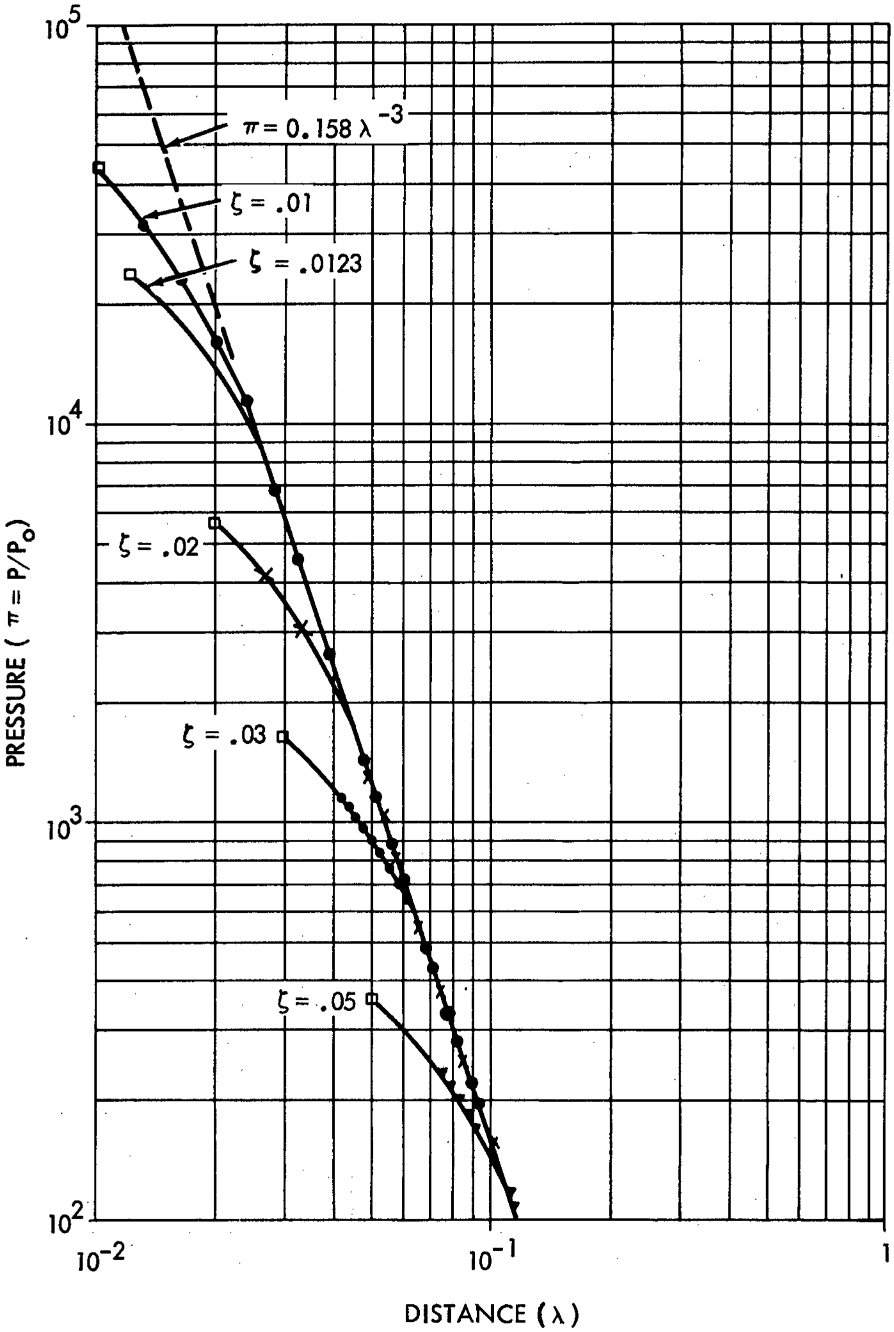

FIG. 1 π VERSUS λ FOR VARIOUS VALUES OF ζ, HIGH - π RANGE

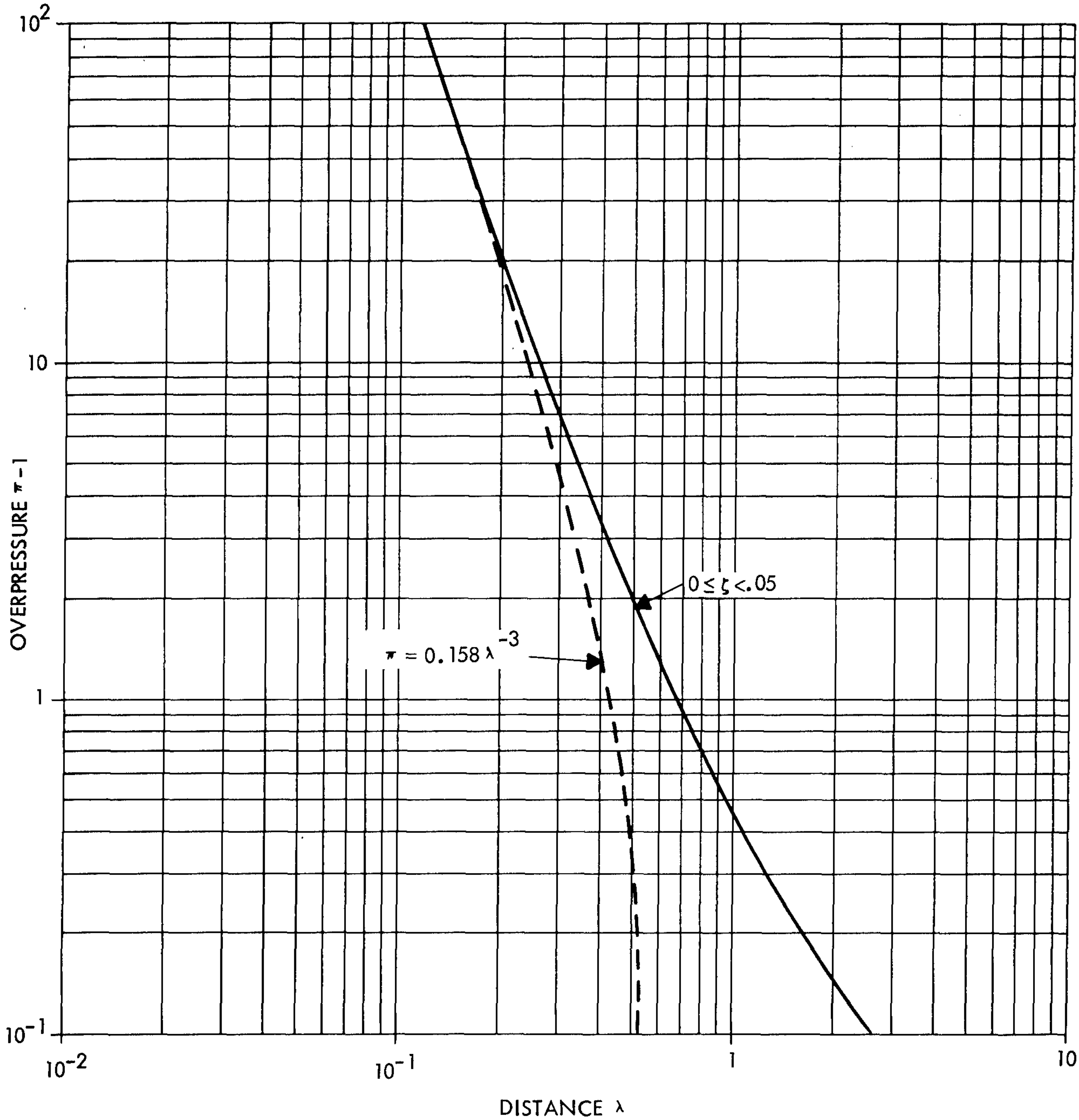

FIG. 2 π VERSUS λ, LOW- π RANGE

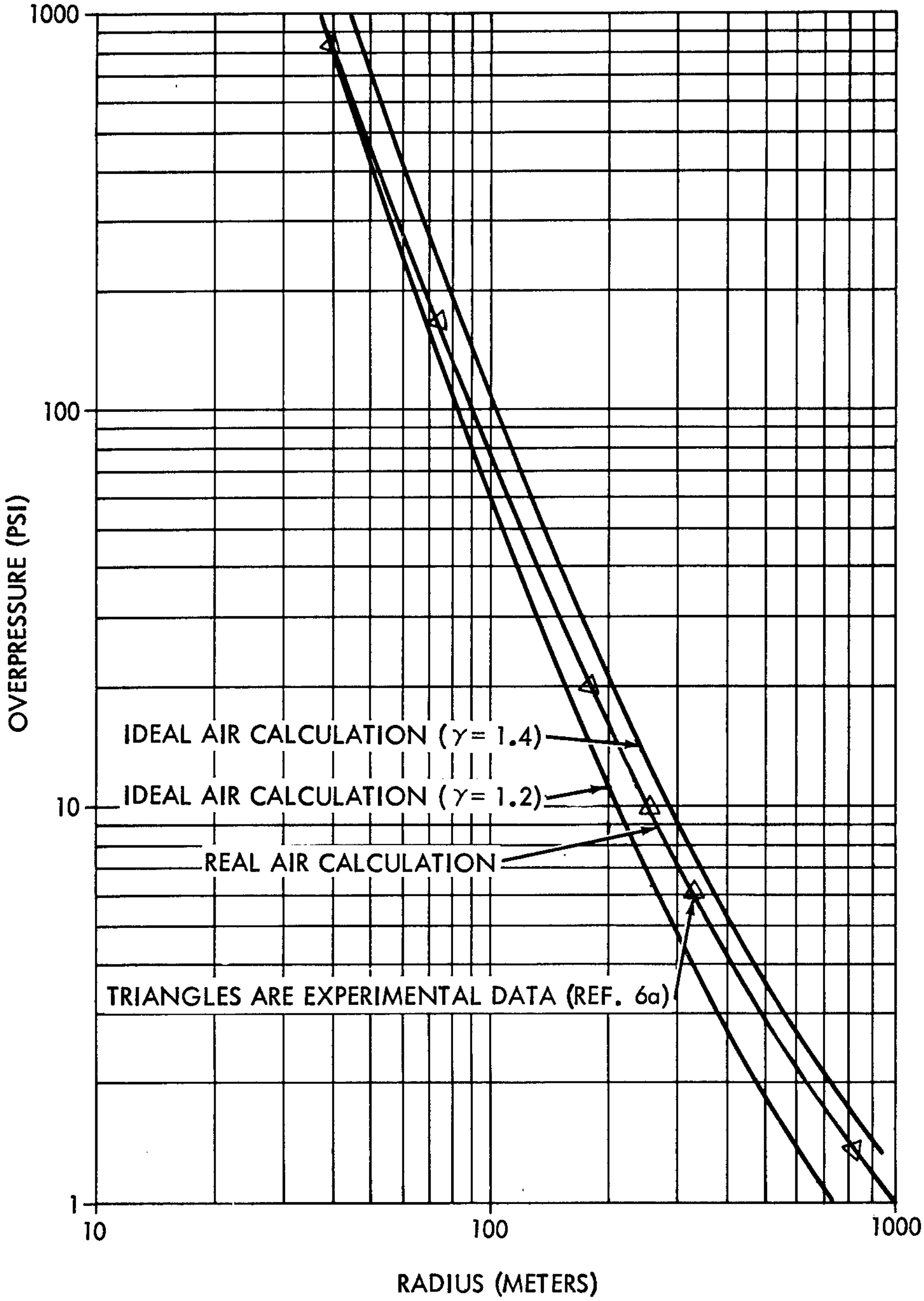

FIG. 3 REAL-AIR VS. IDEAL-AIR PRESSURE-DISTANCE CURVE FOR 1-KT AT SEA LEVEL

APPENDIX A

Initial Pressure Outside the Fireball

Figure A-1 shows some of the computed data points for the case $\zeta = 0.0123$. There is a small gap (labeled "corrected region") between the initial periphery of the fireball and the first meaningful shockfront data because of the finite zone size used in the calculations. This gap can be made smaller by using smaller zones in the problem, but this makes the computer running time excessively long. Instead, we derive theoretically the initial shockfront pressure and extend the curve through the computed data to this derived initial point.

The initial stages of airshock formation at the periphery of the fireball should be very much like those in a linear shock tube, because the interaction region is initially thin compared to the fireball radius. For a linear shock tube of reservoir conditions

P_1 = reservoir (fireball) pressure

c_1 = reservoir sound speed

γ_1 = reservoir specific heat ratio

and similarly defined ambient conditions P_0, c_0, γ_0, a shockfront with pressure P will form. These quantities are related by the equation*

$$\left(\frac{P}{P_0}\frac{P_0}{P_1}\right)^{\frac{\gamma_1 - 1}{2\gamma_1}} = 1 - \frac{c_0}{c_1}(\gamma_1 - 1)\left(\frac{P}{P_0} - 1\right)\left[2\gamma_0\left\{\gamma_0 - 1 + (\gamma_0 + 1)\frac{P}{P_0}\right\}\right]^{-\frac{1}{2}} . \quad \text{(A-1)}$$

The nuclear fireball situation differs from the usual shock tube at this point in that the density is equal on both sides of the interface rather than the temperature. For the fireball model being considered here,

$$\gamma_0 = \gamma_1 = 1.4$$

$$\rho_0 = \rho_1$$

$$\frac{c_0}{c_1} = \left(\frac{P_0}{P_1}\right)^{\frac{1}{2}} .$$

Equation (A-1) now becomes

* W. Bleakney and A. H. Taub, "Interaction of Shock Waves," Rev. Mod. Phys. 21, Oct 1949, p. 590.

$$\left(\frac{P}{P_0}\frac{P_0}{P_1}\right)^{\frac{1}{7}} = 1 - \left(\frac{P_0}{P_1}\right)^{\frac{1}{2}}\left(\frac{P}{P_0} - 1\right)\left[7\left(1 + 6\,\frac{P}{P_0}\right)\right]^{-\frac{1}{2}} \qquad \text{(A-2)}$$

For the high-pressure region where $P/P_0 \gg 1$,

$$\left(\frac{P}{P_1}\right)^{\frac{1}{7}} \cong 1 - \left(\frac{P}{P_1}\right)^{\frac{1}{2}}\frac{1}{\sqrt{42}} \qquad \text{(A-3)}$$

the solution of which is $P/P_1 = 0.464$. Thus, for large initial shock strengths the initial pressure in the airshock is 0.464 times the initial pressure in the fireball. This is the point to which the calculated data are extended in Figure A-1 to fill in the "corrected region."

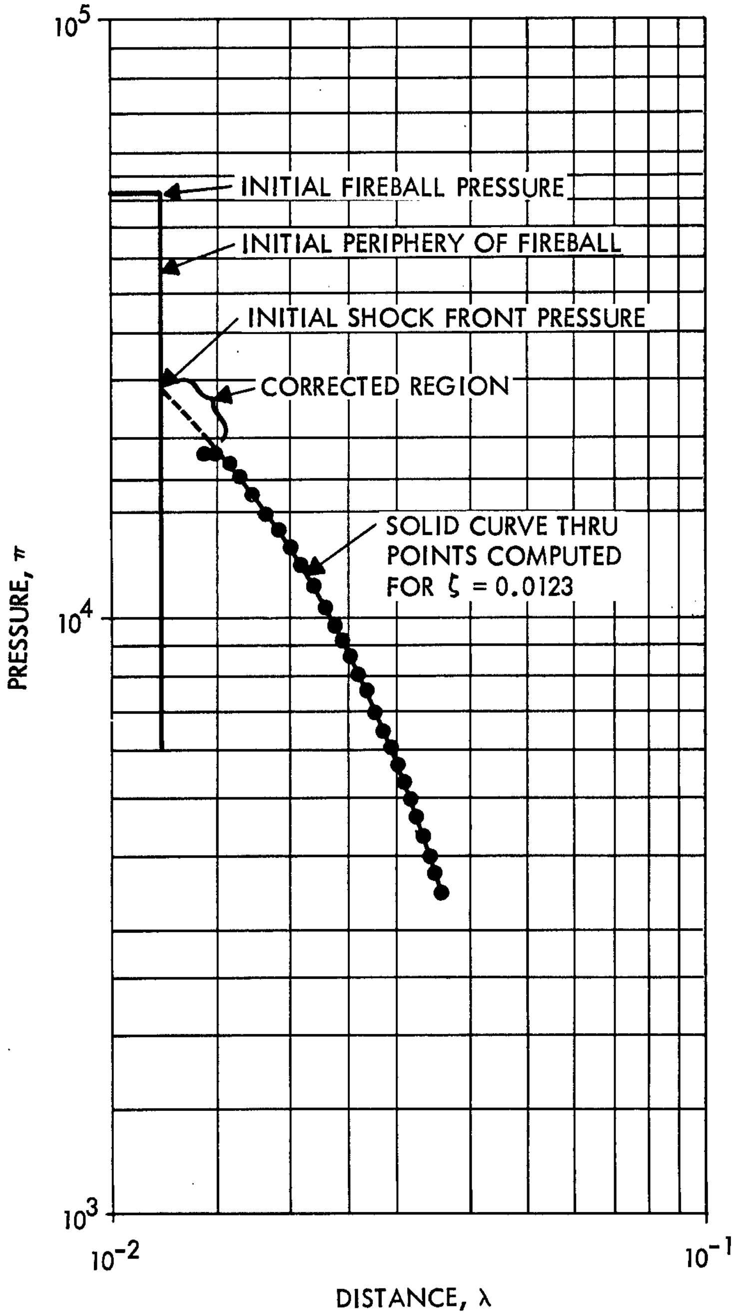

FIG. A-1 CORRECTION TO BEGINNING OF π VERSUS λ CURVE

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