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Prediction of Overpressure from Finite-Volume Explosions

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ABSTRACT

Tri-nitro toluene (TNT) equivalence is not a good criterion for evaluating the practically encountered nonideal blast waves during ignition and in explosion-safety problems. A theoretical model which shows the trends related to the effects of source volume and energy time release on blast wave strength is discussed. A slower energy release and a larger source volume are shown to be necessary to reduce the blast effects.

1. INTRODUCTION

The spontaneous release of energy in a small volume brings about strong pressure waves. The energy release in the source is partly dissipated into the environment through these strong pressure waves known as blast waves. In the literature the characteristics of the blast waves formed from instantaneous release of energy from a point source are well catalogued and are known as ideal blast waves. To a large extent, such blast waves are formed during the detonation of tri-nitro toluene (TNT). The overpressure of the blast wave formed in such idealised situations (instantaneous energy release at a point) is related to the distance travelled by the blast wave nondimensionalised with the characteristic length associated with the source energy. The data for the overpressure are available in safety manuals in the form of standard overpressure charts.

The prediction of the strength of the blast wave is of relevance in applications related to ignition and explosion safety. Most of the energy sources used for ignition, release their energies rather rapidly, thereby creating these strong blast waves. The release of energy, however, takes place over a finite duration in a finite volume unlike in the idealised condition conforming to instantaneous energy release at a point. This is because the ignition source has a definite volume and the energy release by chemical reactions takes some time. The same situation is true in most cases of the practically encountered explosions. The power density of the energy release is therefore finite and it becomes necessary to determine the blast waves generated from these finite power density sources in practical situations.

The present paper considers the trends in the changes of the strength of the blast wave from finite power density source when the duration of energy release and the volume of the energy source are changed. The strength of the blast wave is calculated by considering that the energy release from the source increases the kinetic and internal energies of the gas particles enclosed by the blast waves. The mass of the gas within the blast wave is assumed to be concentrated in the vicinity of the shock wave, following the Newtonian approximation of Laumbach and Probstein[1]. The formulation of this problem is given in Section 4 and the results are examined in Section 5. To focus on the relevant applications of such predictions, the role of dissipation of the source energy by the blast waves and the associated anomalies in igniter design and explosion safety are addressed in Sections 2 and 3.

2. PHYSICS OF THE PROBLEM

Release of energy into a medium takes place in any situation involving combustion and ignition. When the release of energy is slow, weak acoustic (sound) waves

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are formed. There is no dissipation of energy into the medium by these waves as evidenced by entropy generation. The fluid particles in the medium return to their original thermodynamic states upon the passage of the acoustic wave.

When the energy release at the source is very rapid, a decaying strong pressure wave (decaying shock wave), known as a blast wave, is formed. These blast waves have considerable overpressure and impulses. The transient crushing pressure and velocities at the blast wave front are followed by rapid expansion leading to vacuum pressures. Figure 1 shows pressure distribution in the medium as a blast wave passes through it. Before the arrival of the wave, the pressure is ambient pressure (P_0). When the shock wave arrives (time t_a) the pressure rises abruptly to a peak value $P_s^+ + P_0$. The pressure then decays to ambient in a time $t_a + T^+$, drops to partial vacuum with the pressure amplitude P_s^- (pressure $= P_0 - P_s^-$) and eventually returns to the ambient pressure, P_0 in a time $t_a + T^+ + T^-$.

3. APPLICATION TO IGNITER DESIGN AND EXPLOSION SAFETY

3.1 Application to Igniter Design

The overpressure P_s^+ followed by negative or suction pressure leads to a rapid quenching of combustion when the strength of the blast wave is significant and its characteristic time is comparable to that of combustion. In the design of igniters, it is therefore, essential that such blast waves which could quench combustion are not generated by the ignition source. This is true for any igniter which finds application in solid propellant rocket motor, liquid propellant rocket engine, gas turbine or a petrol internal combustion engine.

In addition to the extinguishment produced by the blast, the dissipation of energy into the medium by the shock wave is not available to the ignition source for heating the combustible and contributing to its ignition. It is therefore necessary that this dissipation of energy from the ignition source energy through the blast waves

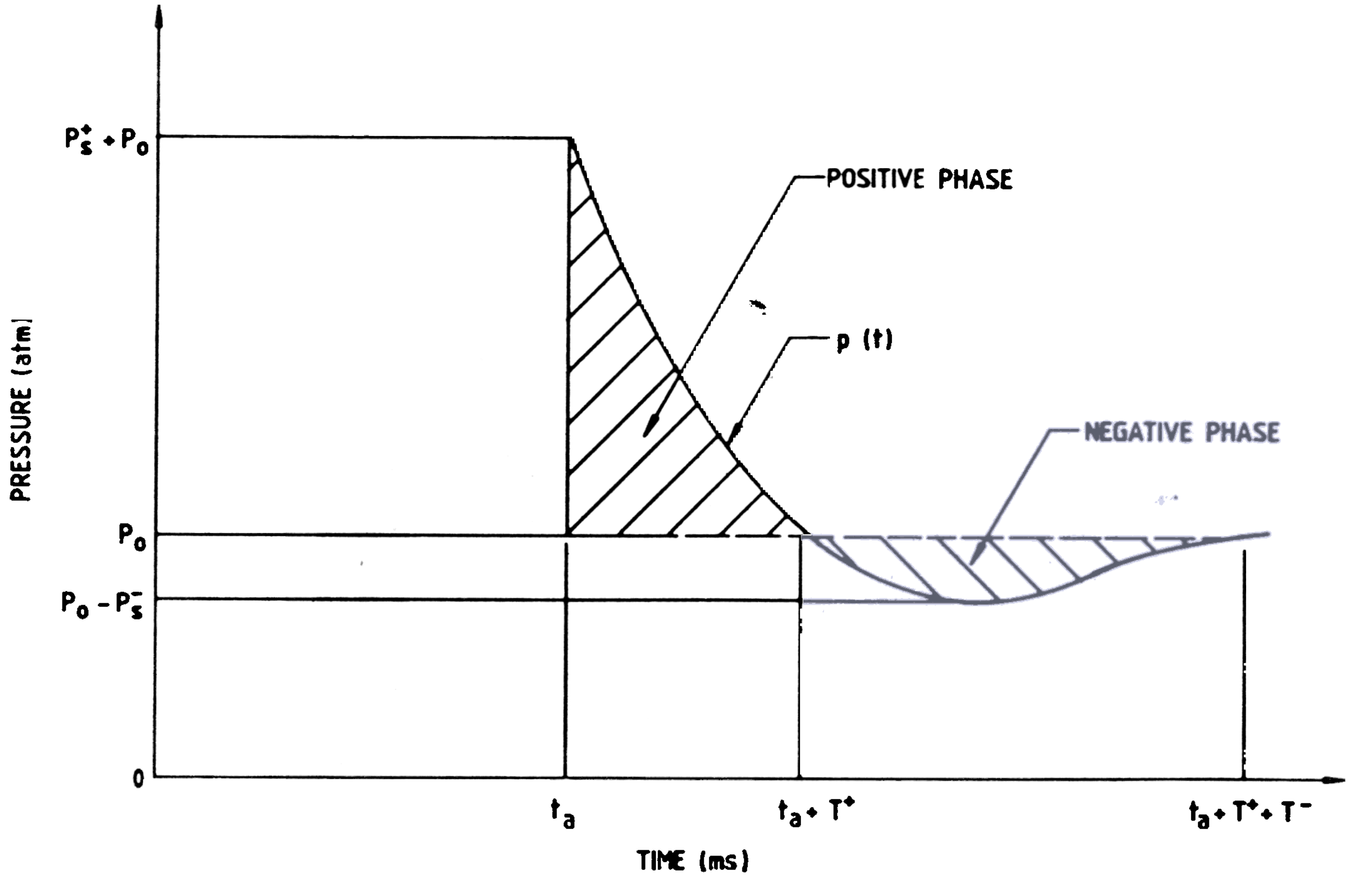

Figure 1. Pressure distribution in a medium during passage of a blast wave.

must be as small as possible to improve the effectiveness of transfer of energy from the source to the medium for ignition.

The existing theories of blast waves based on infinite power density with point sources would not be directly applicable for the ignition problem because the igniter source has a definite volume, and further the duration of energy release occurs over a period depending on the characteristics of the ignition source. It is of interest to characterise the blast waves formed from these finite power density ignition source and choose the design options of the volume and rate of energy released from the igniter (pyrotechnic, electrical spark, etc) such that strong blast waves with a persisting vacuum pressure behind them are not formed.

3.2 Predictions of Overpressure in Explosion

The present method of estimating blast energies on explosions is to first determine the equivalent weight of TNT which produces the same energy as the explosive. The overpressure of the blast wave is then calculated assuming that the blast wave from TNT behaves similar to an ideal blast wave. Experimentally it is shown that the overpressure from an ideal blast is similar to that obtained from TNT. The TNT equivalence is calculated by the following relation :

$$W_{TNT} = \frac{\text{Weight of explosive} \times \text{heat of reaction of explosive}}{4.198 \times 10^3}$$

Here 4.198×10^3 is the heat of explosion of TNT in J/kg. The heat of reaction of explosive is also expressed in J/kg. Since the energy release from the explosive would not be as rapid as TNT, the blast wave formed may not be as strong as that formed with the equivalent weight of TNT.

When we consider huge propellant quantities, such as in say PS125 motor and one is interested in determining the blast pressures in the case of malfunction of the motor, the above equivalence in terms of weight gives an abnormally high value which does not appear to be relevant. This is because of the longer times involved in energy release with the larger quantities of propellant. For this purpose we define the equivalent weight of TNT as that which produces an energy release equal to the pressure work arising from the bursting of the motorcase. The energy from the bursting of a given volume, V when its pressure is P_0 is given by :

$$E_s = V(P - P_0)/(\gamma - 1)$$

Here, γ is the ratio of specific heats, V is the sourc volume, P is the bursting pressure, and P_0 is the ambiei pressure. When V is expressed in cubic feet and P i psi, the equivalent TNT weight in lb is empirically give as[2] :

$$W_{TNT} = \{(1.49 \times 10^{-3} V)/(\gamma - 1)\}\{(P/14.7) - (P/14.7)^{1/\gamma}$$

It is to be noted that the blast waves predicted fro such equivalent TNT energy release source simulate tł point source for which the energy release takes plac instantaneously. It is not certain how the blast wa characteristics will get influenced due to the fini volume of the energy source and the actual duration (the energy release. Computations by Guirao[3] for bla waves from the expanding piston show higher shoc pressures than those formed from a point blast in tł near field. In the far field, however, the solutic matches with that from an ideal point source. It necessary to know the characteristics of blast wav formed in the practically encountered situations where the volume and energy release rates are finite.

In the case of liquid propellant spills which lead explosion, the time taken for the diffusion and mixi of the propellant vapour hinders the net rate of ener release. Small propellant spills for which mixing tim are less produce larger explosive yield than larger spil The yield becomes a function of propellant chemistr the size of the spill and environmental factors, such wind, which influences the mixing. In this situation is difficult to justify the use of an equivalent TNT aı an ideal blast wave theory to describe the overpressure

The role of the source volume and time of ener release in influencing the characteristics of blast wa therefore need to be ascertained and is considered the present investigation.

4. THEORETICAL FORMULATION

Consider the early time behaviour of the sho driven by the energy released as per the profile E_s in a sphere of radius R. The shock is assumed to sufficiently strong. The core of the gases, heated by t energy release, is hot and most of the shocked mass gas is concentrated in the vicinity of the shock froı We can therefore write, following Laumbach a Probstein[1] :

$$R_s \quad \varepsilon (R_s \quad R) \quad (1)$$

where ε is a small quantity, R_s is the shock radius and R and γ are the Lagrangian and Eulerian coordinates of the gas particle entering the shock.

The basic equations for continuity, momentum and energy in Lagrangian coordinates are:

Continuity

$$4\,\pi R^2\,\rho_0 dR = 4\,\pi\gamma^2\,\rho\,d\gamma \quad (2)$$

Momentum:

$$\{\delta^2\gamma(R,t)/\delta t^2\} + \{(\gamma/R)^2\,(1/\rho_0)\,(\delta p/\delta R)\} = 0 \quad (3)$$

Energy:

$$\{P(R,t)/\,\rho^\gamma\,(R,t)\} = P_s(R)/\,\rho_s^\gamma(R) \quad (4)$$

The jump conditions at the shock are given by Rankine Hugoniot relations. For strong shocks they are:

$$\rho_s\,/\,\rho_0 = \gamma+1/\gamma-1 \quad (5)$$

$$P_s = (2/(\gamma+1).\ \mathring{R}_s^2\,\rho_0 \quad (6)$$

Here $\mathring{R}_s$ is the shock velocity given by dR_s/dt. ρ is the density and P is the pressure. Subscript 0 denotes the initial condition of the gas while subscript s denotes the conditions behind the shock. Differentiating Eqn (1) with respect to R and using Eqns (2) and (5) we get

$$R_s - (\gamma \qquad \gamma+1)\ (R \quad R) \quad (7)$$

The energy deposited in the source volume $E_s(t)$ goes to increase the kinetic and internal energies of the gas enclosed by the shock. We can therefore write :

$$E_s(t) = \int_0^{R_s(t)} \frac{1}{2}\left(\frac{d\gamma}{dt}\right)^2 \rho\,4\pi\gamma^2\,d\gamma + \int^{R_s(t)} \frac{p}{\gamma-1}\,4\pi\,\gamma^2\,d\gamma \quad (8)$$

Rewriting dr/dt from Eqn (7) in terms of dR_s/dt and expressing P from Eqn (3) in terms of dR_s/dt and simplifying we get Eqn (8) in the form

$$d^2R_s/dt^2 + (A/R_s)\,(dR_s/dt)^2 - B/R_s^4 = 0 \quad (9)$$

where

$$A = 24\gamma/(\gamma+7)$$

$$B = \{9((\gamma+ \quad (\gamma-1))/(2\pi\rho_0\,(\gamma+7))\} \times E_s(t)$$

The above second order ordinary differential equation can be integrated for any pattern of energy release $E_s(t)$ and for any given size (R_i) of the source. The initial condition at $t = t_0$ can be specified as either

$$R_s = R_i\ ;\ dR_s/dt = C_0$$

where C_0 = acoustic velocity

Alternatively, at a small time t_0, we can write

$$p = \{(\gamma\text{-}1)\ E_s(t_0)\}/(4\ \pi R_i^3/3)$$

$$R_s = R_i$$

$$dR_s/dt = \text{sqrt}\ (p(\gamma+1)/2\rho_0)$$

For the case of instantaneous energy release, viz.,

$$E_s(t) = E_o$$

Equation (9) can be solved to yield

$$R_s = C\ (\gamma)\ (E_0/\rho_0)^{1/5}\ t^{2/5}$$

which is similar to the solution of an ideal blast wave[4].

In the following, the characteristics of blast waves obtained when the volume of the source and the energy release time are changed, are determined by the use of Eqn (9) with initial conditions given by Eqns (10) and (11).

5. RESULTS AND DISCUSSION

Predictions of Eqn (12) for shock radius derived in the limit of instantaneous energy release match reasonably with the ideal blast wave theory. Thus for γ = 1.4, Eqn (12) gives the blast wave trajectory as $0.996\ (E_0/\rho_0)^{1/5}\ t^{2/5}$, whereas the ideal blast wave theory gives the value as $1.067\ (E_0/\rho_0)^{1/5}\ t^{2/5}$. Here, ρ_0 is the ambient density.

Having seen the agreement of Eqn (12) for blast wave in the limit of an ideal blast wave, the shock velocity and trajectory of blast wave are determined as the duration of energy release and the source volume are changed. Figure 2 gives the computed velocity of the blast wave as the volume of the source is increased from 0.1 to 5 m for a given energy release specified by

$E_t = 10^{10}t$ J for $t \le 0.5$ ms

$E_t = 0$ for $t > 0.5$ ms

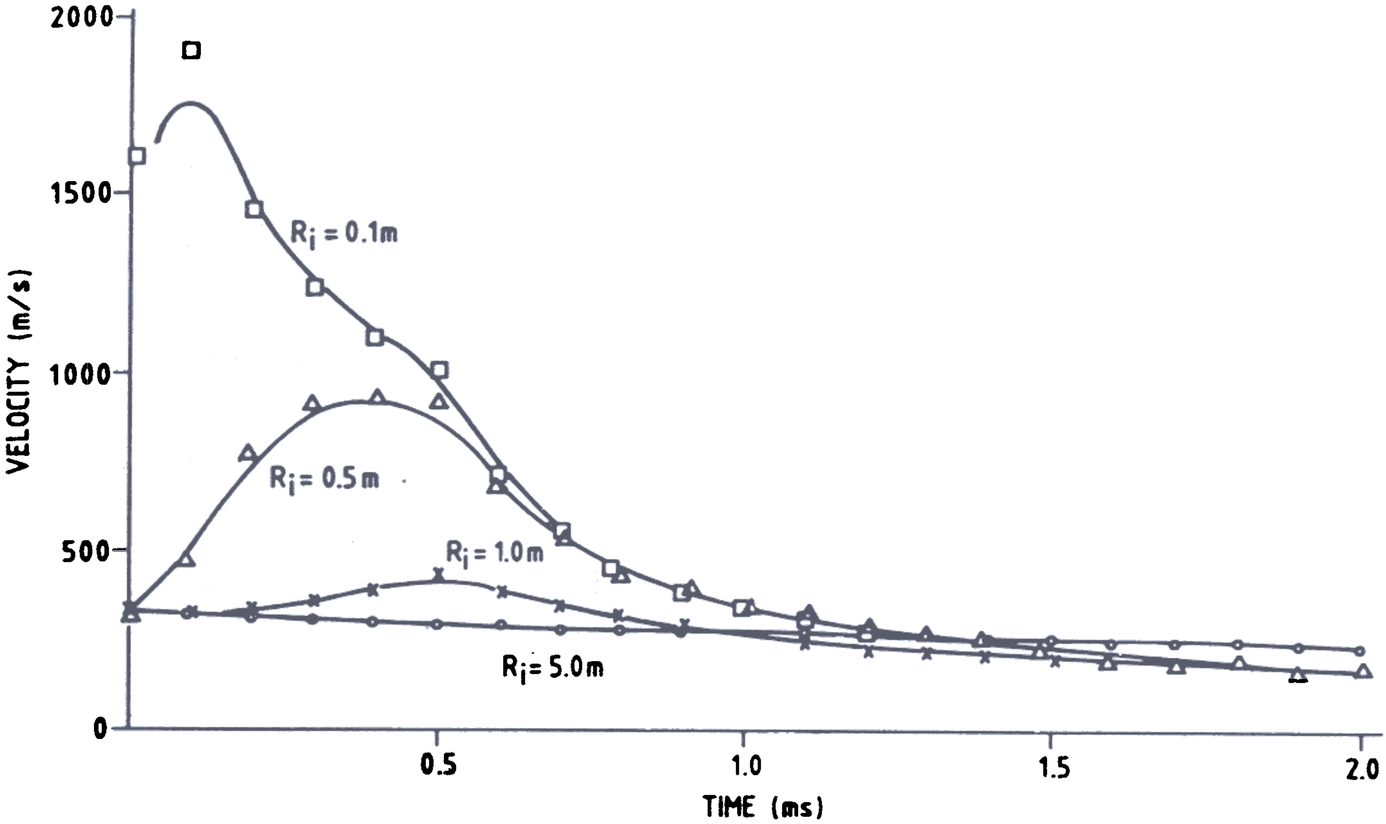

Figure 2. Dependence of blast wave velocity on volume of energy source ($E_s = 10^{10}\ t$ J, $t < 0.5$ ms).

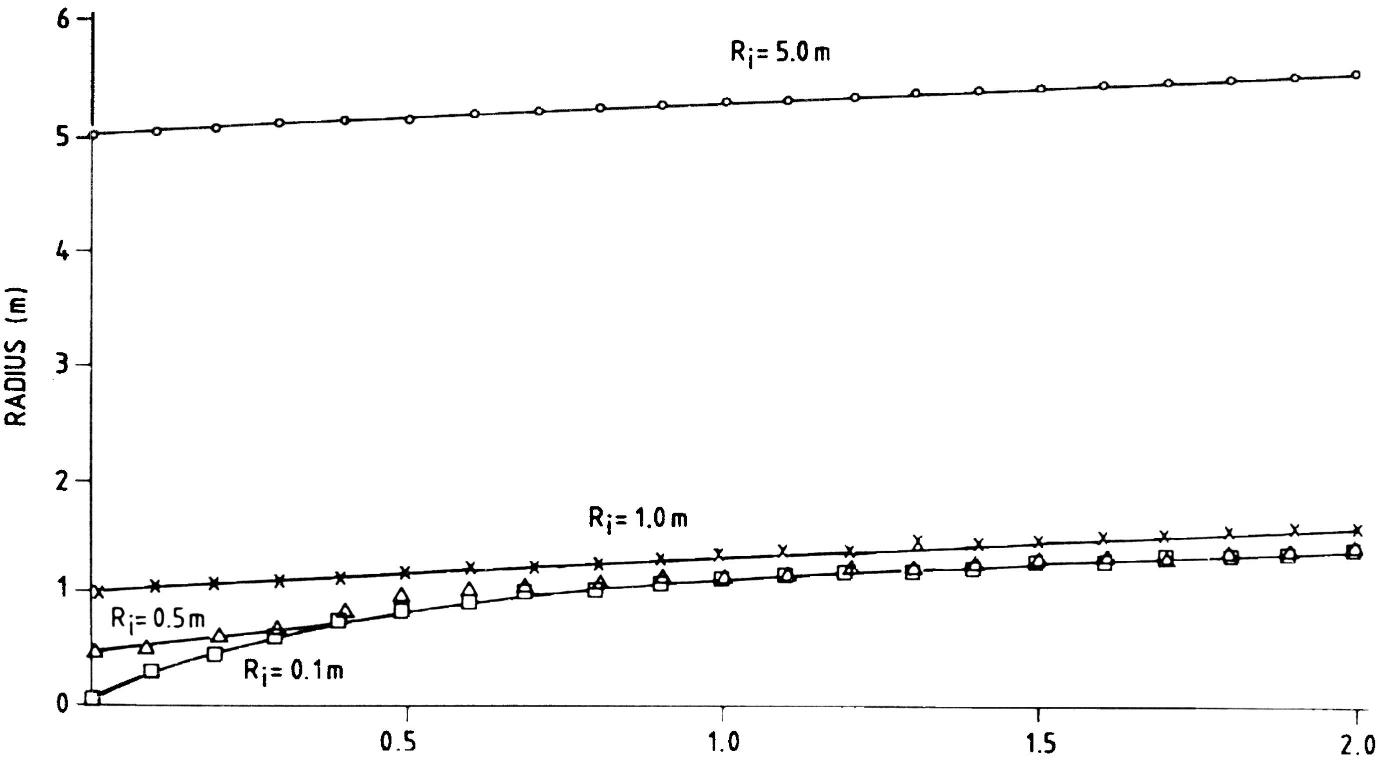

Figure 3. Blast trajectory for source volume changes ($E_s = 10^{10}\ t$ J, $t < 0.5$ ms).

The blast wave trajectory for this case is given in Fig. 3. It is seen from Fig. 2 that the shock velocity rapidly drops as the source volume increases. From the shock velocity, the overpressure can be calculated using the Rankine Hugoniot equations.

A more sustained energy release obtained by keeping the power of the source constant also produces a stronger blast wave. Thus Fig. 4 shows the shock velocity for source energy release given by

$$E_t = 10^{10} tJ \quad \text{for } t \leq 0.5 \text{ ms}$$
$$= 0 \quad \text{for } t > 0.5 \text{ ms}$$

and
$$E_t = 10^{10} tJ \quad \text{for } t \leq 0.1 \text{ ms}$$
$$= 0 \quad \text{for } t > 0.1 \text{ ms}$$

The computations are for an initial shock radius of 0.1 m. It is seen that for sustained energy release rates higher shock velocities are generated. The blast radius is also larger for the sustained energy release as shown in Fig. 5.

To determine the influence of rate of energy release keeping the total energy constant, we consider a total energy release of 100 J in a sphere of diameter 1 mm. We allow this energy to be released at two rates as given in the following:

case A
$$E_t = 10^6 tJ \quad \text{for } t \leq 0.1 \text{ ms}$$
$$= 0 \quad \text{for } t > 0.1 \text{ ms}$$

case B
$$E_t = 10^5 tJ \quad \text{for } t \leq 1 \text{ ms}$$
$$= 0 \quad \text{for } t > 1 \text{ ms.}$$

Computations show that with the slower energy release in the case B, the maximum shock velocities are only one-fourth the values obtained in the case A.

In the case of an instantaneous energy release of 100 J in a spherical source volume whose radius increases from 1 to 10 mm, the blast wave velocity rapidly falls to one-sixteenth as the source volume increases.

The dimensional calculations above show the dominant influence of the source volume and energy release rates on the strength of the blast wave and hence its overpressure. A larger source volume and a slower energy release in nonideal blast waves is seen to bring down the blast strength drastically.

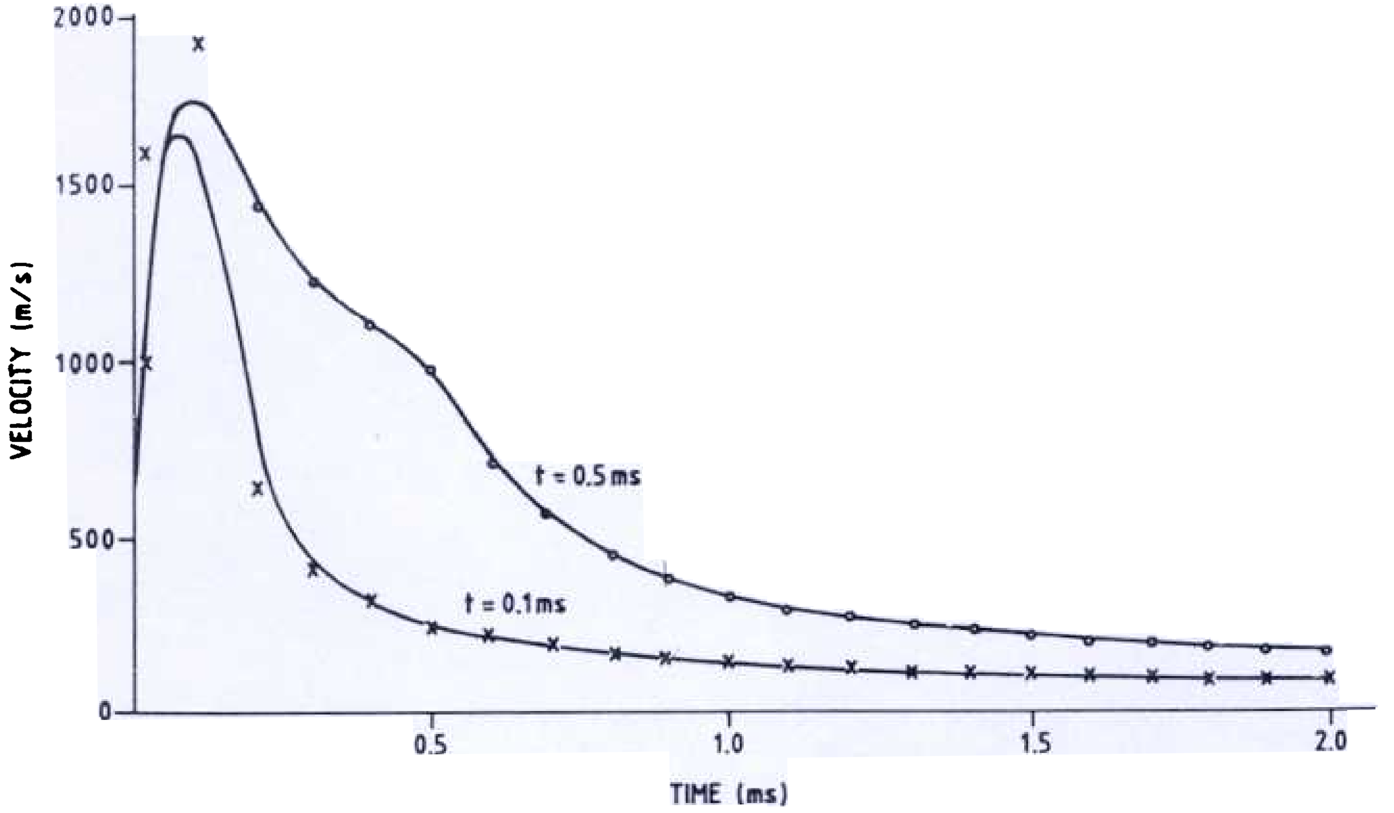

Figure 4. Blast wave augmentation with a sustained energy source.

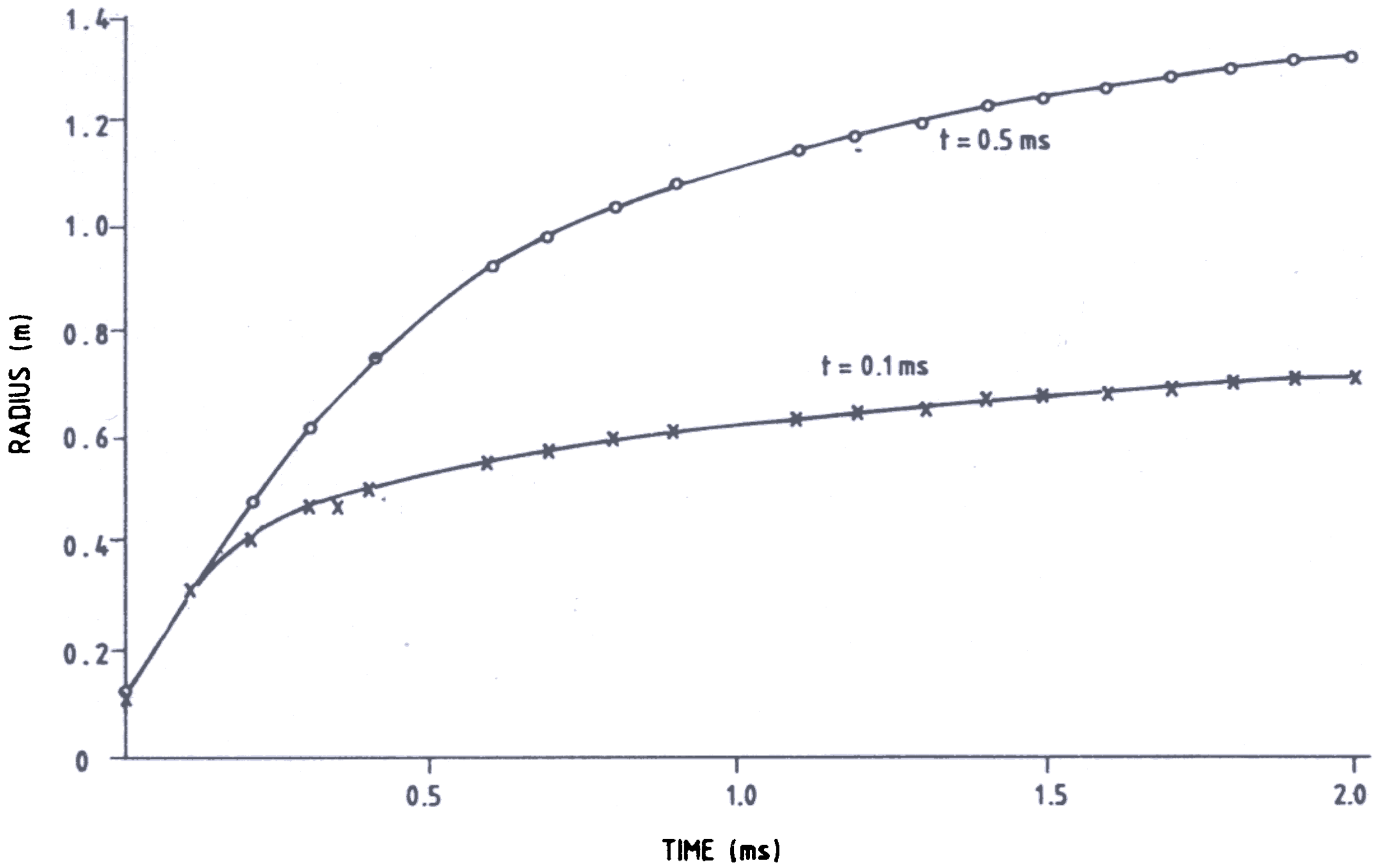

Figure 5. Increased penetration of blast wave with a sustained energy source.

6. CONCLUSIONS

Examination of the blast wave in the near-field region shows the importance of the power density of energy release in influencing blast wave strength through the source volume a... the time of energy release. An increase of the source volume and a lower energy release from the igniter can therefore increase the effectiveness of the igniter. Similarly, a larger volume of explosion produces a lower blast strength for the same energy release. Energy release by electrical discharges of short durations has shown a significant dissipation of the source energy by blast waves[5,6] which is not available for ignition. Similar influences are seen to be true for other energy releases encountered in ignition systems and atmospheric explosions.

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