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APPLICATION OF THE VARIABLE ENERGY  
BLAST WAVE THEORY TO LIQUID MONO-  
PROPELLANT IGNITION BY SHOCK WAVES

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Dover, New Jersey

December 1972

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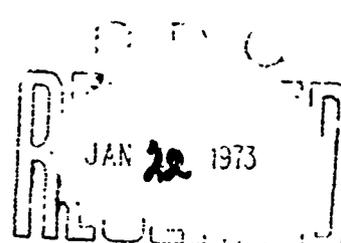
TECHNICAL REPORT 4356

APPLICATION OF THE VARIABLE ENERGY BLAST  
WAVE THEORY TO LIQUID MONOPROPELLANT  
IGNITION BY SHOCK WAVES



E. K. DABORA

DECEMBER 1972



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The zero order solution for a variable energy spherical blast wave in which the total energy release E is deposited proportionally to  $t^\beta$ , where t is the time, is shown to be

$$R = \left[ \frac{\nu E}{4\pi \rho_0 J_0} \left( \frac{5}{2 + \beta} \right)^2 \right]^{1/5} (t/t_i)^{\beta/5} \cdot t^{2/5}$$

where R is the shock radius and  $t_i$  is the duration of energy input. The factor  $J_0$  is related to the flow field via  $\beta$ .

Sample calculations of this equation on the basis of possible energy release from ethyl nitrate droplets and a comparison with experimental results are made. It appears that values of  $\beta = 5$  and  $t_i = 10 \mu\text{sec}$  give reasonable agreement. However, more accurate theoretical calculations need be made and more experimental data need be obtained before firm conclusions could be drawn.

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APPLICATION OF THE VARIABLE ENERGY BLAST WAVE  
THEORY TO LIQUID MONOPROPELLANT  
IGNITION BY SHOCK WAVES

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## NOMENCLATURE

$a_0$	= Speed of sound in the undisturbed gas
$E$	= total energy ( $\alpha=2$ ), energy/unit length ( $\alpha=1$ ), energy/ unit area ( $\alpha=0$ )
$E_\alpha$	= see equation 11
$f$	= nondimensional velocity
$g$	= nondimensional pressure
$h$	= nondimensional density
$J$	= constant defined in equation 26
$J_0$	= value of $J$ when $y \rightarrow 0$
$M$	= Mach number
$p$	= pressure
$r$	= distance from site of energy source
$R$	= shock radius
$R_0$	= explosion scale radius (equation 34)
$R$	= nondimensional shock radius (equation 42)
$t$	= time after start of energy input
$t_i$	= duration of energy input
$u$	= velocity
$U$	= shock velocity
$W$	= proportionality constant
$x$	= $r/R$

- $y$  =  $1/M^2$
- $\alpha$  = geometry index = 2 (spherical), 1 (cylindrical), 0 (planar)
- $\gamma$  = ratio of specific heats
- $\lambda$  = decay coefficient (equation 17)
- $\lambda_0$  = decay coefficient when  $y \rightarrow 0$
- $\rho$  = density

## ABSTRACT

A brief review of the literature on blast wave theory is conducted. Special attention is devoted to the variable energy blast wave because of its possible applicability to two-phase detonation phenomena and the ignition of liquid monopropellants by shock waves.

The zero order solution for a variable energy spherical blast wave in which the total energy release  $E$  is deposited proportionally to  $t^\beta$ , where  $t$  is the time, is shown to be

$$R = \left[ \frac{\gamma E}{4\pi\rho_0 J_0} \left( \frac{5}{2 + \beta} \right)^2 \right]^{1/5} (t/t_i)^{\beta/5} \cdot t^{2/5}$$

where  $R$  is the shock radius and  $t_i$  is the duration of energy input. The factor  $J_0$  is related to the flow field via  $\beta$ .

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## INTRODUCTION

The classical blast wave theory refers generally to the propagation of shock waves in a gaseous medium due to an instantaneous energy input in an infinitesimally small region of that medium. The energy input can be in a point, along a line, or in a plane, with the resultant wave and attendant flow fields being spherical, cylindrical, or planar, respectively. Interest in the theory started in the early forties with the pioneering analysis of G. I. Taylor (Ref 1), which was not published until 1950. Since then a very large amount of work on the subject has been published in the international literature. For comprehensive reviews, the reader is referred to the works of Sakurai (Ref 2), Sedov (Ref 3), and Lee, Knystautas and Bach (Ref 4). The proliferation of analyses naturally has resulted in different and sometimes confusing sets of nomenclatures. A comparison of the symbols used by important contributors for the pertinent parameters is presented by Oppenheim et al (Ref 5).

Early treatment of the subject was based on the assumptions that the energy input is instantaneous and that transport properties are unimportant. With these assumptions, dimensional analysis (Ref 3) yields functional relationships between the energy input and distance, arrival time, and velocity of the shock front without complete solution of the relevant conservation equations. However, for detailed characteristics of the flow field (i. e., pressure, density, temperature, and velocity of the gas behind the shock), numerical solutions are generally required (Ref 1, 2). Solutions for the flow field near the energy source region, where transport properties are important, have appeared in the literature (see, e. g., Bowen (Ref 6) where the method of asymptotic matching technique is used). Problems in which the effect of the energy source mass is important (piston problem) also have been analyzed (Goldsworthy (Ref 7), Grigorian et al (Ref 8)). Also, Lauback and Probstein (Ref 9) treat the case of point explosion in a variable density atmosphere.

While the assumption of instantaneous energy input is adequate for most cases and certainly for time periods much greater than the input times, there are processes in which the energy input, though very fast, can be considered time dependent. Examples are discharges, exploding wire phenomena, accelerating hypersonic body, and chemical energy release. An example of the latter is the

blast wave generated in two-phase detonations (Ref 10, 11) and shock ignition of liquid monopropellant droplets (Ref 12). A certain class of time dependent energy input is known to be amenable to a similarity solution (Ref 2). Freeman (Ref 13) treats this problem in some detail but confines his treatment to a cylindrical geometry, since he was interested mainly in applying his results to spark discharges (Ref 14). This report will be concerned with the variable energy blast wave and its application to two-phase detonations.

## BLAST WAVE EQUATIONS

The conservation equations applicable to blast waves are as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial r} = -\rho \left( \frac{\partial u}{\partial r} + \frac{\alpha u}{r} \right) \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} = -\frac{1}{\rho} \frac{\partial p}{\partial r} \quad (2)$$

$$\frac{\partial}{\partial t} (\rho r^{-\alpha}) + u \frac{\partial}{\partial r} (\rho r^{-\alpha}) = 0 \quad (3)$$

for mass, momentum, and energy, respectively. Here transport terms as might appear in the momentum and energy equations are omitted. The symbol  $\alpha$  characterizes the geometry considered. Thus,

$$\alpha = 0 \rightarrow \text{planar case}$$

$$\alpha = 1 \rightarrow \text{cylindrical case}$$

$$\alpha = 2 \rightarrow \text{spherical case}$$

Combination of equations (3) and (1) yields

$$\frac{\partial p}{\partial t} + u \frac{\partial p}{\partial r} = -\gamma p \left( \frac{\partial u}{\partial r} + \frac{\alpha u}{r} \right) \quad (4)$$

If the position of the shock at time  $t$  after the initiation of energy input is  $R$  from the input location, then the velocity of the shock is given by

$$U = \frac{dR}{dt} \quad (5)$$

The boundary conditions that can be used to solve equations (1), (2), and (4) are the normal shock conditions. Thus, since the velocity of sound in the undisturbed medium is

$$a_0 = \sqrt{\gamma p_0 / \rho_0} \quad (6)$$

and the Mach number of the shock wave is

$$M = U/a_0 \quad (7)$$

the boundary conditions at  $r = R$  are

$$\frac{u}{U} = \frac{2}{\gamma+1} \left( 1 - \frac{1}{M^2} \right) \quad (8)$$

$$\frac{p}{p_0} = \frac{2\gamma}{\gamma+1} M^2 - \frac{\gamma-1}{\gamma+1} \quad (9)$$

$$\frac{\rho}{\rho_0} = \left( \frac{\gamma+1}{\gamma-1} \right) \left( 1 + \frac{2}{(\gamma-1)M^2} \right) \quad (10)$$

These conditions, together with the conditions relating the energy input to the kinetic energy and the internal energy change in the gas behind the shock, are, in principle, sufficient for a complete solution of the problem. The latter condition can be written as:

$$E_\alpha = \int_0^R \left( \frac{1}{2} \rho u^2 + \frac{p-p_0}{\lambda-1} \right) r \alpha dr \quad (11)$$

where:

$E_0$  = Energy input per unit area

$E_1 = \frac{1}{2\pi}$  . (Energy input per unit length)

$E_2 = \frac{1}{4\pi}$  . (Energy input)

The blast wave equations can be transformed in terms of two independent variables which are chosen to fit the similarity solution. These variables are

$$x = r/R \quad (12)$$

and

$$y = 1/M^2 \quad (13)$$

The dependent variables then are

$$u = U f(x, y) \quad (14)$$

$$p = \frac{p_0}{\gamma} g(x, y) \quad (15)$$

$$c = \rho_0 h(x, y) \quad (16)$$

where  $f$ ,  $g$ , and  $h$  are to be determined. If a decay coefficient is defined as

$$\begin{aligned} \lambda &\equiv \frac{d \ln y}{d \ln R} \quad (17) \\ &= -2 \frac{d \ln U}{d \ln R} \\ &= -2 \frac{R d^2 R / dt^2}{(dR/dt)^2} \end{aligned}$$

Then equations (1), (2), and (4), after using equations (12-17), can be transformed, respectively, to

$$(f-x) \frac{\partial h}{\partial x} + \lambda y \frac{\partial h}{\partial y} = -h \left( \frac{\partial f}{\partial x} + \frac{\alpha f}{x} \right) \quad (18)$$

$$-\frac{1}{2} \lambda f + (f-x) \frac{\partial f}{\partial x} + \lambda y \frac{\partial f}{\partial y} = -\frac{1}{\gamma h} \frac{\partial g}{\partial x} \quad (19)$$

$$-\lambda g + (f-x) \frac{\partial g}{\partial x} + \lambda y \frac{\partial g}{\partial y} = -\gamma g \left( \frac{\partial f}{\partial x} + \frac{\alpha f}{x} \right) \quad (20)$$

The boundary conditions of equations (8) to (10) are changed to

$$f(1, y) = \frac{2}{\gamma+1} (1-y) \quad (21)$$

$$g(1, y) = \frac{2\gamma}{\gamma+1} - \frac{\gamma-1}{\gamma+1} y \quad (22)$$

$$h(1, y) = \frac{\gamma+1}{\gamma-1} \left/ \left( 1 + \frac{2y}{\gamma-1} \right) \right. \quad (23)$$

When an explosion scale radius is defined as

$$R_0 \equiv (E_\alpha / p_0) \frac{1}{\alpha+1} \quad (24)$$

then condition (11) becomes

$$y(R_0/R)^{\alpha+1} = J - \frac{y}{(\alpha+1)(\gamma-1)} \quad (25)$$

where

$$J \equiv \int_0^1 \left( \frac{\gamma}{2} hf^2 + \frac{g}{\gamma-1} \right) x^\alpha dx \quad (26)$$

It can be seen that when  $M^2 \gg 1$ ,  $y \rightarrow 0$  and therefore equations (18-20) become ordinary differential equations. Furthermore, the boundary conditions (21-23) are simplified, and the last term in equation (25) can be neglected. Despite these simplifications, however, the integral  $J$  must still be numerically calculated after numerical calculation of  $f$ ,  $g$ , and  $h$ . The zero order value of  $J$ , i.e.,  $J_0$ , under these simplifications, is found to be, for  $\gamma = 1.4$  (see Sakurai, Ref 2)

$$\begin{aligned} J_0 &= 0.596 && \text{(spherical)} \\ &= 0.878 && \text{(cylindrical)} \\ &= 1.696 && \text{(planar)} \end{aligned} \quad (27)$$

It should be mentioned that these values are applicable for the case where  $E_\alpha$  is instantaneous. Under this condition, equations (25) and (24) show that

$$R^{\alpha+1} = \frac{1}{J_0} y \left( \frac{E_\alpha}{p_0} \right)^{\frac{1}{\alpha+1}} \quad (28)$$

and since the independent variable  $y$  from equation (13) is

$$y = a_0^2 / \left( \frac{dR}{dt} \right)^2 \quad (29)$$

then by combining (28) and (29) and integrating, it is found that

$$R = t^{\frac{2}{\alpha+3}} \left[ \left( \frac{\alpha+3}{2} \right)^2 \cdot \frac{E_\alpha a_0^2}{p_0 J_0} \right]^{\frac{1}{\alpha+3}} \quad (30)$$

and

$$\frac{dR}{dt} = \frac{2}{\alpha+3} t^{\frac{-\alpha+1}{\alpha+3}} \left[ \left( \frac{\alpha+3}{2} \right)^2 \frac{E_\alpha a_0^2}{p_0 J_0} \right]^{\frac{1}{\alpha+3}} \quad (31)$$

These are the functional relationships of the shock position and its velocity for the zero order solution. The decay coefficient  $\lambda_0$  in equation (17) can be found to be

$$\lambda_0 = \alpha + 1 \quad (32)$$

The decay coefficient for  $y > 0$  has been calculated by Sakurai (Ref 2), Freeman (Ref 13) and Goldstine and von Neumann (Ref 15). In this case the flow field does not exhibit similarity, and resort to first and higher order solutions must be made for its accurate description (Ref 2, 13).

## VARIABLE ENERGY INPUT

As was mentioned before, Freeman (Ref 13) analyzed in detail the case for a constant rate of energy input in a cylindrical geometry. In this section the zero order solution for the general case will be presented and compared with the instantaneous energy input case. For this, the energy input is assumed to vary with time as follows:

$$E_{\alpha} = W_{\alpha} t^{\beta} \quad (33)$$

where  $W_{\alpha}$  is a dimensional constant of proportionality whose dimensions depend on the power  $\beta$ . The case of the instantaneous energy input is covered by setting  $\beta = 0$ . If an explosion scale radius is defined as

$$R_0 = \left( \frac{W_{\alpha} t^{\beta}}{p_0} \right)^{\frac{1}{\alpha+1}} \quad (34)$$

it can be shown that the shock radius can be written as

$$R = Kt^n \quad (35)$$

where

$$K = \left( \frac{W_{\alpha} a_0^2}{p_0 n^2 J_0} \right)^{\frac{1}{\alpha+3}} \quad (36)$$

and

$$n = \frac{\beta+2}{\alpha+3} \quad (37)$$

Also the decay coefficient becomes

$$\lambda_0 = \frac{2(1+\alpha-\beta)}{2+\beta} \quad (38)$$

It is to be noted that when  $\beta = 0$ , equation (35) reduces to equation (30) since  $W_\alpha = E_\alpha$  and equation (38) reduces to (32). While  $J_0$  appears in the general case, it must be mentioned that its value depends on the flow field (see equation 26). Since the flow field depends on  $\beta$  via  $\lambda$  in equations (19) and (20), the value of  $J_0$  for constant  $\alpha$  has a different numerical value for different  $\beta$ . For example, if  $\nu = 1.4$  and  $\alpha = 1$  (cylindrical case),  $J_0 = .378$  for  $\beta = 0$ , and  $J_0 = .561$  if  $\beta = 1$ . Freeman (Ref 13) calculated  $J_0$  for  $\alpha = 1$ ,  $\beta = 0$  and 1 for various  $\nu$ ; but apparently  $J_0$  for the spherical case has not been calculated for  $\beta \neq 0$  (Ref 16).

To see the effect of energy input duration, we focus our attention to cases where the total energy is constant. Thus, equation (33) can be written as

$$E_\alpha = W_\alpha t_i^{\beta} \quad (39)$$

where  $t_i$  is the duration of input energy. Substituting equation (39) in (36) and using (35), we find

$$R = \left( \frac{a_o^2}{p_o n^2 J_0} \frac{E_\alpha}{t_i^\beta} \right)^{\frac{1}{\alpha+3}} \cdot t^{\frac{\beta+2}{\alpha+3}} \quad (40)$$

Thus, for the same  $\beta$ , as  $t_i$  increases, for the same time after the start of energy deposition, the shock radius is decreased. A similar argument holds for the shock velocity. To see the effect of  $\beta$ , equation (40) can be written as

$$\bar{R} = (t/t_i)^{\frac{\beta+2}{\alpha+3}} \quad (41)$$

where

$$\bar{R} = R / \left( \frac{a_o^2}{n^2 p_o J_0} E_\alpha t_i^{\beta} \right)^{\frac{1}{\alpha+3}} \quad (42)$$

Equation (41) is plotted in Fig 1 for  $\alpha = 2$  and several  $\beta$  ( $\beta \neq 0$ ). The nondimensional radius  $\bar{R}$  decreases with increasing  $\beta$ , and because of the change in the value of  $n$  and the expected change in  $J_0$ , the actual shock radius is expected to decrease with increasing  $\beta$  also.

While we have focused our attention on the zero order solution, it must be mentioned that techniques for higher order solutions also are available. However, these are somewhat involved; but they certainly should be used in the future when a more accurate description of the problem is warranted.

## COMPARISON OF SOME EXPERIMENTAL RESULTS WITH THE VARIABLE ENERGY BLAST WAVE EQUATION

As was mentioned in the Introduction, shock ignition of mono-propellant droplets can result in a blast wave emanating from the wake of the drop. Figure 2, reproduced from the work of Lu and Slagg (Ref 12), shows clearly a distorted spherical shock wave surrounding a 2 mm ethyl nitrate drop ignited by a Mach 3.3 shock wave in oxygen. It is reasoned that, in such a phenomenon, the reaction requires a finite time for the energy release, and therefore comparison of the experimental results should be made with the variable energy blast wave solution.

For complete combustion in oxygen, ethyl nitrate liberates 345 Kcal/mole, which amount to approximately  $7 \times 10^8$  ergs for a 2 mm drop. For spherical symmetry, equation (40) can be written as

$$R = \left[ \frac{\gamma}{\rho_0} \left( \frac{5}{\beta+2} \right)^2 \frac{E}{4\pi J_0} \right]^{\frac{1}{5}} \cdot \left( \frac{t}{t_i} \right)^{\frac{3}{5}} \cdot t^{\frac{2}{5}} \quad (43)$$

Using the values of:

$$E = 7 \times 10^8 \text{ ergs}$$

$$\rho_0 = 5.6 \times 10^{-3} \text{ g/cm}^3 \text{ (oxygen at Mach 3.3)}$$

$$\gamma = 1.4$$

$$J_0 = .596 \text{ (assumed not to vary with } \beta)$$

we obtain

$$R = 1.71(t/10)^{2/5} \quad \text{for } \beta = 0 \quad (44)$$

$$= 1.45(t/t_i)^{1/5}(t/10)^{2/5} \quad \text{for } \beta = 1 \quad (45)$$

$$= 1.29(t/t_i)^{2/5}(t/10)^{2/5} \quad \text{for } \beta = 2 \quad (46)$$

$$= 1.18(t/t_i)^{3/5}(t/10)^{2/5} \quad \text{for } \beta = 3 \quad (47)$$

$$= 1.10(t/t_i)^{4/5}(t/10)^{2/5} \quad \text{for } \beta = 4 \quad (48)$$

$$= 1.03(t/t_i)(t/10)^{2/5} \quad \text{for } \beta = 5 \quad (49)$$

where  $R$  is in cm and  $t$ ,  $t_i$  in  $\mu\text{sec}$ .

Equations (44), (47), and (49) were selected for comparison with limited experimental results of Lu and Slagg (Ref 12). In Fig 3, it can be immediately seen that the experimental data cannot be explained by the instantaneous energy input case, Equation 44, and that the best fit is obtained by the case where  $\beta = 5$  (Equation 49) when  $t_i$  is taken to be 10  $\mu\text{sec}$ . It should be recalled that this equation is applicable up to time  $t = t_i$ . Beyond that time,  $R$  is expected to drop off from what the equation indicates, due to the fact that the energy deposition ceases beyond that time. While more data and more accurate calculations of  $J_0$  are needed before final conclusions can be drawn, the idea of interpreting the consequences of monopropellant ignition by variable energy blast wave theory seems to be reasonable. The behavior of energy release in a chemical reaction is usually exponential in nature, and a manifestation of this, judging from observations of the behavior of the blast wave, appears also to be true for liquid ethyl nitrate.

## CONCLUSIONS AND RECOMMENDATIONS

It appears that analysis of the experimental data on shock ignited liquid monopropellant behavior can be profitably made on the basis of variable energy blast wave. Extensive data, if compared with more accurate theory than described here, should lead to estimation of energy release time and hence to the initial exothermic reaction time.

It is recommended that:

1. The zero order solution for variable energy blast wave be obtained for various values of  $\beta$ , by determining  $J_0$ .
2. The flow field within the blast wave be evaluated more accurately than obtainable by the zero order solution, using first and higher orders for  $J$ 's and  $\lambda$ 's.
3. The flow field and shock velocity be assessed at times after the cessation of energy release.
4. More data on ethyl nitrate and other monopropellants be obtained and compared with the more comprehensive theory.

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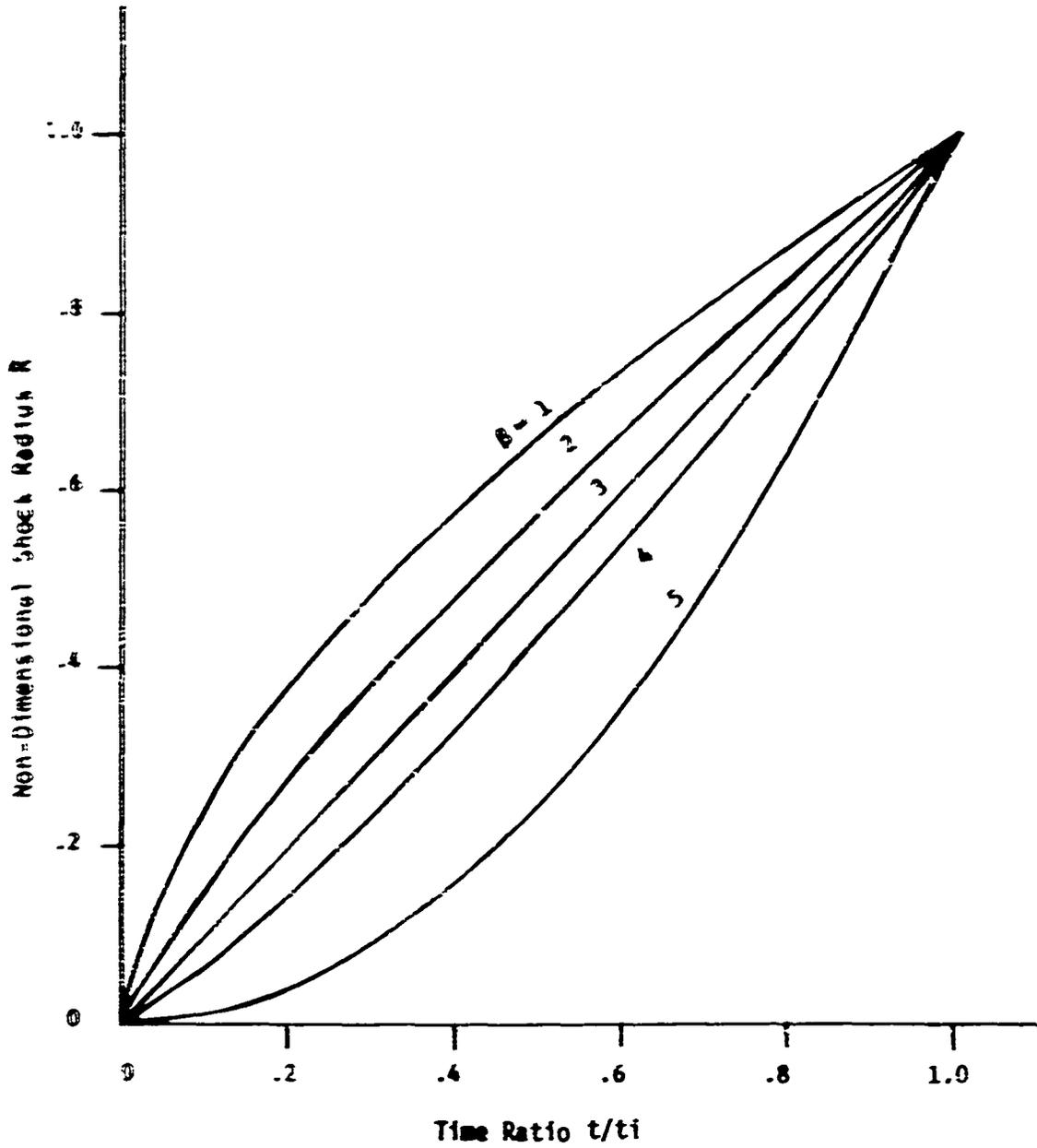


FIGURE 1 Shock radius vs time for variable energy spherical blast wave



Fig 2 3 mm propyl nitrate drop after the passage of a Mach 3.31 shock wave in oxygen ( $t = 40 \mu\text{sec}$ )

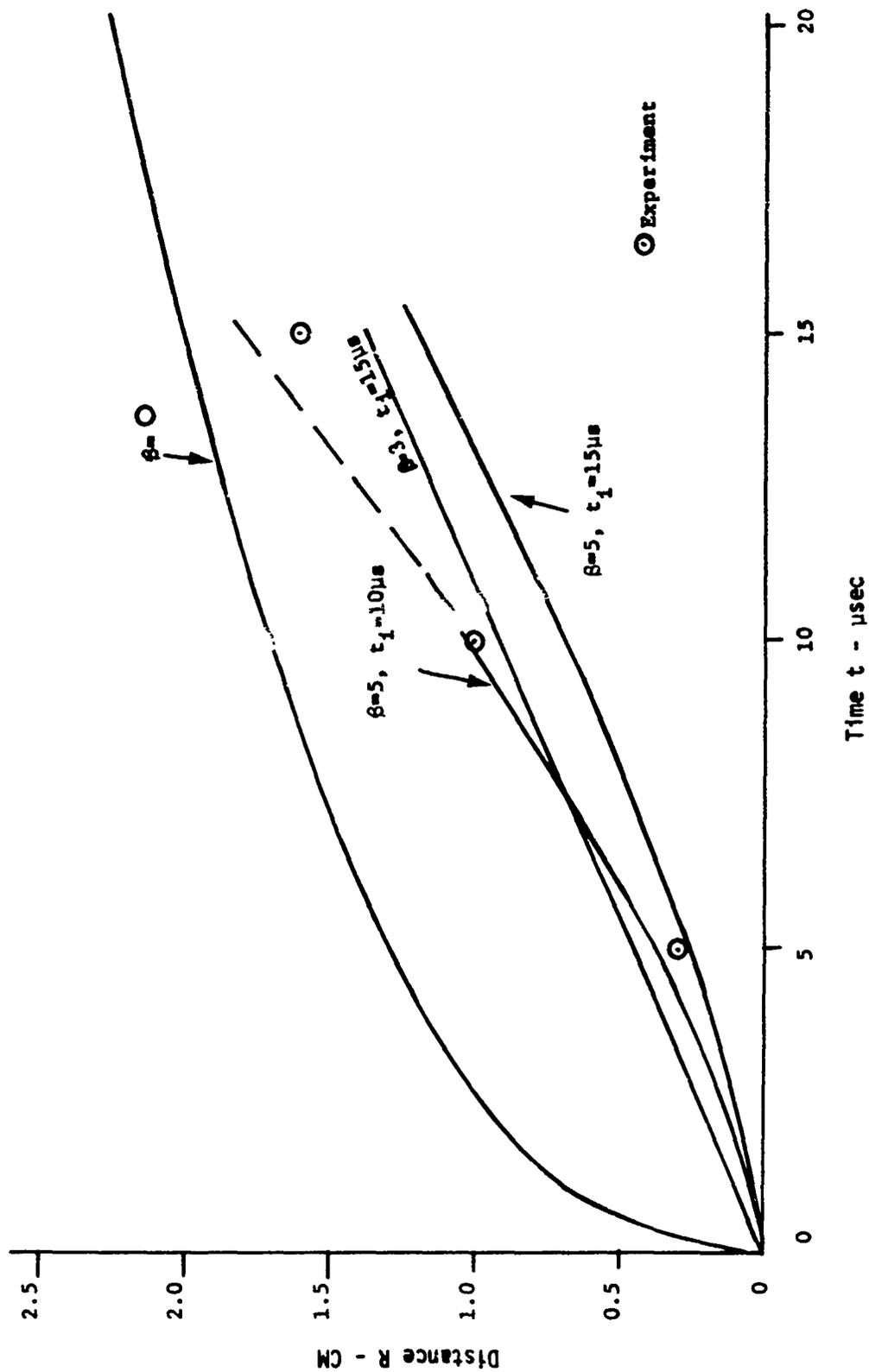


FIGURE 3 Blast wave radius for ethyl nitrate