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NAVORD REPORT 6105

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SENSITIVITY OF EXPLOSIVES VII

TRANSITION FROM SLOW BURNING TO DETONATION: A MODEL FOR SHOCK FORMATION IN A DEFLAGRATING SOLID

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NAVORD Report 6105

SENSITIVITY OF EXPLOSIVES VII

TRANSITION FROM SLOW BURNING TO DETONATION: A MODEL FOR SHOCK FORMATION IN A DEFLAGRATING SOLID

By

ANDREJ MAČEK

Approved by: EVAN C. NOONAN, Chief
Physical Chemistry Division

ABSTRACT: A simple one-dimensional physical model of explosive burning under confinement is assumed and used as a basis for calculations of (a) the rate of pressure increase behind the plane of deflagration; (b) the time and the distance necessary to start a shock in the solid explosive. The pressure increase, approximately exponential in time, compares rather well with experimental results. The calculated distance of incipient shock formation is about 12 cm. This result supports the hypothesis that transition from slow burning to detonation is due to a shock, which arises spontaneously in a confined burning medium.

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Three well defined phases appear to exist in the initiation of explosives. Ignition occurs first by a variety of paths such as friction, shear or compression of occluded gas bubble; the end result being to produce enough heat to initiate combustion. The relatively slow combustion process then goes through a transition step where the linear consumption rate must increase by a factor of about 10^5. Finally, stable detonation ensues governed essentially by thermodynamic and hydrodynamic laws.

The least understood phase is the second; the transition phenomenon. This report attempts a quantitative treatment of transition based on the qualitative notions advanced by Professor Kistiakowsky (3) and is part of a broad study of the sensitivity of explosives. This work was performed under Task NO 800-667/76004/01040.

W. W. WILBOURNE
Captain, USN
Commander

Albert Lightbody
ALBERT LIGHTBODY
By direction

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I. INTRODUCTION

The experimental portion of the Laboratory's program of transition from slow burning to detonation in explosives (1,2) led to the following conclusions:

1. In confined cast explosives (tests were carried out on DINA and pentolite) the build-up of detonation from thermally initiated deflagration is quite reliable if the explosive charge is sufficiently long. The process of transition to steady state detonation includes a relatively long (50 μsec or more) interval of rapid sub-detonation velocities. The length of travel between ignition and detonation often exceeds 10 cm.

2. The pressure-time history of the region of thermal initiation is characterized by a long (seconds) delay during which the pressure remains below a relatively low value p_0. (The experimental procedure did not allow an actual pressure-time determination below p_0.) Once the pressure exceeds this value (usually about 0.3 kbar), however, the subsequent build-up to about 5 kbar requires only an additional 40-60 μsec. An oscilloscope record of the pressure build-up is reproduced in Fig. 1.

It has been suggested (3,4) that shock, or shocks, which may arise during the deflagration of a solid explosive under confinement are the direct cause of transition to detonation. The hypothesis, of course, can be correct only if the shock forms within the confines of the explosive charge, hence, in most practical cases, within a reasonably short distance. The above cited empirical evidence furnishes a quantitative basis for a theoretical inquiry of the possibility of shock formation. This paper reports the findings of such an inquiry. The paper is concerned only with the formation of a shock, not with its effect on unburnt explosive.

As a basis of the discussion the following one-dimensional physical model is assumed (Fig. 2):

A rigidly confined charge of a solid explosive deflagrates in a plane perpendicular to the direction of burning. The plane of deflagration separates the product gas, Region I, from the unburnt solid, Region II. The linear burning rate is proportional to the pressure, $S = \beta p$; this assumption is fairly well supported by experimental evidence.

The model is not intended to reproduce the conditions employed to obtain the experimental data (1,2) exactly, but only to simulate them in a general way.

The following discussion consists of two parts:

1. The calculation of pressure increase in the product gas (Region I) due to the deflagration.

2. An analytical treatment of the propagation of compression waves and a calculation of the distance of incipient shock formation in the cast solid (Region II).

II. PRESSURE INCREASE IN THE PRODUCT GAS

The product gas is assumed to obey two relations:

$$p = RT \frac{n}{V-bn}, \tag{1}$$

$$T = \text{const.} \tag{2}$$

Here T, n and V are absolute temperature, number of moles and total volume of the product gas respectively; b is the molar covolume of the Abel equation of state. Equation (1) holds well up to a density of about 0.5 gm/cc, corresponding to pressures of 5 to 6 kbar. The isothermal assumption is probably not quite realistic.

From Eqns. (1) and (2)

$$dp = \frac{RT}{V-bn}\left[dn - \frac{n(dV-bdn)}{V-bn}\right].$$

Substituting

$$dn = \frac{\rho_o}{M}\, dV,$$

$$n-n_o = \frac{\rho_o}{M}\,(V-V_o).$$

where ρ_0 is the initial density of the solid, M the average molecular weight of the gas, and V_0 and n_0 the initial volume and the initial number of moles of gas respectively, the expression reduces to

$$\frac{dp}{dt} = \frac{CV_0}{[V(1-B) + BV_0]^2} \frac{dV}{dt} , \qquad (3)$$

or $$\frac{dp}{dt} = \frac{CV_0}{[V(1-B) + BV_0]^2} A\beta p . \qquad (3')$$

Here A is the burning surface area, $C = RT(\rho_0/M - n_0/V_0)$ and $B = b\rho_0/M$. Since $n_0M/V_0\rho_0$ is small compared to 1/B, Eqn. 3 integrates to

$$p-p_0 = \frac{C}{1-B} \left[1 - \frac{V_0}{BV_0+(1-B)V}\right] . \qquad (4)$$

Eliminating V between (3') and 4,

$$\frac{dp}{dt} = \frac{A\beta}{V_0C} p (E - Dp)^2,$$

where $D = 1-B$ and $E = C + p_0D$.

Hence, time necessary to build up the pressure from p_0 to p is

$$t = \frac{V_0}{A} \frac{C}{\beta} \int_{p_0}^{p} \frac{dp}{p(E-Dp)^2} . \qquad (5)$$

At low pressures ($Dp \ll E$) Eqn. 5 approximates an exponential function. As t increases, the curve becomes less steep and the pressure approaches asymptotically the value $p = E/D$. (The equation of state, however, as noted above, is not adequate beyond 5 or 6 kbar, which is considerably below the value of E/D.)

The p=p(t) from Eqn. 5 has been computed.* The integrated Eqn. 5 is unwieldy for analytical work, but it can be approximated quite well by the simple exponential $p=p_0 \exp(k/t)$. In Fig. 3 three pressure-time functions are plotted: the experimental p=p(t) curve (transcribed from Fig. 1), the p=p(t) from Eqn. 5 and the exponential (p_0=0.08 kbar, k=0.1 μsec^{-1}). As in the calculations with Eqn. 5, the choice of p_0 is arbitrary; it was used in order to fit the exponential to the high pressure portion of the experimental curve, since the later stages of p=p(t) influence decisively the pattern of shock formation.

The validity of Eqn. 5 rests on several assumptions, explicit and tacit, which would have to be removed, at the expense of simplicity, in a more rigorous treatment. The derivation, as presented, is heuristic.

III. SHOCK FORMATION IN THE SOLID EXPLOSIVE

Consider the effect upon solid explosive, Region II, of the pressure rise, $p=p_0 \exp(k/t)$ (the exponential being fitted to the high pressure portion of the experimental curve, Fig. 3), of the product gas. Compression of the solid is assumed to follow the equation

$$p = a \left[\left(\frac{\rho}{\rho_0}\right)^3 - 1 \right] , \qquad (6)$$

where a is a constant (5,6).

---

* The following values were assumed: b = 13 cc mole^{-1}, ρ_0 = 1.6 gm cc^{-1}, M = 32 gm mole^{-1}, T = 3000°K, β = 7 cm sec^{-1} kbar^{-1}. The proportionality constant $\frac{V_0}{A}$ was chosen to give p=5 kbar in t=42 µsec. The value used for the initial pressure, p_0 = 0.1 kbar, is somewhat below the experimental p_0, i.e. the pressure at which the oscillcscope starts to sweep in the experiments described earlier.

Motion of the solid-gas boundary, G, and propagation of compression waves through the solid is conveniently represented in an x-t diagram (Fig. 4).

According to the Riemann analysis, $u-\sigma$ = const. along a u-c characteristic, where u is the particle velocity $\sigma = \int (c/\rho)d\rho$ and $c = \sqrt{(dp/d\rho)_{adiab}}$. The problem is simplified by the fact that, for the assumed compression relation (Eqn. 6), $c = (c_0/\rho_0)\,\rho(t)$ and consequently $\sigma(t) = c(t)$; also, the characteristics in this calculation are straight lines. Since $u_0 = 0$, the particle velocity is

$$u(t) = \sigma(t) - \sigma_0 = c(t) - c_0 \ . \qquad (7)$$

The velocity of propagation of compression waves is $u(t)+c(t)$ and the position of the boundary

$$x(t) = \int_0^t (c-c_0)dt \ . \qquad (8)$$

The calculation of both u(t) and c(t) is very simple. The determination of the position of the boundary at time t (Eqn. 8), which necessitates the evaluation of $\int_0^t \rho(t)dt$, is somewhat laborious, but it can be carried out readily with the help of a desk computer.* In this calculation the assumed constants were p_0 = 0.08 kbar, k = 0.1 μsec^{-1} (see Fig. 3). The cast explosive density, ρ_0, was taken to be 1.6 gm/cc. The constant a = 35 kbar was then chosen to give the sonic velocity of about 2.5 mm/μsec.

The calculated u + c characteristics and the boundary path G are plotted in Fig. 4. It is seen that the region of incipient shock formation is about 12 cm from the original gas-solid boundary; the compression waves begin to coalesce when the pressure exceeds several kilobars.

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* The form to be evaluated is $I = \int_0^t \left[(p_0/a)e^{kt} + 1\right]^{1/3} dt$. Substituting $x^3 = (p_0/a)\exp(kt)+1$, $dt = (3/k)\left[x^2/(x^3-1)\right]dx$, the integral becomes $I = (3/k)\int_{x_0}^{x}\left[x^3/(x^3-1)\right]dx$. The integrated form is $(k/3)\,I = x + (1/6)\ln\left[(x-1)^2/(x^2+x+1)\right] - (1/3)\sqrt{3}\ \arctan\,(2x+1)/\sqrt{3}$.

It is interesting to note that a pressure-time function less steep than the exponential may not be sufficient to generate a shock within a comparable distance. If the calculation is repeated assuming that the pressure rises 5 kbar in 42 μsec linearly ($p = kt$) instead of exponentially, the shock starts 115 cm instead of 12 cm from the boundary. Thus the requirement that the pressure rise to the incipient shock value in about 50 μsec is necessary but not sufficient for the shock formation within a short distance (order of 10 cm).

IV. ADDITIONAL NOTES

1. Compression waves which originate at the boundary prior to time $t = 0$ are so weak that they cannot have any effect upon the explosive (at $t = 0$, $p = 0.08$ kbar, $\rho/\rho_0 = 1.00076$). Hence it appears entirely justified to assume that the initial compression wave (c_0 in Fig. 4) propagates through uncompressed explosive.

2. Fig. 4 shows that the locus of intersections of positive characteristics in the compressed region shifts towards lower values of x and t as the pressure, and consequently $u + c$, increases. Yet, an attempt to specify the exact coordinates x and t of the point of incipient shock formation would not be realistic on the basis of the experimental arrangement employed in Ref. (2), since the strength of the confining tube (which even in the case of experimental dynamic loading probably does not exceed 10 kbar) sets a limit to the strength of compression waves which can be formed. This does not mean that pressures in excess of the bursting pressure of the tube cannot exist for small time intervals: additional confinement will be furnished by the inertia of the tube wall. This effect, however, has not been considered. Hence the value for the distance of incipient shock formation of about 12 cm must be considered a high estimate, though probably a good one.

V. CONCLUSION

The proposition that transition from slow burning to detonation is due to a shock which arises in the burning medium has been examined on the basis of experimental evidence. Conditions of pressure and density, which govern the propagation of compression waves through the unreacted explosive, are such that the proposed hypothesis appears reasonable.

ACKNOWLEDGEMENTS

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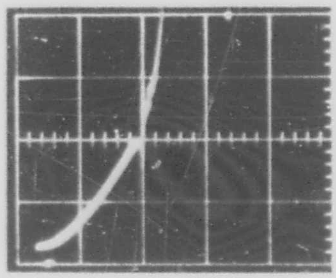

HORIZONTAL SCALE : 1 CM = 20 μ SEC
VERTICAL SCALE : 1 CM = 50 MVOLT = 1.14 KBAR
THE INITIAL PRESSURE p_0 = 0.31 KBAR

FIG. 1 PRESSURE - TIME RECORD OF THE REGION OF INITIATION IN DINA

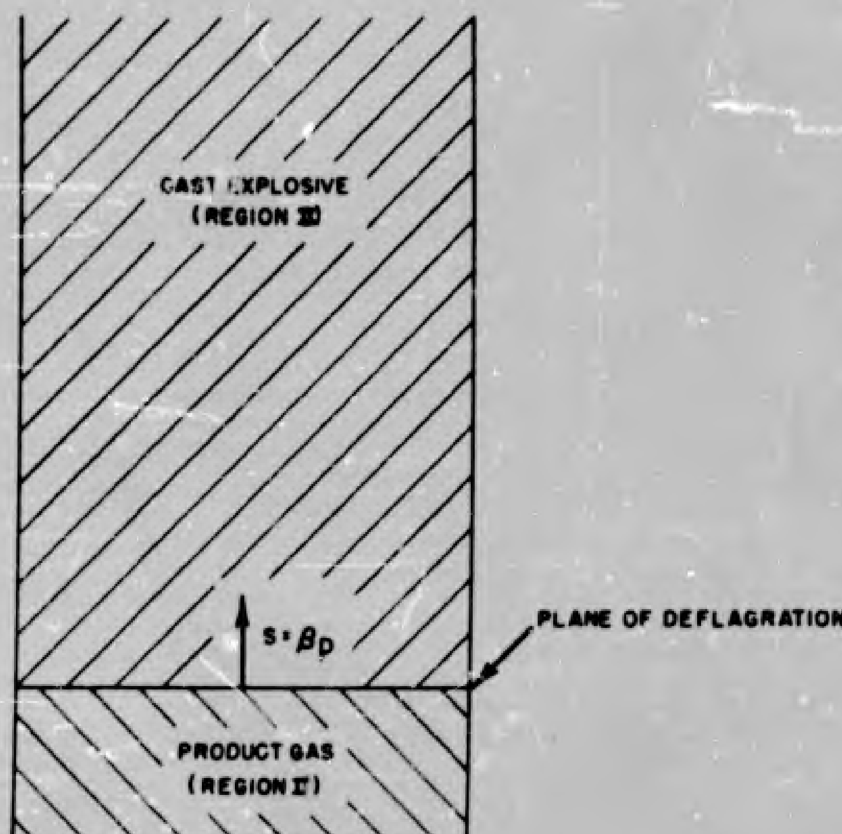

FIG. 2 ONE - DIMENSIONAL PHYSICAL MODEL

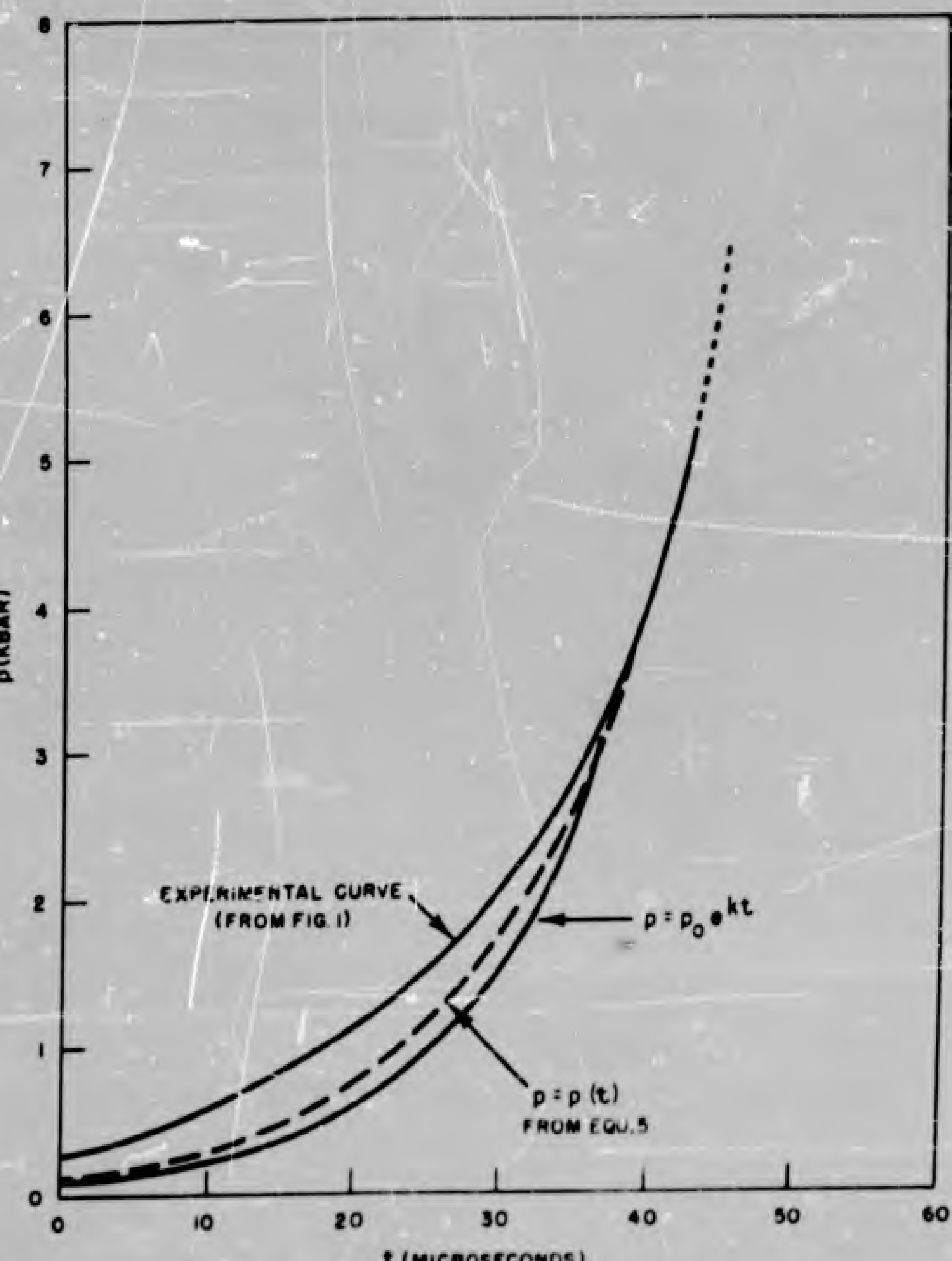

FIG. 3 PRESSURE INCREASE IN THE REGION OF INITIATION

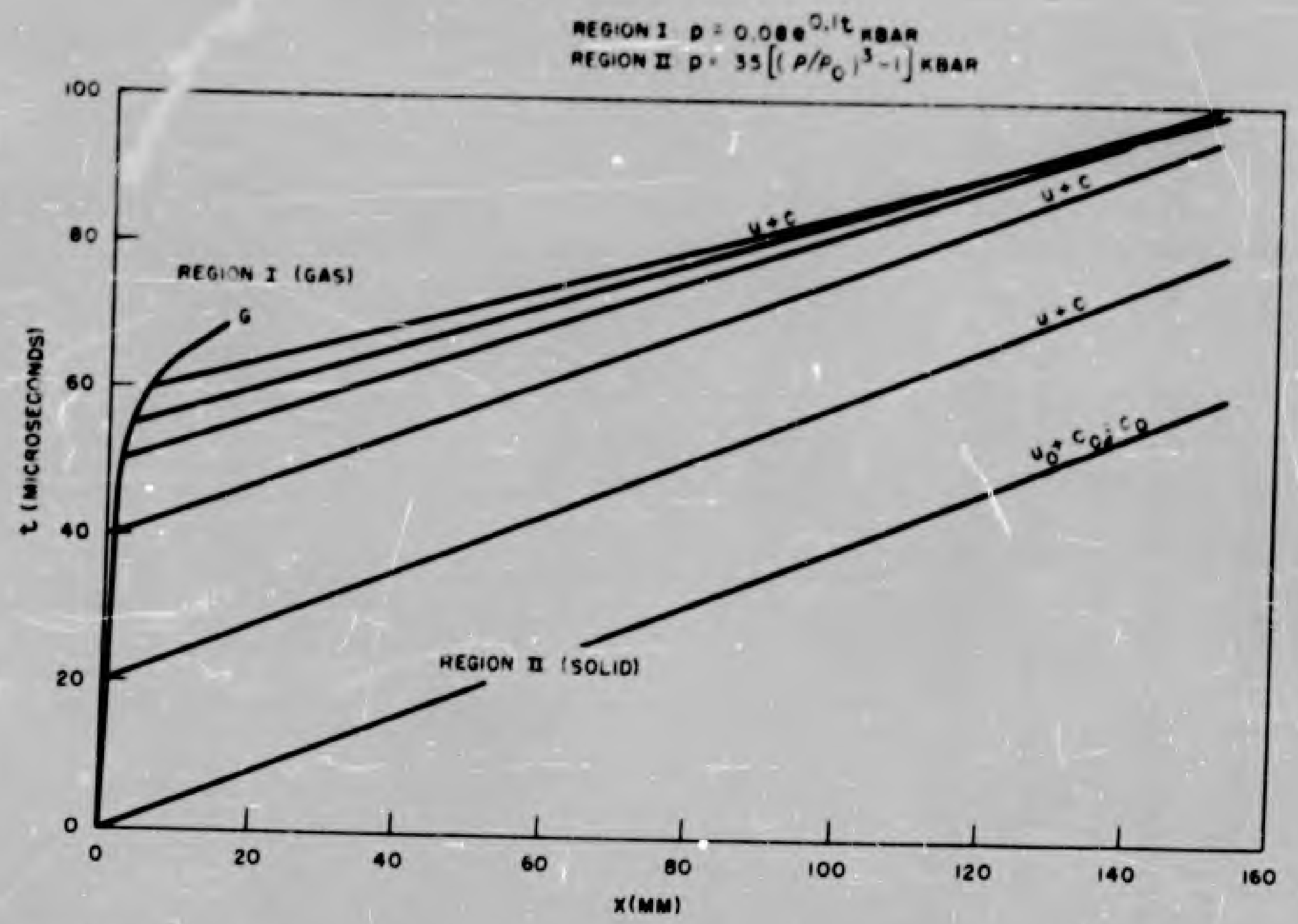

FIG. 4 PROPAGATION OF COMPRESSION WAVES THROUGH SOLID EXPLOSIVE
SHOCK BEGINS TO FORM ABOUT 12 CM FROM THE ORIGIN

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