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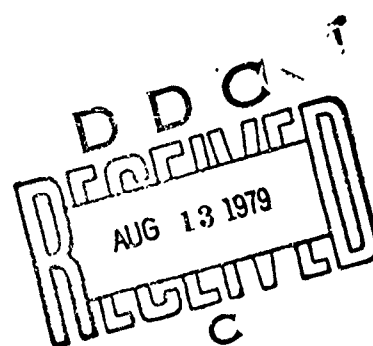
HIGH EXPLOSIVE DETONATION AND ELECTROMAGNETIC INTERACTION

BY EDWARD T. TOTON

RESEARCH AND TECHNOLOGY DEPARTMENT

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The effect of stationary, uniform, electric, and magnetic fields on steady-state detonation of condensed explosives is studied. The electrical conductivity profile in the region of the reaction zone provides a current path and Joule heating. Expected increases of detonation velocity and pressure by Joule heating are computed using an Abel equation of state. It is shown that the detonation pressure of TNT can be increased by as much as 12% and detonation velocity by as much as 6% before electrical

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breakdown can occur.

SUMMARY

The investigation described in this report is an outgrowth of a suggestion by D. J. Pastine of NSWC that the detonation wave of a condensed explosive provides a conductive region for the deposition of electrical energy and that augmentation of detonation parameters is therefore possible. The investigation consisted of preliminary calculations for steady-state detonation in the presence of uniform electric and magnetic fields. Beginning with the differential equations governing the one-dimensional hydrodynamic character of the reacting explosive, we develop suitable jump conditions when joule heating is present in the region of the reaction zone. It is apparent from the results that joule heating provides an energy deposition mechanism that emulates the chemical energy release of the reacting explosive.

In order to evaluate the relative merits of electromagnetic energy deposition, we have considered an Abel equation of state for TNT as representative of a condensed explosive. Although the precise values of detonation pressure and velocity depend on the equation of state employed, the general features of electromagnetic coupling are expected to be unchanged. When the voltage to which TNT is subjected is below the breakdown voltage, a maximum of 12% increase of detonation pressure and 6% increase of detonation velocity theoretically can be achieved.

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

The large energy release of explosives (typically four kilojoules per gram for high explosives) and the rapidity of the detonation process (detonation velocities typically seven millimeters per microsecond) present considerable difficulty for real time control of detonating high explosives. In the case of gases, however, the lower densities and pressures present a more accessible regime for experimental investigation. Plett and Toong[1] demonstrated the effect of electromagnetic fields on detonating gases as modifications of pressure in the product zone; and Mar, Makios, and Plett[2] observed wave speeds of more than twice the Chapman-Jouguet speeds for hydrogen-oxygen mixtures when electromagnetically driven. Furthermore, these investigators demonstrated a definite electromagnetic enhancement of shock waves in argon. Thus, the electromagnetic control and enhancement of condensed explosives is an intriguing possibility.

Owing to the overall charge neutrality of explosives, the coupling of a detonation process with electromagnetic fields requires the microscopic appearance of mobile charge carriers. The enhancement of shock waves in argon shows that some degree of ionization must exist behind the shock front even in a non-reactive substance. Electrical conductivities in the detonation waves of condensed explosives were measured by Cook[3] in 1956; Brish, Tarasov, and Tsukerman[4] in 196^; Hayes[5] in 1965; Ershov, Zubkov, and

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[1]Plett, E. G., and Toong, T. Y., "Electromagnetic Effect on Flows Behind Gaseous Detonations," AIAA Journal, Vol. 7, No. 6, June 1969, p. 1127.

[2]Mar, J. Y. S., Makios, V., and Plett, E. G., "Electromagnetic Detonation in a Magnetic Annular Shock Tube," The Physics of Fluids, Vol. 16, No. 12, December 1973, p. 2160.

[3]Cook, M. A., The Science of High Explosives, Reinhold Publishing Corp., New York, 1958, pp. 144-150.

[4]Brish, A. A., Tarasov, M. S., and Tsukerman, V. A., "Electrical Conductivity of the Explosion Products of Condensed Explosives," Soviet Physics JETP, Vol. 34 (10), No. 6, June 1960, p. 1095.

[5]Hayes, B., "On the Electrical Conductivity in Detonation Products," Fourth Symposium (International) on Detonation, Proceedings, Office of Naval Research, Department of Navy, Washington, D.C., October 1965, p. 595.

Luk'yanchikov[6] in 1974; and by others. Reported values of the average conductivities vary widely among investigators, in part due to the extreme difficulty of the required experimental arrangements. But it is generally agreed that average conductivities vary within the range of 0.1 per ohm-cm to 10 per ohm-cm for various condensed explosives and that the conduction zone coincides with the reaction zone.[6]

If it is assumed that the charge carriers are electrons and that the electrical resistance arises from collisions of the electrons with molecules in the reaction and product zones, then an estimate of the density of electrons can be made. Ershov[7] argues from the expression for the mean electrical conductivity

$$\sigma = n_e e^2 \lambda / mv$$

that the electron density is about 10^{19} cm^{-3} for TNT and about 10^{18} cm^{-3} for PETN. Here λ is the mean free path, v the mean thermal velocity of the electrons, n_e the density, and e the charge of the electrons.

Such electron densities cannot be explained by thermal ionization. An equilibrium density of electrons can be calculated from the Saha equation,

$$\frac{n_e^2}{n} = 2 \left(\frac{mkT}{2\pi\hbar^2} \right)^{3/2} \exp(-I/kT)$$

where I is the ionization potential of either intermediate or final products of the explosive.* In order for the equilibrium densities to approach those found from the mean conductivities, the ionization potential must be about 2eV for TNT and 3.5eV for PETN. However, the ionization potential for intermediates is at least 6eV (Ershov[7]). Thus, the ionization which accounts for the conductivity is several orders of magnitude above the expected equilibrium value and must be regarded as originating from non-equilibrium processes within the reaction zone.

Any definitive treatment of the interaction of electromagnetic fields with a detonation wave of a condensed explosive must take into account the mechanism responsible for the degree of ionization

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[6]Ershov, A. P., Zubkov, P. I., and Luk'yanchikov, L. A., "Measurements of the Electrical Conductivity Profile in the Detonation Front of Solid Explosives," Combustion, Explosion, and Shock Waves, Vol. 10, No. 6, November-December, 1974, p. 776.

[7]Ershov, A. P., "Ionization During Detonation of Solid Explosives," Combustion, Explosion, and Shock Waves, Vol. 11, No. 6, November-December 1975, p. 798.

*Here, $\hbar$ is the rationalized Planck constant, approximately 10^{-27} erg-sec.

observed. In the case in which joule heating is the dominant electro-magnetic contribution (to be discussed at length in the following), the electrical conductivity of the detonation wave must be altered significantly if the deposited energy approaches in magnitude the energy chemically released. Such an effort constitutes a significant research program in its own right and therefore will be deferred to another time. Our immediate aim is the characterization of the large phenomenological features of detonation waves of condensed explosives in the presence of electromagnetic fields, assuming no significant alteration of the conductivity. In the following, we discuss the approximations to be used, the energy and momentum balance equations, and the implications of these considerations to detonation wave enhancement and control.

DETONATION WAVE CHARACTERIZATION - FUNDAMENTAL EQUATIONS

The detonation process of a condensed explosive constitutes a multifluid hydrodynamic problem in which the various fluid components are comprised of different reacting species. For the purposes of electromagnetic coupling, however, it is sufficient to regard the fluid components to be electrons, ions, and neutral molecules. Because of the high density of the fluid and high temperature in the reaction and product zones, the collision frequency is high. Thus, except for magnetic field frequencies in excess of the electron collision frequency, charge separation does not occur. Furthermore, the displacement current of Maxwell's equations is assumed negligible in comparison to other currents present. The fluid is then to be regarded as a single conducting fluid characterized by a (local) conductivity σ as well as the usual hydrodynamic variables of density, pressure, density, and temperature.

In addition to the magnetohydrodynamic approximation, we must determine the character of the magnetic field interaction with the moving detonation wave. If the magnetic field diffuses rapidly through the conducting fluid, then currents within the conducting fluid interact directly with the external magnetic field, and the effects of magnetic pressure and induced currents are negligible. If τ is the magnetic field diffusion time, V a characteristic velocity of the fluid, and L a characteristic dimension, then the magnetic Reynolds number

$$R_m = \frac{V\tau}{L} \tag{1}$$

must be small for small magnetic pressures. The diffusion time

τ can be written in terms of the conductivity as (Jackson[8])

$$\tau = \frac{4\pi\sigma L^2}{c^2} . \tag{2}$$

Thus, R_m becomes

$$R_m = \frac{4\pi\sigma VL}{c^2} . \tag{3}$$

Using as characteristic values $V \sim 7\times10^5$ cm/sec, $L \sim 10^{-1}$cm, $\sigma \sim 10^2$ (ohm-cm)$^{-1}$($= 9\times10^{13}$sec^{-1}) and $c = 3\times10^{10}$cm/sec^{-1}, we find R_m is 10^{-2}. On this basis, we will assume that magnetic diffusion occurs rapidly and that magnetic pressures are small.

The equations applicable to a conducting detonating explosive in the presence of an electromagnetic field are the MHD equations (Krall and Trivelpiece[9]):

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{u}) = 0 , \tag{4}$$

$$\rho\frac{\partial\vec{u}}{\partial t} + \rho\vec{u}\cdot\nabla\vec{u} = \frac{\vec{J}\times\vec{B}}{c} - \nabla P , \tag{5}$$

$$\vec{J} = \sigma\left(\vec{E} + \frac{\vec{u}\times\vec{B}}{c}\right) , \tag{6}$$

$$\nabla\times\vec{E} = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t} , \tag{7}$$

$$\nabla\times\vec{B} = \frac{4\pi}{c}\vec{J} . \tag{8}$$

Eqs. (4) and (5) are expressions of continuity and momentum, respectively. Eq. (6) is Ohm's law and expresses the (assumed) proportionality between the current density and the electric field, i.e., $\vec{J} = \sigma\vec{E}_{rest}$. Eqs. (7) and (8) are Maxwell's equations (in the cgs

[8]Jackson, J. D., Classical Electrodynamics, John Wiley and Sons, Inc., New York, 1963, p. 313.
[9]Krall, N. A., and Trivelpiece, A. W., Principles of Plasma Physics, McGraw-Hill Book Co., New York, 1973, pp. 95-97.

system of units) with the approximation of negligible displacement current.[†] To these must be added an equation of state.

We are also interested in characterizing the energy of the fluid. If ε is the internal energy per unit mass, the energy of a unit volume of fluid is

$$\rho\varepsilon + \tfrac{1}{2}\rho u^2 . \tag{9}$$

Consider the time rate of change of this quantity

$$\frac{\partial}{\partial t}(\tfrac{1}{2}\rho u^2 + \rho\varepsilon) = \frac{\partial}{\partial t}(\tfrac{1}{2}\rho u^2) + \frac{\partial}{\partial t}(\rho\varepsilon) . \tag{10}$$

We may write the first term as

$$\frac{\partial}{\partial t}(\tfrac{1}{2}\rho u^2) = \tfrac{1}{2}u^2\frac{\partial\rho}{\partial t} + \rho\vec{u}\cdot\frac{\partial\vec{u}}{\partial t} . \tag{11}$$

Using the equation of continuity, we may write

$$\tfrac{1}{2}u^2\frac{\partial\rho}{\partial t} = -\tfrac{1}{2}u^2\nabla\cdot(\rho\vec{u}) , \tag{12}$$

and the equation of motion (Equation (5)) yields

$$\rho\vec{u}\cdot\frac{\partial\vec{u}}{\partial t} = -\rho\vec{u}\cdot\nabla\left(\frac{u^2}{2}\right) + \frac{\vec{u}\cdot\vec{J}\times\vec{B}}{c} - \vec{u}\cdot\nabla P . \tag{13}$$

Eq. (11) can then be written

$$\frac{\partial}{\partial t}(\tfrac{1}{2}\rho u^2) = -\nabla\cdot(\tfrac{1}{2}\rho u^2\vec{u}) + \frac{\vec{u}\cdot\vec{J}\times\vec{B}}{c} - \vec{u}\cdot\nabla P . \tag{14}$$

In order to obtain an expression for the second term of Eq. (10), we consider the thermodynamic relation for a small co-moving element of fluid

$$d\varepsilon = \left(w + \frac{\vec{J}\cdot\vec{E}}{\mu}\text{rest}\right)dt - PdV , \tag{15a}$$

_____

[†]We also assume that dielectric properties have small effect on the detonation process and thus suppress dielectric parameters in these equations.

$$d\varepsilon = \left(w + \frac{\vec{J}\cdot\vec{E}}{\rho}rest\right)dt + \frac{P}{\rho^2}d\rho \ . \tag{15b}$$

The first term is comprised of two energy production rates; w is the rate of chemical energy release per unit mass, and $\vec{J}\cdot\vec{E}_{rest}$ is the joule energy deposition per unit volume of the moving element of fluid. The second expression is valid because $V = 1/\rho$. In view of these equations, we can write

$$d(\rho\varepsilon) = \rho d\varepsilon + \varepsilon d\rho$$

$$= (\varepsilon + P/\rho)d\rho + (\rho w + \vec{J}\cdot\vec{E}_{rest})dt \ . \tag{16}$$

Thus

$$\frac{\partial}{\partial t}(\rho\varepsilon) = (\varepsilon + P/\rho)\frac{\partial\rho}{\partial t} + \rho w + \vec{J}\cdot\vec{E}_{rest} \ . \tag{17}$$

By use of Eq. (4) we may write this as

$$\frac{\partial}{\partial t}(\rho\varepsilon) = - (\varepsilon + P/\rho)\nabla\cdot(\rho\vec{u}) + \rho w + \vec{J}\cdot\vec{E}_{rest} \ . \tag{18}$$

Combining Eqs. (14) and (18) we have

$$\frac{\partial}{\partial t}(\rho\varepsilon + \tfrac{1}{2}\rho u^2) = - (\varepsilon + \frac{P}{\rho})\nabla\cdot(\rho\vec{u})$$
$$- \nabla\cdot(\tfrac{1}{2}\rho u^2\vec{u}) - \vec{u}\cdot\nabla P$$
$$+ \rho w + \vec{J}\cdot\vec{E}_{rest} + \frac{\vec{u}\cdot\vec{J}\times\vec{B}}{c} \ . \tag{19}$$

This may be rewritten as

$$\frac{\partial}{\partial t}(\rho\varepsilon + \tfrac{1}{2}\rho u^2) = - \nabla\cdot\left[(\rho\varepsilon + \tfrac{1}{2}\rho u^2)\vec{u}\right]$$
$$+ \rho\vec{u}\cdot\nabla\varepsilon - \frac{P}{\rho}\nabla\cdot(\rho\vec{u}) - \vec{u}\cdot\nabla P$$
$$+ \rho w + \vec{J}\cdot\left(\vec{E}_{rest} - \frac{\vec{u}\times\vec{B}}{c}\right) \ . \tag{20}$$

From Eq. (15b) we see that

$$\nabla \epsilon = \frac{P}{\rho^2} \nabla \rho \ . \tag{21}$$

Substituting this into Eq. (20) we finally obtain

$$\frac{\partial}{\partial t}(\rho\epsilon + \tfrac{1}{2}\rho u^2) = -\nabla \cdot \left[(\rho\epsilon + \tfrac{1}{2}\rho u^2)\vec{u}\right]$$
$$-\nabla\cdot(P\vec{u}) + \rho w + \vec{J}\cdot\vec{E} \ , \tag{22}$$

where $\vec{E}$ refers to the electric field in the laboratory frame.

In order to appreciate the significance of the terms occuring in Eq. (22), we integrate over a volume V of the fluid. Then, by the divergence theorem

$$\frac{\partial}{\partial t}\int_V (\rho\epsilon + \tfrac{1}{2}\rho u^2)dV = -\int_S (\rho\epsilon + \tfrac{1}{2}\rho u^2)\vec{u}\cdot d\vec{S}$$
$$-\int_S P\vec{u}\cdot d\vec{S} + \int_V (\rho w + \vec{J}\cdot\vec{E})dV \ . \tag{23}$$

The left hand side is the rate of change of energy of a volume V of fluid. The first term on the right hand side of Eq. (23) is the energy flux through the surface S bounding the volume V. The second surface integral expresses the rate at which the surrounding fluid does work on the fluid in V through the pressure. The volume integral consists of volume contributions from chemical release (ρw), and from joule heating ($\vec{J}\cdot\vec{E}$).

The equations which characterize a detonating condensed explosive in the presence of electromagnetic fields with the usual approximations of low viscosity and thermal conductivity are taken to be the set Eqs. (4-8) and (22) as well as an appropriate equation of state.

STEADY-STATE DETONATION

BALANCE EQUATIONS. Since the electromagnetic contributions in Eq. (23) appear in the same way as the chemical release term, it is necessary that these contributions vanish at some finite distance behind a detonation front for steady state detonation to be achieved. The recognition that the electrical conduction zone coincides with the reaction zone (Ershov (7)) insures that this is the case since the current density $\vec{J}$ (and thus the electromagnetic terms in Eq. (23)) is proportional to the conductivity.

9

We begin, then, with a discussion of the jump conditions for one-dimensional steady state detonation in the presence of an electromagnetic field.

Because of Eq. (8) we have

$$\nabla \cdot \vec{J} = 0 , \tag{24}$$

an expression compatible with the assumption that no charge separation occurs. Since the conductivity varies within the detonation wave, Eqs. (6) and (24) yield the necessary condition on the electromagnetic field,

$$\nabla \cdot \left[\sigma \left(\vec{E} + \frac{\vec{u} \times \vec{B}}{c} \right) \right] = 0 , \tag{25}$$

or

$$\nabla \cdot \left(\vec{E} + \frac{\vec{u} \times \vec{B}}{c} \right) + \frac{\nabla \sigma}{\sigma} \cdot \left(\vec{E} + \frac{\vec{u} \times \vec{B}}{c} \right) = 0 . \tag{26}$$

We show in Fig. 1 an idealized one-dimensional steady-state detonation wave as seen in the rest frame of the wave. The electric and magnetic fields are chosen constant and to have the directions indicated. Since the gradient of σ lies solely in the x direction, we see that Eq. (26) is identically satisfied.

The differential equations (Eqs. (4-8, 22)) are applicable to any reacting flow in the presence of electromagnetic fields (subject to the enumerated assumptions we have made) and, in particular, are applicable to one-dimensional flow as viewed from a laboratory frame, or as viewed from a stationary wave frame. If we assume that the chemical energy release rate can be characterized by a spatial dependence when viewed from the stationary wave frame, then the appropriate equations for characterizing the wave are obtained from Eqs. (4-8, 22) by setting all time derivatives equal to zero. Eq. (4) becomes

$$\frac{d}{dx}(\rho u(x)) = 0 , \tag{27}$$

or

$$\rho u = \text{const.} \tag{28}$$

We evaluate Eq. (28) at x=0 and find

$$\rho u = \rho_o D = \frac{D}{V_o} , \tag{29}$$

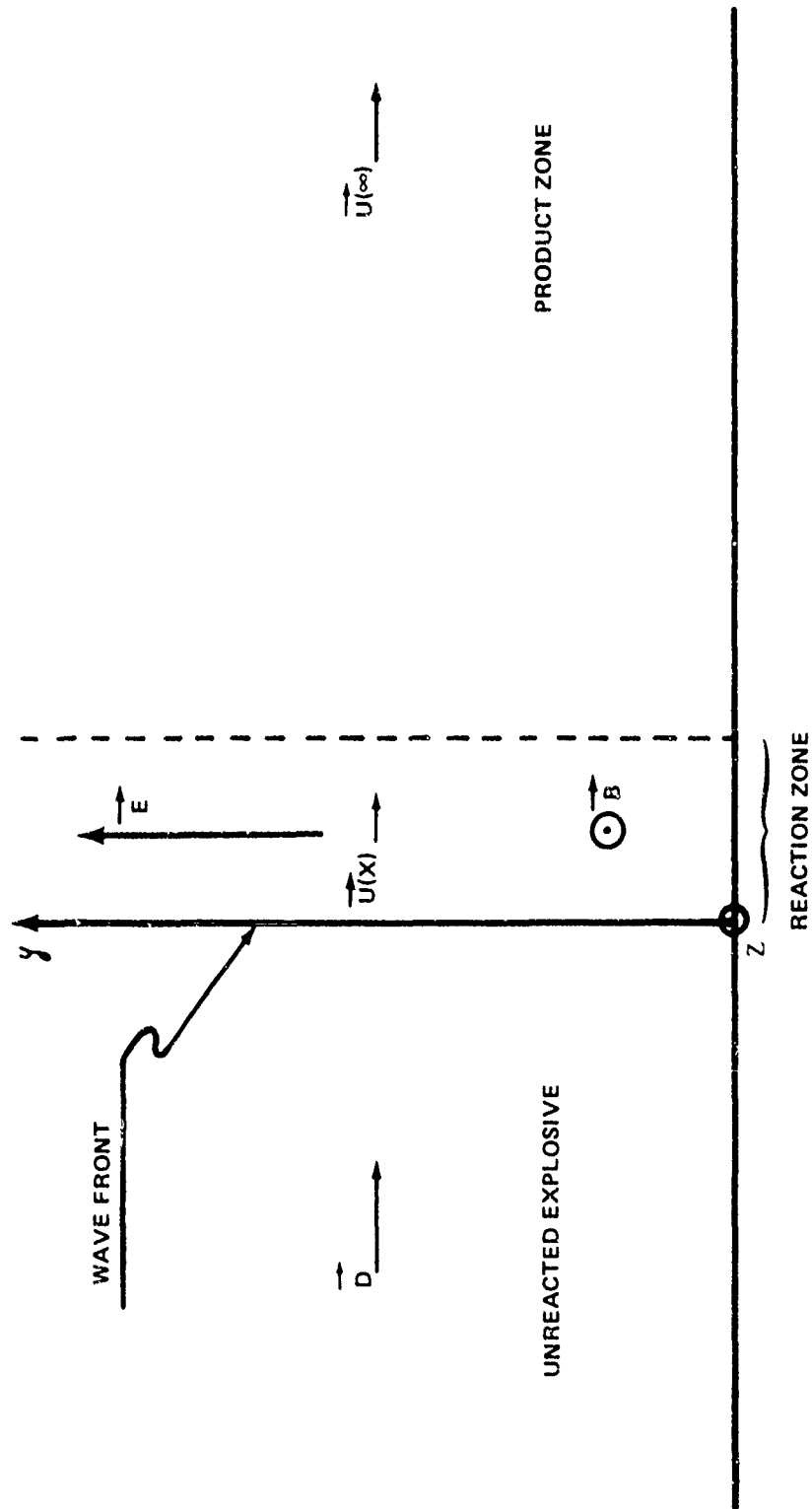where V_o is the specific volume of the unreacted explosive, and D is the detonation velocity.

FIGURE 1. STATIONARY DETONATION WAVE GEOMETRY

Referring to Eq. (6) we see from Fig. 1 that $\vec{J} \times \vec{B}$ has a component only in the x-direction. Eq. (5) becomes

$$\rho u \frac{du}{dx} = \frac{(\vec{J} \times \vec{B})}{c} x - \frac{dP}{dx} \ . \tag{30}$$

From Eq. (29) we write in place of Eq. (30)

$$\frac{D}{V_o} \frac{du}{dx} = \frac{(\vec{J} \times \vec{B})}{c} x - \frac{dP}{dx} \ . \tag{31}$$

Integrating from x=0 to x=∞ we find

$$\frac{D}{V_o} (u - D) = \int_0^\infty \frac{(\vec{J} \times \vec{B})}{c} x \ dx - (P_1 - P_o) \ , \tag{32}$$

where u=u(∞). Thus

$$P_1 + \frac{Du}{V_o} = P_o + \frac{D^2}{V_o} + \int_0^\infty \frac{(\vec{J} \times \vec{B})}{c} x \ dx \ . \tag{33}$$

Also, from Eq. (29) we have

$$\frac{U}{V_1} = \frac{D}{V_o} \ , \tag{34}$$

so that Eq. (33) becomes

$$P_1 + \frac{U^2}{V_1} = P_o + \frac{D^2}{V_o} + \int_0^\infty \frac{(\vec{J} \times \vec{B})}{c} x \ dx. \tag{35}$$

Referring to the energy equation (Eq. (22)) we have

$$\frac{d}{dx} \left[\rho(\epsilon + \tfrac{1}{2}u^2) u + Pu \right] = \rho w + \vec{J} \cdot \vec{E} \ . \tag{36}$$

In view of Eq. (29) we may write Eq. (36) as

$$\frac{d}{dx} \left[\frac{D}{V_o} (\epsilon + \tfrac{1}{2}u^2) + \frac{P}{\rho} \frac{D}{V_o} \right] = \rho w + \vec{J} \cdot \vec{E} \ . \tag{37}$$

Integrating, we find

$$\Delta\epsilon + \tfrac{1}{2}(U^2 - D^2) + P_1 V_1 - P_o V_o$$

$$= \frac{V_o}{D} \int_0^\infty dx \left[\rho w + \vec{J}\cdot\vec{E} \right] , \qquad (38)$$

where $\Delta\epsilon = \epsilon(\infty) - \epsilon(0)$. Instead of Eq. (38) we write the energy equation in the form

$$\Delta\epsilon + \tfrac{1}{2}U^2 + P_1 V_1$$

$$= \tfrac{1}{2}D^2 + P_o V_o + \frac{V_o}{D} \int_0^\infty dx \left[\rho w + \vec{J}\cdot\vec{E} \right] . \qquad (39)$$

The chemical energy release per gram of explosive is

$$\Delta Q_{CH} = \frac{V_o}{D} \int_0^\infty dx\ \rho w ,$$

$$= \int_0^\infty dx\ \frac{w}{u} , \qquad (40)$$

by means of Eq. (29). Similarly, we define an electromagnetic energy release per gram

$$\Delta Q_{EM} = \frac{V_o}{D} \int_0^\infty dx\ \vec{J}\cdot\vec{E} , \qquad (41)$$

and write Eq. (39) as

$$\Delta\epsilon + \tfrac{1}{2}U^2 + P_1 V_1 = \tfrac{1}{2}D^2 + P_o V_o + \Delta Q_{CH} + \Delta Q_{EM} . \qquad (42)$$

Eqs. (29, 35, 42) are the basic mass, momentum, and energy balance equations. The more usual forms of the equations can be obtained from these. Substituting Eq. (34) into Eq. (35) we find

$$U^2 = \frac{V_1^{\ 2}}{(V_o - V_1)} \left[P_1 - P_o - \int_0^\infty \frac{(\vec{J}\times\vec{B})}{c} x\ dx \right] . \qquad (43)$$

13

Also by use of Eq. (34)

$$D^2 = \frac{V_o^2}{(V_o - V_1)} \left[P_1 - P_o - \int_0^\infty \frac{(\vec{J} \times \vec{B})}{c} x \, dx \right] . \tag{44}$$

Substituting Eqs. (43) and (44) into Eq. (42) yields

$$\Delta \varepsilon = \Delta Q_{CH} + \Delta Q_{EM} - (V_o + V_1) \int_0^\infty \frac{(\vec{J} \times \vec{B})}{c} x \, dx$$

$$+ \tfrac{1}{2}(P_1 + P_o)(V_o - V_1) . \tag{45}$$

DETONATION VELOCITY, PRESSURE. In order to evaluate the degree
of influence the electromagnetic field exerts on a detonating
explosive, explicit expressions for D, P, and V must be obtained
in terms of the initial state parameters and the energy release.
The Chapman-Jouguet condition and an equation of state for the explosive
and explosive products are necessary to complete the description
and allow an explicit calculation of the detonation parameters.
An analysis of a specific example in the following will show that
strong electromagnetic fields produce relatively small shifts in the
detonation parameters. Hence an equation of state chosen to describe
the explosive products at the C-J point in an ideal detonation can
be used to investigate the degree of influence of the electromagnetic
field on the detonation parameters. To this end we introduce
(following Eyring, et al[10]) the Abel equation of state for the
dense product gases

$$P(V - \alpha) = RT , \tag{46}$$

where a constant covolume α and the Chapman-Jouguet condition

$$C = V_o \left[- \gamma \left(\frac{\partial P}{\partial V} \right)_T \right]^{\tfrac{1}{2}} = U , \tag{47}$$

is assumed constant, recognizing that more refined equations of state
may be used without altering the general results presented here.

From Eqs. (46, 47) we immediately find

$$U^2 = V_1^2 \gamma \frac{P_1}{V_1 - \alpha} , \tag{48}$$

[10]Eyring, H., Powell, R. E., Duffey, G. H., and Parlin, R. B.,
"The Stability of Detonation," Reprinted from Chemical Reviews,
Vol. 45, No. 1, August 1949, p. 76.

where γ is the ratio of specific heats. Using Eq. (48) in Eq. (43) we obtain

$$\frac{V_1}{V_O} = \frac{\gamma + \alpha\beta/V_O}{\gamma + \beta} \tag{49}$$

where β is given by

$$\beta = 1 - \frac{P_O}{P_1} - \frac{1}{P_1} \int_0^\infty \frac{(\vec{J}\times\vec{B})}{c} x \, dx \; . \tag{50}$$

If C_v is taken to be the mean specific heat of the explosive in the range $T_O \leq T \leq T_1$, then the use of Eq. (49) and the relationship of specific heats in Eq. (45) yields

$$C_v(T_1 - T_O) = \Delta Q + \frac{(V_O - V_1)RT_1}{2(V_1 - \alpha)} + \tfrac{1}{2}P_O(V_O - V_1) \; , \tag{51}$$

where we have taken

$$\Delta Q = \Delta Q_{CH} + \Delta Q_{EM} - (V_O + V_1) \int_0^\infty \frac{(\vec{J}\times\vec{B})}{c} x \, dx \; . \tag{52}$$

From Eq. (49) we have

$$\frac{(V_O - V_1)}{(V_1 - \alpha)} = \frac{\beta}{\gamma} \; , \tag{53}$$

and Eq. (52) becomes

$$\left[C_v - \frac{\beta R}{2\gamma} \right] T_1 = C_v T_O + \Delta Q + \tfrac{1}{2}P_O(V_O - V_1) \; . \tag{54}$$

Using the relations

$$\gamma = C_p/C_v \; , \quad C_p - C_v = R \tag{55}$$

we reduce Eq. (55) to the form

$$T_1 = \frac{2\gamma}{C_v \beta + (2 - \beta)\gamma} \left[\Delta Q + C_v T_O + \frac{\beta P_O V_O (1 - 2/V_O)}{\gamma + \beta} \right] \; . \tag{56}$$

Inserting Eqs. (46, 49) into Eq. (44) we obtain

$$D^2 = \frac{V_O^2 (\gamma + \beta)^2 RT_1}{\gamma (V_O - \alpha)^2} \; , \tag{57}$$

which, by virtue of Eq. (57), becomes

$$D^2 = \frac{2(\gamma - 1)(\gamma + \beta)^2}{[\beta + (2 - \beta)\gamma](1 - \alpha/V_o)^2}\left[\Delta Q + C_v T_o + \frac{\beta P_o V_o(1 - \alpha/V_o)}{\gamma + \beta}\right]. \quad (58)$$

Eqs. (49, 56, 58) are expressions for the specific volume V_1, the temperature T_1 of the reaction products, and detonation velocity D. Using the equation of state we can write P_1 as

$$P_1 \approx \frac{2(\gamma + \beta)(\gamma - 1)}{(V_o - \alpha)[\beta + (2 - \beta)\gamma]}\left[\Delta Q + C_v T_o + \frac{\beta P_o V_o(1 - \alpha/V_o)}{\gamma + \beta}\right]. \quad (59)$$

These equations characterize the one-dimensional steady detonation wave in terms of the unreacted state of the explosive, the energy release per gram of explosive, and the electric and magnetic field strengths present.

STEADY-STATE DETONATION $(\vec{B} = 0)$. The magnetic field appears in the expressions for the final state parameters and the the detonation velocity through two terms, ΔQ and β. In the next section we show that for fields substantially less than a megagauss, the approximation that $\vec{B} = 0$ is valid.

Referring to Eq. (50) we see that in the absence of $\vec{B}$

$$\beta = 1 - P_o/P_1. \quad (60)$$

Even without the added energy release due to the electric field, the final pressure of reaction products is considerably larger than the initial pressure of a condensed explosive. Thus, in Eqs. (49, 57, 58, 60) we set $P_o = 0$ and $\beta = 1$ (as well as $\vec{B} = 0$). We have then

$$\frac{V_1}{V_o} = \frac{1 + \alpha/V_o}{\gamma + 1}, \quad (61)$$

$$T_1 = \frac{2\gamma}{C_v(1 + \gamma)}\left[\Delta Q(\vec{B} = 0) + C_v T_o\right], \quad (62)$$

$$D^2 = \frac{2(\gamma^2 - 1)}{(1 - \alpha/V_o)^2}\left[\Delta Q(\vec{B} = 0) + C_v T_o\right], \quad (63)$$

$$P_1 = \frac{2(\gamma - 1)}{(V_o - \alpha)}\left[\Delta Q(\vec{B} = 0) + C_v T_o\right]. \quad (64)$$

Eqs. (41, 53) yield

$$\Delta Q(\vec{B} = 0) = Q_{CH} + \frac{V_o}{D} \int_0^\infty \vec{J} \cdot \vec{E} \; dx \; .$$ (65)

Using Eq. (65) in Eq. (63) we write

$$D^2 = \frac{2(\gamma^2 - 1)}{(1 - \alpha/V_o)^2} \left[\Delta Q_{CH} + C_v T_o \right] + \frac{2(\gamma^2 - 1)V_o}{(1 - \alpha/V_o)^2 D} \int_0^\infty \vec{J} \cdot \vec{E} \; dx \; .$$ (66)

The first term on the right hand side of this equation is the square of the detonation velocity in the absence of the electric field, i.e. D_o^2. Dividing both sides of Eq. (66) by D_o^2 we find

$$\frac{D^2}{D_o^2} = 1 + \frac{V_o}{D} \frac{\int_0^\infty \vec{J} \cdot \vec{E} \; dx}{(\Delta Q_{CH} + C_v T_o)} \; .$$ (67)

Let

$$\Gamma = \frac{\frac{V_o}{D_o} \int_0^\infty \vec{J} \cdot \vec{E} \; dx}{(\Delta Q_{CH} + C_v T_o)} \; .$$ (68)

Then

$$\frac{D^2}{D_o^2} = 1 + \Gamma \frac{D_o}{D} \; ,$$

or

$$\left(\frac{D}{D_o}\right)^3 - \frac{D}{D_o} - \Gamma = 0 \; .$$ (69)

The detonation velocity is thus determined by a cubic equation in which the adjustable parameter is the joule deposition term as given by Γ. The quantity Γ is a measure of the ratio of electrical power dissipation to a chemical power release of the explosive in the absence of electromagnetic interaction. Once D/D_o is determined by the specification of Γ, the pressure and temperature of the reaction zone (relative to their values in the absence of electromagnetic interaction) can be determined. From Eqs. (62, 64) we have

$$T_1/T_{1_O} = 1 + D_O \Gamma/D \ , \tag{70}$$

$$P_1/P_{1_O} = 1 + D_O \Gamma/D \ , \tag{71}$$

where the subscript "o" has been used to designate values in the absence of electromagnetic interaction.

Approximate Behavior. The effect of both large and small electrical energy deposition on the detonation parameters can be estimated from the preceding equations. In the case of small Γ we may assume

$$D/D_O \sim 1 + \delta \ , \quad \delta << 1 \ . \tag{72}$$

Then from Eq. (69) we find

$$\delta = \Gamma/2 \ . \tag{73}$$

We may write for small Γ

$$D/D_O = 1 + \Gamma/2 \ , \tag{74}$$

$$P_1/P_{1_O} = T_1/T_{1_O} = 1 + \Gamma \ . \tag{75}$$

In the limit of large Γ it is immediately clear from Eq. (69) that D/D_O is large compared to unity. We can thus write

$$\frac{D}{D_O} \sim \Gamma^{1/3} \ , \quad \Gamma >> 1 \ , \tag{76}$$

and from Eqs. (70, 71)

$$\frac{P_1}{P_{1_O}} = \frac{T_1}{T_{1_O}} \sim \Gamma^{2/3} \ , \quad \Gamma >> 1 \ . \tag{77}$$

Figures 2 and 3 provide curves of the detonation parameters for intermediate values of Γ.

Finally, as a specific example we apply the above equations to TNT. Table 1 is taken from Eyring, et al[10]. In order to simulate the one-dimensional character of the detonation process, we imagine a slab of explosive positioned between two parallel conducting sheets. A detonation wave is initiated so that it propagates in a direction parallel to the sheets, and thus the wave remains perpendicular to the conducting walls. If the walls are maintained
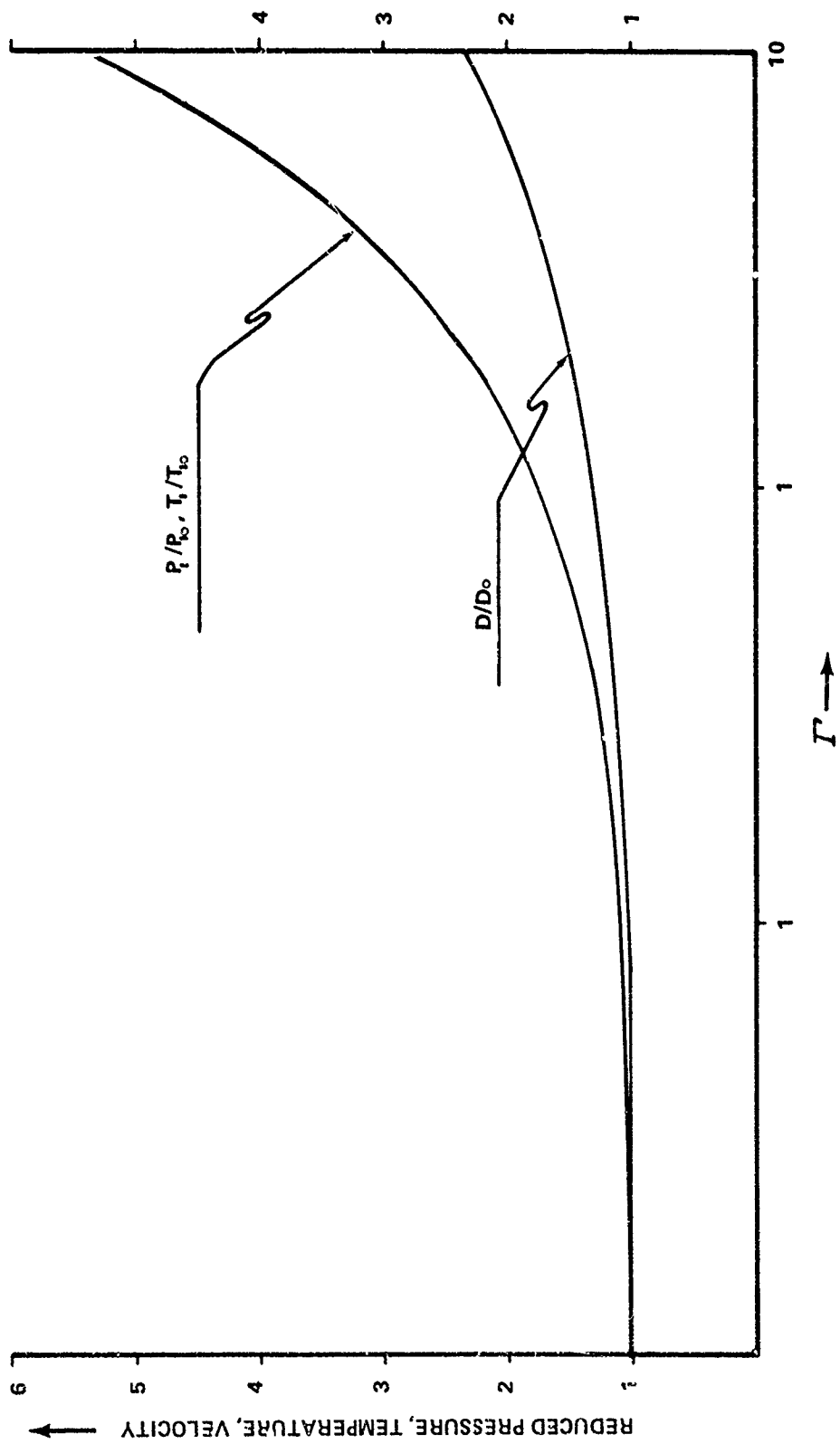
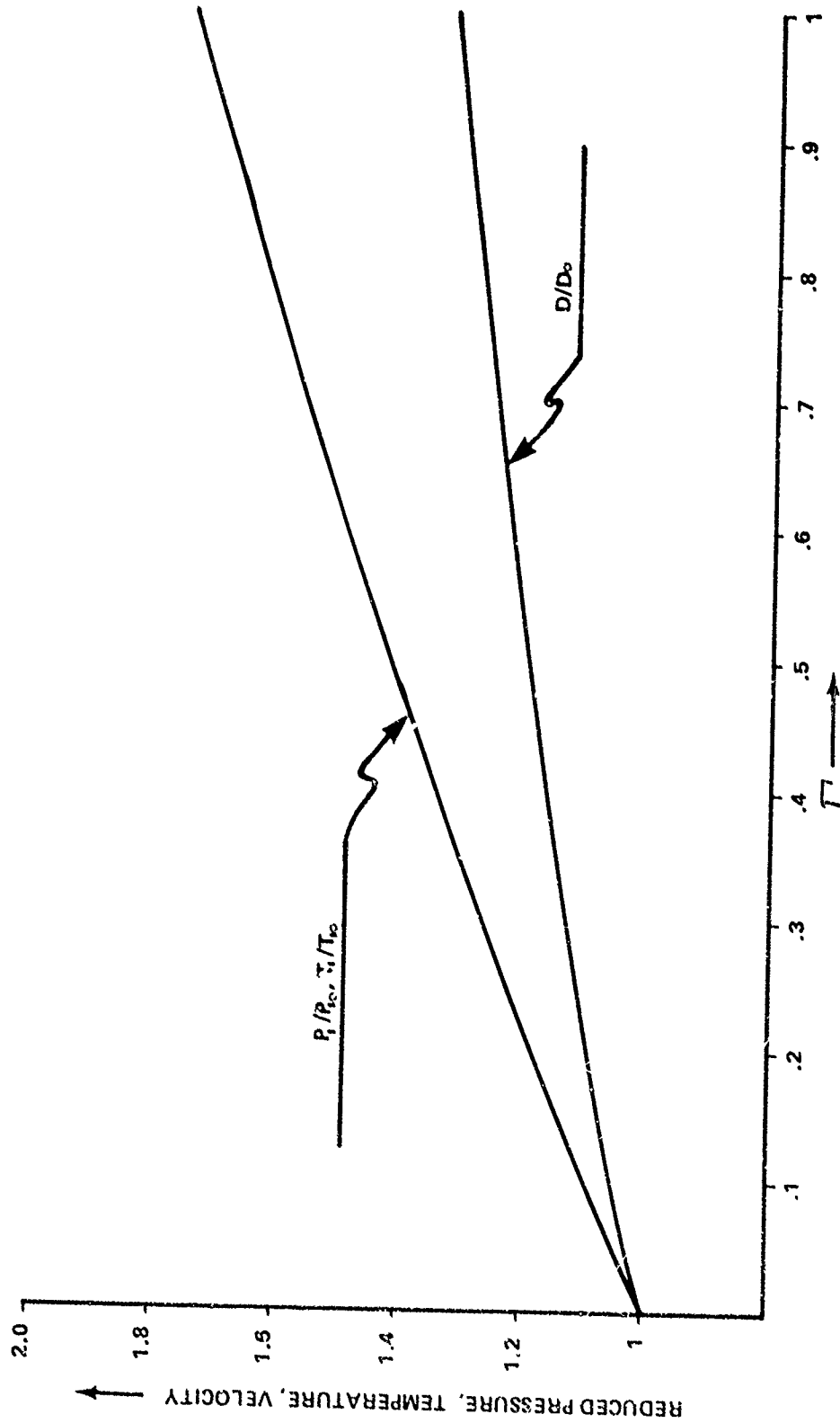FIGURE 2. DETONATION VELOCITY, PRESSURE, TEMPERATURE VS. ELECTRIC POWER DISSIPATION

FIGURE 3. DETONATION VELOCITY, PRESSURE, TEMPERATURE
VS. ELECTRIC POWER DISSIPATION

at a potential difference V, a constant electric field is produced
which remains parallel to the detonation wave surface. The
geometrical requirements of Fig. 1 are thus met.

Because the unreacted explosive is in contact with the
conducting walls, (in order to provide a conducting path for the
moving detonation wave) arbitrarily large potential differences
cannot be supported without dielectric breakdown of the unreacted
explosive and subsequent initiation at points in front of the
detonation wave. The breakdown voltage of TNT has been found to
be[11] 3.7×10^4 volts cm^{-1}. Values of breakdown voltages for various
other explosives have been obtained by J. W. Forbes at NSWC/White Oak
and are given in Table 2.

Table 1
Detonation Characteristics for TNT
(Source: Eyring, et al., Ref. 10)

$$V_O = 0.6360 \ cm^3 gm^{-1}$$
$$C_V = 0.326 \ cal \ deg^{-1} gm^{-1}$$
$$\gamma = 1.240$$
$$D_O = 6.85 \times 10^5 \ cm \ sec^{-1}$$
$$\Delta Q = 1080 \ cal \ gm^{-1}$$
$$\alpha = 0.4225 \ cm^3 gm^{-1}$$

Table 2
Voltage Breakdown Levels of Secondary Explosives

Sample	Density ($gm \ cm^{-3}$)	Distance Between Electrodes (cm)	Breakdown Voltage (V)
Laboratory air	10^{-3}	.165	5,700 ± 160
Silicone potting compound (RTV-61)	1.02	.08	20,000 ± 200
HBX-1 (cast)	1.69	.20	410 ± 55
Type S-1 (cast)	1.69	.20	1,550 ± 90
Comp B (cast)	1.62	.20	10,200 ± 420
TATB	1.84	.20	11,500 ± 890
PBX-9404	1.81	.20	> 24,000

[11]Fedoroff, B. T., and Sheffield, O. E., Encyclopedia of
Explosives and Related Items, PATR 2700, Vol. 5, Picatinny
Arsenal, Dover, N.J., 1972, p. D 1221.

Table 3
Electrical Conductivity of Various Explosives
(Source: Brish, Tarasov, and Tsukerman, Ref. 4)

Explosive	Density $(gm \; cm^{-3})$	Detonation Speed $(\times 10 \; cm^5 sec^{-1})$	Average Conductivity $(ohm^{-1}cm^{-1})$
Alloy of 50% TNT & 50% RDX (molded)	1.64	7.7	5.0
50% TNT and 50% RDX (powdered)	0.8	5.7	1.0
RDX (powdered)	0.8	6.2	0.23
TNT (powdered)	0.8	4.5	4.0
PETN (powdered)	0.8	5.2	0.13
Tetryl (powdered)	0.8	5.0	0.16
Lead azide (powdered)	~0.9	2.7	6.2

We take the breakdown voltage of TNT as a practical limitation on the maximum field to which the explosive is subjected as an illustrative example, bearing in mind that other procedures exist for achieving greater field strengths within the conduction zone.

Table 3 is taken from Brish, Tarasov, and Tsukerman[4] as reliable conductivity values for secondary explosives. We see that the conductivity varies from 4 $ohm^{-1}cm^{-1}$ for powdered TNT to 5 $ohm^{-1}cm^{-1}$ for Composition B. We take a value of 5 $ohm^{-1}cm^{-1}$ as representative of TNT in the above equations.

Collecting the results of the previous paragraphs, we have

$$\sigma \approx 5 \; ohm^{-1}cm^{-1} \; ,$$
$$E \approx 3.7 \; 10^4 \; volts \; cm^{-1} \; , \qquad (78)$$
$$L \approx 0.1 \; cm \; ,$$

where the conduction zone length is approximately the reaction zone thickness (Ershov[7]). Referring to Eq. (68) we can write Γ in terms of the mean conductivity as

$$\Gamma = \frac{\dfrac{V_o}{D_o} L \bar{\sigma} E^2}{(\Delta Q_{CH} + C_v T_o)} \; . \qquad (79)$$

22

We find that for the values appropriate to TNT that

$$\Gamma \simeq 0.13 \qquad (80)$$

and a value of J

$$J = 1.9 \times 10^5 \text{ amp cm}^{-2}. \qquad (81)$$

Reference to Fig. (3) gives

$$P_1/P_{1_O} = T_1/T_{1_O} \simeq 1.12 , \qquad (82)$$

and

$$D/D_O \simeq 1.06 . \qquad (83)$$

Thus the pressure and temperature in the product zone are increased by approximately 12% by the energy deposition provided by the electric field, and the detonation velocity is increased by approximately 6% over what is obtained in the absence of electromagnetic interaction.

STEADY-STATE DETONATION ($\vec{B} \neq 0$). An examination of Eqs. (57, 59, 60) as well as Eq. (50) shows that the magnetic field influence arises primarily through the ratio

$$\frac{1}{P_1} \int_0^\infty \frac{(\vec{J} \times \vec{B})}{C} x \, dx .$$

We can estimate the magnetic field strength necessary to produce significant alteration of the detonation parameters for the case of TNT discussed in the previous section. Let P_1 be the product zone pressure in the absence of interaction. Then a magnetic field necessary to make the pressure ratio to be of the order of unity is given by

$$\frac{JBL}{C} \backsim P_1 ,$$

or

$$B \backsim \frac{CP_1}{JL} , \qquad (84)$$

where J is the mean current density for which we assume the value in Eq. (91). Referring to Table 1 we find $B \backsim 10^8$ gauss; it appears that only for strong magnetic fields can the detonation parameters be substantially altered.

A more severe limitation on the magnetic field strength in
the applicability of the preceding analysis is found on closer
scrutiny of the mechanism of electrical conductivity. The
conductivity is determined by the number density of the electrons,
their mean velocity, and the collision cross-section with ions.
The ions are themselves screened by the mobile electrons providing
an effective cutoff to the Coulomb scattering at the Debye length

$$\delta_D = \left[\frac{kT_e}{4\pi e^2 n_e}\right]^{\frac{1}{2}} , \tag{85}$$

where T_e is a representative electron temperature and n_e is
the number density of the electrons. In the presence of a magnetic
field, the collision cross-section of the electrons and ions may
be assumed unchanged only if the radius of curvature of the electrons
in the magnetic field exceeds the Debye length. Free electrons
in a magnetic field have an orbital radius

$$R = \left[\frac{3kT_e mc^2}{e^2 B^2}\right]^{\frac{1}{2}} . \tag{86}$$

Equating R and δ_D we find that B has a value

$$B_{max} \sim \left[12\pi nmc^2\right]^{\frac{1}{2}} \tag{87}$$

If we use a representative value for n of $10^{18}cm^{-3}$, we find

$B_{max} \sim 5\times 10^6$ gauss . This is two orders of magnitude lower

than the estimate determined from pressure considerations, even
for the large value of current assumed. We therefore treat the
magnetic field effects as perturbations on the jump conditions.

Let Δ be given by

$$\Delta = \frac{1}{P_{1_0}} \int_0^\infty \frac{(\vec{J}\times\vec{B})}{C} x \ dx . \tag{88}$$

Δ is a measure of the magnetic interaction relative to the detonation
pressure in the absence of electromagnetic interaction. By the
arguments of this section it can have a value as large as 0.1.
Instead of Eq. (50) we write

$$\beta \simeq 1 - \Delta , \tag{89}$$

24

valid to first order in Δ (P_o/P_1 is small compared to Δ).

Each of the expressions for the detonation parameters can be written in terms of their values in the absence of electromagnetic interaction. From Eqs. (57, 59, 60) we write

$$\frac{T_1}{T_{1_o}} = \frac{(1 + \gamma)}{[2\gamma + (1 - \gamma)\beta]} \bar{R} , \tag{90}$$

$$\frac{P_1}{P_{1_o}} = \frac{(\gamma + \beta)}{[2\gamma + (1 - \gamma)\beta]} \bar{R} , \tag{91}$$

$$\frac{D^2}{D_o^2} = \frac{(\gamma + \beta)^2}{(\gamma + 1)[2\gamma + (1 - \gamma)\beta]} \bar{R} , \tag{92}$$

where

$$\bar{R} = \frac{\Delta Q + C_v T_o}{\Delta Q_{CH} + C_v T_o} , \tag{93a}$$

$$= 1 + \frac{D_o}{D} \Gamma - \frac{2(\gamma - 1) \Delta}{(1 - \alpha/V_o)(\gamma + \beta)} \left[2\gamma + \beta(1 + \alpha/V_o)\right] . \tag{93b}$$

The expression Eq. (93b) is found from Eq. (53) and from Eq. (49), which we reproduce here for convenience

$$\frac{V_1}{V_o} = \frac{\gamma + \alpha\beta/V_o}{\gamma + \beta} . \tag{49}$$

To first order in Δ we find

$$\frac{D}{D_o} = \left(\frac{D}{D_o}\right)_{\Delta=0} (1 + x\Delta) , \tag{94a}$$

$$x = -\left[2\left(\frac{D}{D_o}\right)_{\Delta=0} + 3\Gamma\right]^{-1}\left(\frac{D}{D_o}\right)_{\Delta=0}\left[\left(\frac{D}{D_o}\right)_{\Delta=0}^2 + \frac{2(\gamma - 1)(2\gamma + (1 + \alpha/V_o))}{(\gamma + 1)(1 - \alpha/V_o)}\right] , \tag{94b}$$

$$\frac{P_1}{P_{1_o}} = \left(\frac{P_1}{P_{1_o}}\right)_{\Delta=0} (1 + y\Delta) , \tag{95a}$$

25

$$y = - \left[\left(\frac{D}{D_o}\right)_{\Delta=0} + \Gamma\right]^{-1} \left[x\Gamma + 2\left(\frac{D}{D_o}\right)_{\Delta=0} \frac{(\gamma - 1)(2\gamma + (1 + \alpha/V_o))}{(\gamma + 1)(1 - \alpha/V_o)}\right]$$
$$- \frac{\gamma}{\gamma + 1} , \tag{95b}$$

$$\frac{T_1}{T_{1_o}} = \left(\frac{T_1}{T_{1_o}}\right)_{\Delta=0} (1 + z\Delta) , \tag{96a}$$

$$z = y + \frac{1}{\gamma + 1} , \tag{96b}$$

$$\frac{V_1}{V_o} = \left(\frac{V_1}{V_o}\right)_{\Delta=0} \left[1 + \Delta\left(\frac{1}{\gamma + 1} - \frac{\alpha/V_o}{(\gamma + \alpha/V_o)}\right)\right] . \tag{97}$$

The sign of Δ can be determined by the choice of the direction of the magnetic field (Eq. (88)). It is apparent from these equations that the magnetic field can have an accelerating or retarding effect on the detonation wave. The quantities x and y are intrinsically negative leading to an enhancement of detonation velocity and pressure by the magnetic field if Δ is chosen to be negative, and a retarding effect otherwise.

Returning to the example of TNT, we determine the extent of magnetic interaction for the largest current which can be established subject to breakdown limitations, namely a current density of 1.9×10^5 amp cm^{-2}. Using the parameters given in Table 1 and Figure 3 we obtain the values x = -1.58, y = -2.70, z = -2.26. If, finally, we choose a value of Δ of -0.1 corresponding to a magnetic field of 5×10^6 gauss (with an appropriate direction chosen), we see that the detonation velocity is further increased by approximately 16% and that the detonation pressure is further increased by approximately 27% above the values obtained by joule heating alone. Note that both the detonation velocity and pressure changes occur in the same direction for a given Δ (x and y are both negative).

DISCUSSION

We have obtained the jump equations for steady-state detonation of condensed explosives in the presence of stationary, uniform, electric, and magnetic fields. Final state pressures and temperatures and the detonation velocity have been characterized for the model using an Abel equation of state. The prescription can be used with

more realistic equations of state, but it is expected that the qualitative features of this report would be unchanged.

We can conclude from the specific example of TNT that the control of the detonation wave of a condensed explosive by means of electromagnetic fields is a real possibility requiring electric field strengths on the order of 10^4 volts cm^{-1} and magnetic field strengths on the order of 10^6 gauss.

The analysis presented here must be regarded as preliminary because of the approximations used. A more substantive analysis should treat the multifluid character of the reacting explosive; the treatment of the reaction and product zones as a three-component fluid of electrons, ions, and neutral particles would provide a more realistic framework for understanding the details of electromagnetic interaction with a detonating explosive. The expression of Ohm's law used in this Report is at best a crude approximation for this problem and can be supplanted by a more accurate expression derived from the species equations of motion.

The conductivity of the detonating explosive has been assumed to be unchanged by the presence of the electromagnetic field. This was assured in part by the restriction on the allowable magnetic field strength. In view of the fact that the current is induced by the local fields, the joule heating depends quadratically on the electric field strength, and the magnetic terms are proportional to (with proportionality factor σ) and depend bilinearly on E and B. Thus, deviations of the conductivity should only arise in higher order considerations.

One other assumption has been made with regard to the dielectric properties of the explosive. It has been assumed that no induced polarization occurs either in the unreacted explosive or in the reaction zone. Since the stored energies in induced polarization are small, this does not change the jump conditions, but it does affect the field distribution within the reaction zone if the field is generated by an external capacitor plate configuration. This is an added feature which can be incorporated in the multifluid treatment.

Finally, it is worth mentioning that the maximum field strength to which the detonation wave could be subjected is limited by the breakdown voltage of the unreacted explosive. A similar limitation could exist for the product zone. Korol'kov, Mel'nikov, and Tsyplenko[12] have shown that the breakdown voltages of the detonation products of PETN and RDX are of the same order as the unreacted explosives themselves. Hence, the breakdown voltage limitations are unchanged.

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