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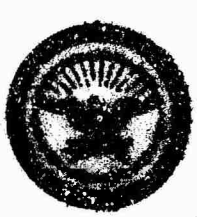

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REPORT NO. 1620

# THEORY AND COMPUTATIONS OF COLLAPSE AND JET VELOCITIES OF METALLIC SHAPED CHARGE LINERS

by

A. R. Kiwan
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November 1972





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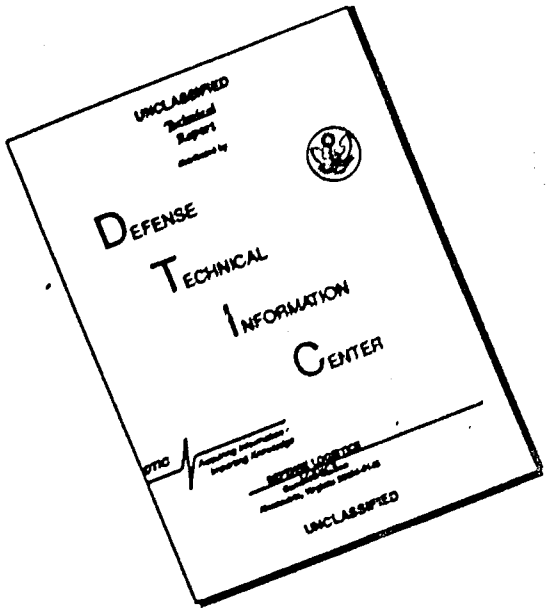


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# THEORY AND COMPUTATIONS OF COLLAPSE AND JET VELOCITIES OF METALLIC SHAPED CHARGE LINERS

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RDT&E Project No. 1T0061102A33E

A B E R D E E N  P R O V I N G  G R O U N D,  M A R Y L A N D

B A L L I S T I C  R E S E A R C H  L A B O R A T O R I E S

REPORT NO. 1620

ARKiwan HWisniewski/ng
Aberdeen Proving Ground, Md.
November 1972

# THEORY AND COMPUTATIONS OF COLLAPSE AND JET VELOCITIES OF METALLIC SHAPED CHARGE LINERS

## ABSTRACT

A model to compute the collapse velocities of various elements of a metallic liner of a shaped charge from the known detonation properties of the explosive used and the geometrical configurations of the charge is proposed. The calculated collapse and jet velocities increase from the apex of the liner toward the base, reach a maximum, and then decrease monotonically thereafter. The calculated velocity distribution in the jet after it goes through compression agrees qualitatively and quantitatively with available experimental measurements.

TABLE OF CONTENTS

## LIST OF SYMBOLS

| | |
|---|---|
| $x,y,z$ | Eulerian Coordinates |
| $t$ | time variable |
| $p$ | pressure |
| $p_f$ | pressure at the detonation front |
| $p_o$ | ambient atmosphere pressure |
| $I$ | impulse |
| $u$ | particle velocity in the pressure wave |
| $c$ | sound speed in the pressure wave |
| $U$ | detonation velocity |
| $2k$ | the height of the charge |
| $2\ell$ | the thickness of the charge |
| $\alpha$ | half angle of the charge liner |
| $n$ | number of liner zones |
| $\beta$ | half angle of collapsing liner |
| $\delta m^k$ | the $k^{th}$ element of liner mass |
| $\delta m_j^k$ | the mass of the $k^{th}$ jet element |
| $\delta m_g^k$ | the mass of the $k^{th}$ slug element |
| $\overline{uc}$ | average value of (u+c) over the pressure wave |
| $V_j^k, v_j^k$ | velocities of $k^{th}$ liner jet element relative to stationary and moving coordinate systems |
| $V_g^k, v_g^k$ | velocities of $k^{th}$ liner slug element relative to stationary and moving coordinate systems. |
| $e$ | coefficient of restitution |

# I. INTRODUCTION

The existing theory of explosives with metallic lined cavities was first published in the open literature in 1948 by Birkhoff, MacDougall, Pugh and Taylor [1]*. The paper gave a qualitative description of the phenomenon of collapse of a metallic liner of a shaped charge and the formation of a jet. The quantitative part of the theory provided a first order approximation to the various characteristics of the phenomenon. The whole theory was based on simulating the relative motion of the metallic liner during collapse with the steady flow of two jets of water impinging upon each other as developed by Milne-Thomson in [2] . The relative motion considered here is with respect to an observer at the stagnation point. The theory assumed that each element of the liner collapses with a constant velocity $V_o$, and thus the ensuing jet was a uniform one of a constant length $\ell$, equal to the length of the side of the uncollapsed liner, and had a uniform distribution of velocity along it. Pugh, Eichelberger and Rostoker [3] modified the earlier theory by assuming the velocity of collapse $V_o$ to be a function of position on the liner which decreases monotonically from apex to base. This modification had the effect of elongating the ensuing jet and producing a velocity gradient along its length. An enormous amount of literature has appeared since then which is mostly of an experimental nature and expounds the various aspects of the theory of shaped charges. In 1955 R. J. Eichelberger re-examined the non-steady theory of jet formation [4] and in his conclusion raised some doubts about the hydrodynamical model. Moreover, the theory, as developed in [1] and modified in [3] , fails to correlate the velocity of collapse of a liner element to the properties of the explosive used, or to the

*References are listed on page 24

geometrical configuration of the charge in question. The application of the theory as developed in [1] and [3], necessitated the experimental measurement of collapse velocities of various elements of a liner for each charge with a specified explosive and a given geometry.

The present paper takes into account the varying properties of various explosives and the different geometrical configurations of various charges and predicts quantitatively the collapse velocities of the various elements of a liner and the subsequent formation of a jet. The main ideas in the current investigation are the following:

1. The liner is replaced by a system of discrete solid liner elements. We assume that we may neglect forces of interaction between liner elements and strength properties of liner material. This is justified since the pressure at the detonation front is several orders of magitude greater than the ultimate tensile strength of a typical liner material e.g. the peak pressure at the detonation front for pentolite at 1.65 $gm/cm^3$ density is approximately 2389.55 $Kg/mm^2$ (see [5]) while the ultimate tensile strength for quenched copper aluminum is 85.40 $Kg./mm^2$.

2. The impulse transmitted by the detonation products to a liner element is obtained by integrating the excess pressure $p(x,y,t)$ along the path of the liner element. Thus if

$$x=x^k(t) \qquad y=y^k(t) \tag{1.1}$$

are the parametric equations of the path of a typical liner element, then

$$I^k = \int_{t_o^k}^{t_s^k} p(x^k(t), y^k(t), t)\, dt, \quad (k=1,2,\ldots,n) \tag{1.2}$$

represents the total impulse per unit area of liner given to the $k^{th}$ element by the time it reaches its stagnation point, where $p(x,y,t)$ is the excess pressure over the atmosphere at the point $(x,y)$ and time $t$, $t_o^k$ the instant the detonation front reaches the $k^{th}$ element, $t_s^k$ is the stagnation time of the same element and $k$ is a Lagrangian coordinate indicating the initial position of the element. Flow properties behind the detonation front in T.N.T. were studied by Sir G. I. Taylor [6] and similar studies for pentolite were performed by R. Shear [5] . In this paper we shall restrict our considerations to wedge shaped liners Figure 1.

## II. PRESSURE APPROXIMATION

In this section we obtain an approximation to the pressure wave behind the detonation front in a shaped charge warhead. The starting point is the Taylor wave [6] . The pressure wave in the detonation products behind the front is approximated in the space $(p,x/Ut)$ by a triangular pressure pulse. The variables $p$, $U$, $t$, and $x$ denote the overpressure, the detonation velocity, the time measured from initiation, and the abscissa of the point under consideration. Let the origin of our stationary coordinate system be at the center of the plane of initiation of the charge as shown in Figure 1. We consider the function

$$p(Z) = p_f - p_o + (p_f - p_o)\ (Z-1)/(1-\lambda_o),\ \lambda_o \leq Z \leq 1 \qquad (2.1)$$

where, $Z=x/Ut$, $p_f$ the detonation pressure, $p_o$ the ambient atmospheric pressure, to be an approximation to the overpressure distribution in a completely confined charge which has its initiation end open. Equivalently $p(Z)$ is considered as an approximation to the one dimensional plane Taylor wave in a tube with an open end. The parameter $\lambda_o$, in Equation (2.1) is the value of $Z$ for which the part-

icle velocity u vanishes in the Taylor wave. The overpressure p(Z) as given by Equation (2.1) is modified whenever the charge is unconfined, and secondly it has to be modified further due to the presence of the cavity in the explosive which causes a reduction in the total available energy greater than otherwise assumed. For an unconfined charge the parameter $\lambda_c$ in Equation (2.1), which determines the slope of the linear fit to the Taylor wave is replaced by $\lambda_1$ where,

$$\lambda_1 = \lambda_o + (1-\lambda_o)\{ \sum_{S_i} \delta A \ (1 - \ell_n/\ell_{\overline{uc}}) \ H \ (t-t^o_{\delta A}).H(1-\ell_n/\ell_{\overline{uc}} )\}/A_t. \quad (2.2)$$

In Equation (2.2), $\delta A$ is an element of area of an unconfined surface $S_i$ of the charge, $\ell_{\overline{uc}}(t)$ the distance traveled by the sound wave propagating from $\delta A$ inward normal to the plane $z = o$ at time t, $\ell_n$ is the total distance along that normal from $\delta A$ to the plane $z = o$, $t^o_{\delta A}$ is the time of arrival of the detonation front at the element $\delta A$, $A_t$ is the total surface area of the charge up to the detonation front, $\overline{uc}$ is the average value of $(u + c)$ over the wave as it sweeps over $\delta A$, u is the particle velocity, c is the sound speed in the wave, and H (x) is the Heaviside step function. The summation in (2.2) is carried out over all unconfined surfaces $S_i$ of the charge. Effectively Equation (2.2) accounts for the lack of confinement on the charge surface by increasing the slope of th linear fit to the pressure wave in the plane (p,x/Ut), thus causing faster pressure decay. The contribution from an unconfined surface element $\delta A$ is seen from equation (2.2) to be $(1-\lambda_o)\ \delta A\ (1-\ell_n/\ell_{\overline{uc}})/A_t$, and its effect is felt only after the disturbance from $\delta A$ has reached the plane z=o by virtue of $H\ (1-\ell_n/\ell_{\overline{uc}})$. Let $E_i$, i = 1,2,3,4, be a confinement function associated with surface $S_i$ of the charge where,

$E_i = o$ if $S_i$ is confined.

$E_i = 1$ if $S_i$ is unconfined.

Writing equation (2.2) in integral form one obtains

$$\lambda_1=\lambda_o+ (1-\lambda_o) \{ (E_1 + E_3) I_1 + (E_2 + E_4) I_2\}/ 4 (K+\ell) Ut, \qquad (2.3)$$

where

$$I_1 = \int_o^{Ut} 2K [1-\ell/ \{\overline{uc} (t-x/U)\}] H (t-x/U). H(1-\ell/\{\overline{uc}(t-x/U)\}) dx,$$

$$I_2 =\int_o^{Ut} 4dx\int_o^{\ell} \{1-z/\overline{uc} (t-x/U)\}H(t-x/U).H\{1-z/\overline{uc} (t-x/U)\}d z. \quad (2.4)$$

Evaluating the integrals $I_1$ and $I_2$ and substituting in (2.3) one obtains

$$\lambda_1= \lambda_o+ (1 - \lambda_o) N/4 (K + \ell) Ut \qquad (2.5)$$

where,

$$N=\{2(E_1 + E_3) KU [ (t-\ell/\overline{uc}) + (\ell/\overline{uc})\ell n (\ell/\overline{uc}.t)] +2(E_2+E_4)$$

$$U\ell [ 2t - 3\ell / 2 \overline{uc} + (\ell/uc). \ell n (\ell/\overline{uc}.t)]\} H (t-\ell/\overline{uc}),$$

where,

$$\overline{uc}= av (u+c) = av \frac{(u+c)t}{Ut}\cdot U=av \frac{X}{R}. U = av Z.U= U (1+\lambda o)/2. \qquad (2.6)$$

Equation (2.1) would thus be replaced by

$$p (Z) = p_f - p_o + (p_f - p_o) (Z - 1) / (1 - \lambda_1). \qquad (2.7)$$

The overpressure distribution as given by (2.7) needs one further

modification due to the presence of the cavity in the explosive and hence the loss of available energy. This modification is effected as before by increasing the slope of our linear fit. Equation (2.7) is modified to

$$p(Z) = p_f - p_o + (p_f - p_o)\ (Z - 1) \ /\ [\ 1-\{\ \lambda_1 + (1-\lambda_1)V_c/V_t\}], \quad (2.8)$$

where $V_c$ is the volume of the cavity up to the detonation front, $V_t$ is the total volume of the explosive which would have been present from the apex of the liner up to the detonation front had the cavity been absent. $V_c$ and $V_t$ are given by

$$V_c = 2\ell\ (Ut-d)^2 \tan\ \alpha\ .\ H\ (t - t_o^1\ )$$

$$V_t = 4\ell\ K\ [\ (Ut-d)\ H\ (t_o^n - t) + (U\ t_o^n - d)\ H\ (t-t_o^n)\ ].$$

Equation (2.8) then reduces to

$$p(x,y,t) = p_f - p_o + (p_f - p_o)\ (x/Ut - 1)/[1-\{\lambda_1 + (1-\lambda_1)\ (Ut-d)^2 .$$

$$\tan\ \alpha\ .\ H\ (t-t_o^1)/2K\ [(Ut-d)\ H(t_o^n - t) + (U\ t_o^n - d)H(t-t_o^n)]\}]\ . \quad (2.9)$$

Equation (2.9) reveals our assumption of plane detonation wave in the fact that p is independent of y and z and is a function of x and t only. Figure 2 shows a schematic of a cross section of the charge, and Figure 3 shows the triangular wave profile for charge 5 at different times measured from initiation.

## III. NUMERICAL INTEGRATION OF THE EQUATIONS OF MOTION

For each strip of the liner we integrate numerically the following set of equations which are obtained from Newton's laws of motion

$$\sigma \ddot{x}^k = p\,(x^k(t),\ y^k(t),\ t).\ \sin\alpha \qquad (3.1)$$

$$\sigma \ddot{y}^k = -p\,(x^k(t),\ y^k(t),\ t).\ \cos\alpha \qquad (3.2)$$

$k = 1,2,\ldots, n$, where $p(x,y,t)$ is given by (2.9), $\sigma$ is the mass per unit area of the liner and the dot indicates differentiation with respect to t. This implicitely involves the assumption that each element of the liner collapses in a direction perpendicular to the surface of its initial position on the liner. This assumption is consistent with assuming the flow in the detonation products to be inviscid and was made earlier by G. Birkhoff [7]. The integration of (3.1), (3.2) is carried out subject to the conditions:

$$\text{at } t = t_o^k;\ x^k = x_o^k = d + h\,(2k-1)/2n,\ \dot{x}^k = 0$$

$$y^k = y_o^k = h\tan\alpha(2k-1)/2n,\ \dot{y}^k = 0 \qquad (3.3)$$

and

$$t_o^k = x_o^k/U \quad k=0,1,2,\ldots,n \qquad (3.4)$$

The numerical integration of (3.1), (3.2) is terminated at $t_1^k$ which is such that

$$P(x^k, y^k, t_1^k) = 0 \qquad (3.5)$$

or at $t_s^k$ which satisfies (see Fig. 3)

$$y^k(t_s^k) = 0. \qquad (3.6)$$

In the case of $t_1^k < t_s^k$, the motion of the $k^{th}$ element for $t_1^k < t < t_s^k$ is given by

$$x^k = x_1^k + (t-t_1^k)\,\dot{x}_1^k \qquad (3.7)$$

$$y^k = y_1^k + (t-t_1^k)\,\dot{y}_1^k \qquad (3.8)$$

where $x_1^k$, $y_1^k$, $\dot{x}_1^k$, $\dot{y}_1^k$ are the coordinates and the velocity components of the $k^{th}$ element at $t = t_1^k$. The stagnation time $t_s^k$ is obtained in this case by setting in (3.8)

$$y^k = 0$$

i.e.
$$t_s^k = t_1^k - y_1^k/\dot{y}_1^k \tag{3.9}$$

and the stagnation point in this case

$$x_s^k = x_1^k - \dot{x}_1^k . y_1^k/\dot{y}_1^k \tag{3.10}$$

The velocity of collapse at the stagnation point is given in this case by

$$V_p^k = \left\{ (\dot{x}_1^k)^2 + (\dot{y}_1^k)^2 \right\}^{1/2} \tag{3.11}$$

In the other case of $t_s^k < t_1^k$, i.e., when the particle reaches the axis before the overpressure vanishes,

$$V_p^k = \left\{ (\dot{x}_s^k)^2 + (\dot{y}_s^k)^2 \right\}^{1/2} . \tag{3.12}$$

Combining Equations (3.1), (3.2) one obtains

$$\ddot{x}^k + \tan \alpha \cdot \ddot{y}^k = 0. \tag{3.13}$$

Integrating (3.13) subject to (3.3) one arrives at

$$\dot{x}^k + \tan \alpha . \dot{y}^k = 0$$

$$y^k = (d-x^k) \cdot \cot \alpha + 2h(2k-1)/2n \sin 2\alpha \tag{3.14}$$

This is the equation of the trajectory of the $k^{th}$ particle. Setting $y^k = 0$ in Equation (3.14) one obtains

$$x_s^k = d + h \sec^2\alpha(2k-1)/2n \qquad (3.15)$$

Equation (3.15) may be used to check the numerical integration.

When the $k^{th}$ particle reaches the stagnation point, the distribution of velocities is as shown in Figure 4, where $\vec{V}_p^k$ is the actual velocity of the $k^{th}$ particle relative to our fixed coordinate system as it enters the stagnation point. $\vec{V}_s^k$ is the velocity of the stagnation point, relative to the fixed axes as the $k^{th}$ particle enters it, and

$$\vec{V}_r^k = \vec{V}_p^k - \vec{V}_s^k \qquad (3.16)$$

is the velocity of the $k^{th}$ particle relative to the stagnation point. Since $\vec{V}_p^k$ has been determined above it remains to determine $\vec{V}_s^k$, $\beta^k$ and $\vec{V}_r^k$. $|\vec{V}_s^k|$ is determined numerically, thus

$$V_s^k(t_s^k) \simeq (x_s^{k+1} - x_s^{k-1})/(t_s^{k+1} - t_s^{k-1}).$$

Using Equation (3.15) this reduces to

$$V_s^k(t_s^k) \simeq 2h \sec^2\alpha/n(t_s^{k+1} - t_s^{k-1}) \quad (k=1,2,\ldots,n). \qquad (3.17)$$

$t_s^1, t_s^2, \ldots t_s^n$ are obtained above in the numerical integration,

$$t_s^o = (d - h \sec^2\alpha/2n)/U$$

by definition and $t_s^{n+1}$ is obtained by quadratic extrapolation i.e.,

$$t_s^{n+i} = a(n+1)^2 + b(n+1) + c, \qquad (3.18)$$

where ,

$$a = [\, t_s^n - 2t_s^{n-1} + t_s^{n-2} \,]/2$$

$$b = (3-2n)t_s^n/2 + 2(n-1)t_s^{n-1} - (3n-1)t_s^{n-2}/2$$

and $$c = (n-1)(n-2)t_s^n/2 - n(n-2)t_s^{n-1} + n(n-1)t_s^{n-2}/2.$$

From Figure 4

$$|\vec{v}_r^k|/\cos\alpha = |\vec{v}_p^k|/\sin\beta^k = |\vec{v}_s^k|/\sin(\pi/2 + \alpha - \beta^k) \quad (3.19)$$

and hence

$$\cot\beta^k = |\vec{v}_s^k| \cdot \sec\alpha/|\vec{v}_p^k| - \tan\alpha$$

i.e.

$$\cot\beta^k = |\vec{v}_s^k|/|\dot{y}_s^k| - \tan\alpha \quad (3.20)$$

and hence $\beta^k$ may be evaluated. At the stagnation point the $k^{th}$ particle $\delta m^k$ is divided into two parts $\delta m_j^k$ and $\delta m_g^k$ and we have by the laws of conservation of mass and momentum

$$\delta m^k = \delta m_j^k + \delta m_g^k \quad (3.21)$$

$$-\delta m^k . |\vec{v}_r^k| \cos\beta^k = \delta m_j^k . v_j^k + \delta m_g^k . v_g^k \quad (3.22)$$

where $v_j^k$ and $v_g^k$ are the velocities of $\delta m_j^k$ and $\delta m_g^k$ relative to an observer at the stagnation point. An observer stationed at the stagnation point will observe the flow of the liner material to be nonsteady, however for the sake of simplicity we shall assume that

$$v_g^k = -|\vec{v}_r^k| = -v_j^k. \quad (3.23)$$

Equation (3.23) amounts to assuming the flow of liner material relative to the stagnation point to be steady and that the law of conservation

of energy holds there. It is to be observed that equation (3.23) was first used by G. Birkhoff, D. P. MacDougall, E. M. Pugh and Sir G. I. Taylor in [1] and later by E. M. Pugh, R. J. Eichelberger and N. Rostoker [3]. Using (3.23) in (3.22) and then solving (3.21), (3.22) one obtains the familiar results

$$\delta m_j^k / \delta m^k = \sin^2(\beta^k/2) \tag{3.24}$$

$$\delta m_g^k / \delta m^k = \cos^2(\beta^k/2) \tag{3.25}$$

If $\vec{V}_j^k$ and $\vec{V}_g^k$ are the respective velocities of $\delta m_j^k$ and $\delta m_g^k$ relative to fixed coordinate axes as they leave the stagnation point then

$$|\vec{V}_j^k| = |\vec{V}_s^k + \vec{v}_j^k| = |\vec{V}_s^k| + |\vec{v}_r^k| \tag{3.26}$$

$$|\vec{V}_g^k| = |\vec{V}_s^k + \vec{v}_g^k| = |\vec{V}_s^k| - |\vec{v}_r^k| . \tag{3.27}$$

Substituting for $V_s^k$ and $|\vec{v}_r^k|$ their values from (3.19) one obtains

$$|\vec{V}_j^k| = |\vec{V}_p^k| \cos(\alpha - \beta^k/2)/\sin(\beta^k/2) \tag{3.28}$$

$$|\vec{V}_g^k| = |\vec{V}_p^k| \sin(\alpha - \beta^k/2)/\cos(\beta^k/2) \tag{3.29}$$

Equations (3.28) and (3.29) agree with equations (5) and (6) of Pugh, Eichelberger and Rostoker [3] when one substitutes in the latter equations $\delta = 0$.

An examination of the computed jet velocity distribution when plotted as a function of its initial position (Lagrangian coordinate) on the liner reveals that this distribution cannot be stable. This instability is due to the presence of an inverse(positive) velocity gradient Figure 9. From a physical point of view this means that

as the various jet elements form and emerge from their stagnation points; the jet undergoes a continuous process of compression. During compression, momentum and energy are continuously transferred from the rear portion of the jet to the front portion until a physically stable velocity distribution is attained in the jet. A physically stable velocity distribution is one which has no inverse velocity gradient and in fact is what would be observed experimentally. This phenomenon of jet compression has been well known to experimenters for sometime. To simulate mathematically the process of jet compression, in its generality, is a rather complex task. The compression phase can be simulated in a simplified form, by treating it as the elastic collision of a string of heavy particles with the instantaneous mass and velocity distributions. Mathematically this is accomplished by an iterative procedure. Suppose the $\ell^{th}$ liner element has already collapsed and reached its stagnation point and the jet underwent compression. Let the jet velocities at that stage be denoted by $u^k$, k=1,...,$\ell$. As the $(\ell+1)^{th}$ liner element collapses and reaches its stagnation point then we set $u_o^k = u^k$, k=1,...,$\ell$, and $u_o^{\ell+1} = V_j^{\ell+1}$. For i=o,1,2,... one compares $u_i^k$ and $u_i^{k+1}$, (k=1,2,...,$\ell$). If $u_i^k < u_i^{k+1}$ then this means that particles k and (k+1) go through a collision process and acquire new velocities

$$u_{i+1}^k = [\delta m_j^k\, u_i^k + \delta m_j^{k+1}\, u_i^{k+1} - e\delta m_j^{k+1}(u_i^k - u_i^{k+1})]/[\delta m_j^k + \delta m_j^{k+1}] \quad (3.30)$$

$$(u_{i+1}^{k+1}) = [\delta m_j^k\, u_i^k + \delta m_j^{k+1}\, u_i^{k+1} + e\delta m_j^{k+1}\,(u_i^k - u_i^{k+1})]/\,[\delta m_j^k + \delta m_j^{k+1}], \quad (3.31)$$

otherwise the velocities of particles k, (k+1) remain unchanged. Next we turn our considerations to particles (k+1) and (k+2) where the velocity of (k+1) is given by Equation (3.31). The $i^{th}$ iteration is terminated when k assumes the values 1,2,...,$\ell$. The whole iteration process is terminated when the condition $u_i^{k+1} \leq u_i^k$ is satisfied for all k=1,2,...,$\ell$. Equations (3.30) and (3.31) are obtained by

solving the equations of conservation of momentum together with the equation defining the coefficient of restitution,e [8]. The parenthesis surrounding $u_{i+1}^{k+1}$ in Equation (3.31) indicates that this velocity is not the final one for this iteration. The above iterative process is analogous to the Gauss-Seidel method.

## IV. APPLICATION

The preceeding theory was applied to charges with geometry as shown in Figures 5 and 6 loaded with composition B with loading density 1.7 gms/cm$^3$. These charges are 4 inches thick. Figure 7 shows the collapse velocity curves of liner elements as functions of their initial positions. Figure 8 shows collapse angle curves and Figure 9 shows the jet velocity curves for the various liner elements as they emerge from their stagnation points. The dotted curves are the final jet velocity distributions after these jets go through a compression process. Two compression cases have been considered e=1 (perfectly elastic), and e=0 (perfectly inelastic), and are shown in Figure 9. Table 1 shows how the various computed properties of charge 5 vary as functions of the number of zones across the liner and hence is indicative of the speed of convergence. The velocity of the tip of the jet for charge 6 was found to be 0.591 cms/$\mu$ sec, (e=1) and 0.543 cms/ $\mu$sec(e=0), while the ratio of the liner's mass in the slug was found to be 0.79. The calculation reveals that the tip of the jet reaches its terminal velocity rather early in the collapse process, for example for charge 6 the tip of the jet (e=1) reaches its terminal velocity after 0.09 of the liner had collapsed. R. Dipersio observed that the calculated slug velocity distributions for some cases reveals the existence of an inverse velocity gradient in the slug and indicates a compression process similar to that occuring in the jet. This phenomenon of slug compression is known experimentally.

TABLE 1

| No. of Liner Zones | Percentage of Liner Mass in Slug | Velocity of Tip of Jet cm/μsec (e=1) | Velocity of tip of Jet cm/μsec (e=0) |
|---|---|---|---|
| 10 | 0.856 | 0.714 | 0.706 |
| 20 | 0.863 | 0.732 | 0.691 |
| 30 | 0.865 | 0.737 | 0.688 |
| 40 | 0.866 | 0.741 | 0.686 |
| 50 | 0.866 | 0.743 | 0.685 |
| 100 | 0.867 | 0.746 | 0.684 |
| 200 | 0.867 | 0.747 | 0.684 |

The geometry and dimensions of charges 5 and 6 were taken from a report by Dipersio, Whiteford, and Simon[9]. The experimental scatter in the results given in [9] is rather large and prevents a precise comparison, although the calculation results are in agreement with accepted experimental values for such charges.

This model has a virtue of simplicity, does not need any experimental measurements for its utilization and can therefore be used for parametric study. Two computer codes exist with one difference between them. The first code performs the compression of the jet in real physical time while the second delays the compression until the whole collapse phenomenon is terminated. The second code is about twice as fast as the first code. The second code runs in about 3 to 4 minutes on BRLESC II for a case using 100 liner zones.

A possible future improvement for this model would result if one computes the pressure wave using a convenient hydro-code and then couple this calculation with the present code to predict the collapse and jet formation characteristics. The inclusion of strength properties

of the liner material might also be important in the collapse process near the base of the liner

## ACKNOWLEDGMENTS

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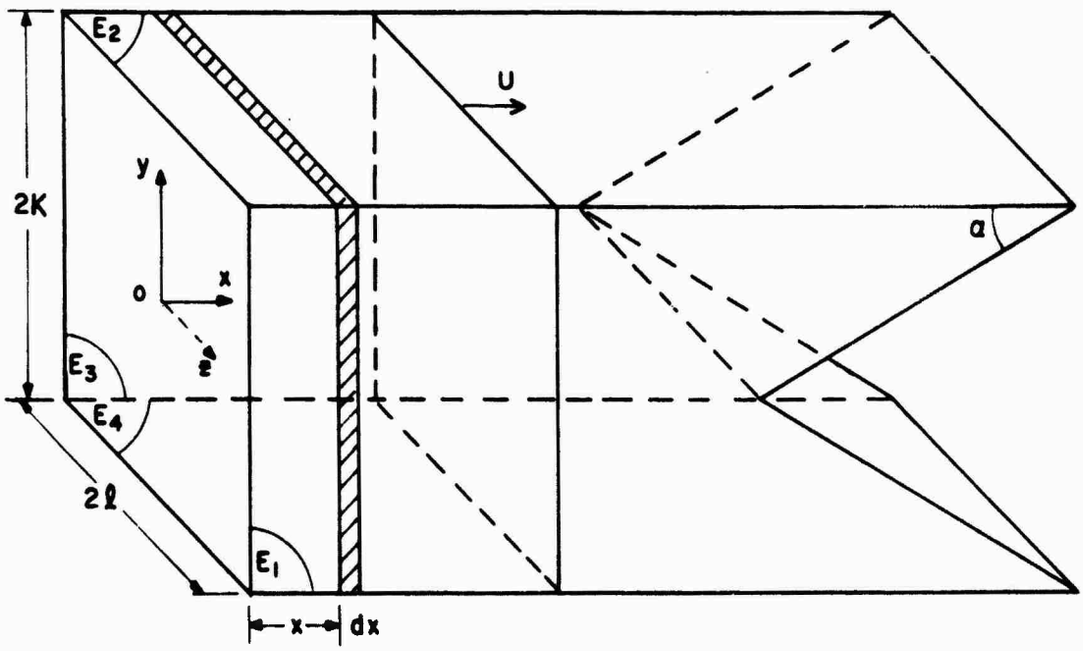



Figure 1. Schematic Drawing of a Typical Charge.

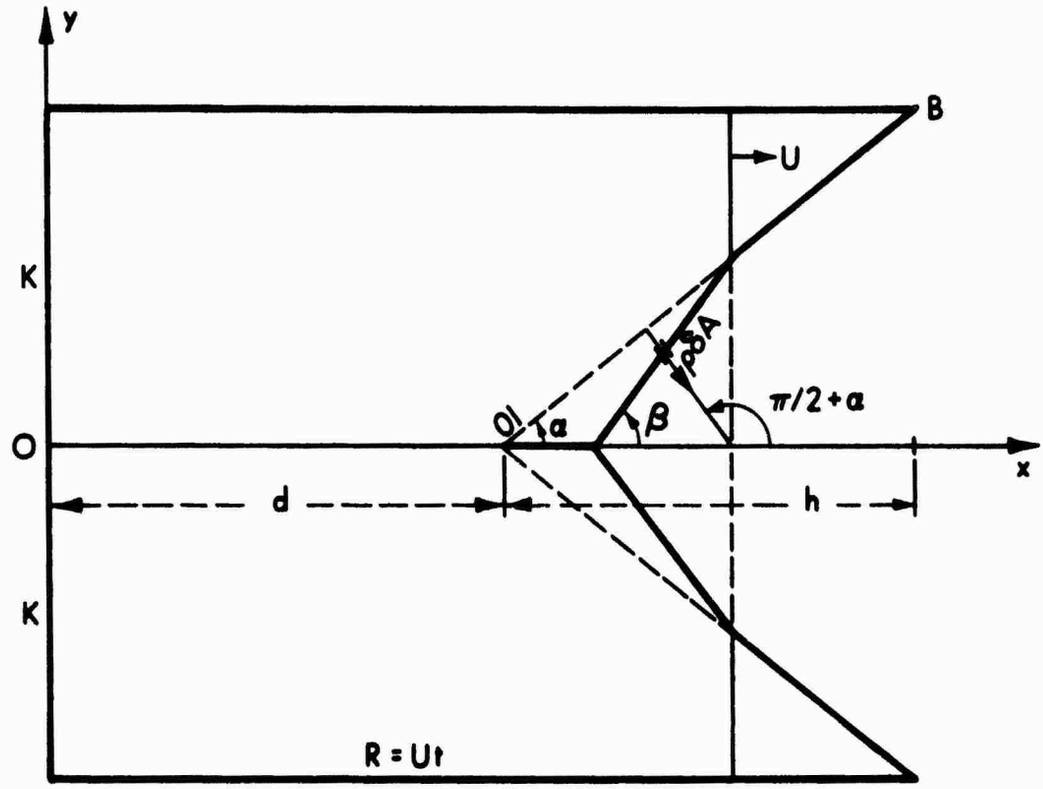



Figure 2. Schematic Representation of the Collapsing Liner.

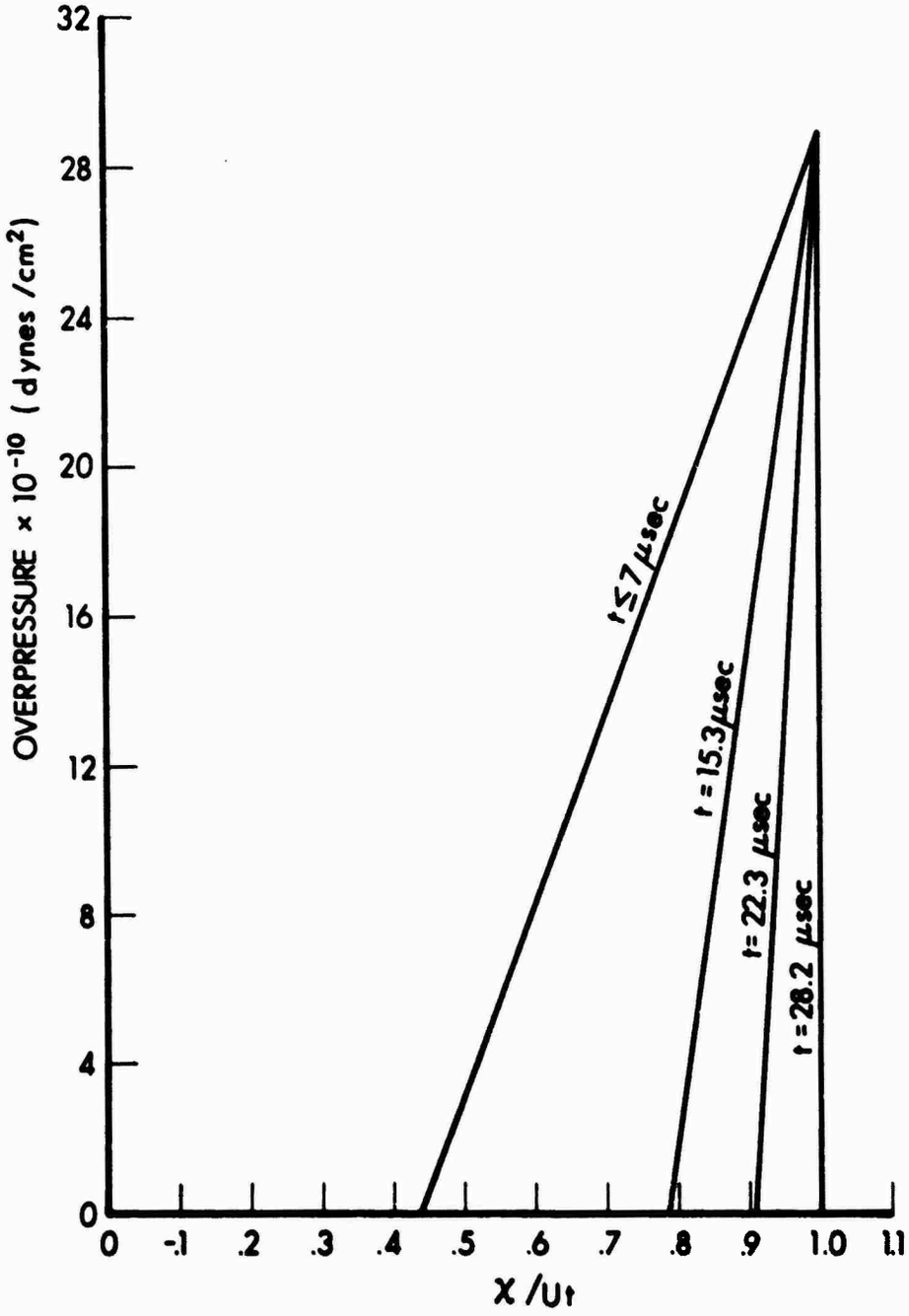



Figure 3. Profile of the Pressure Wave for Charge 5 at Various Times.

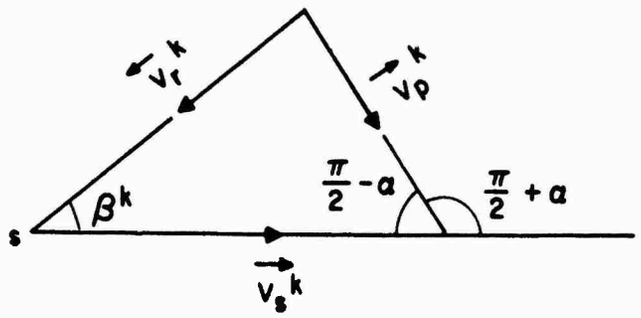



Figure 4. Distribution of Velocities at the Stagnation Point.

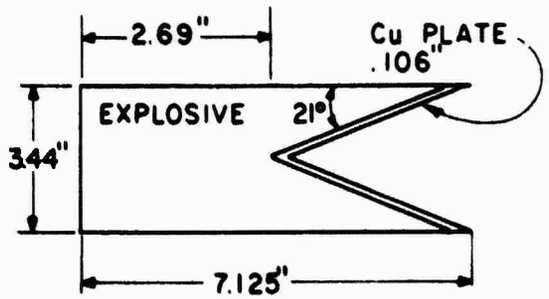



Fig 5

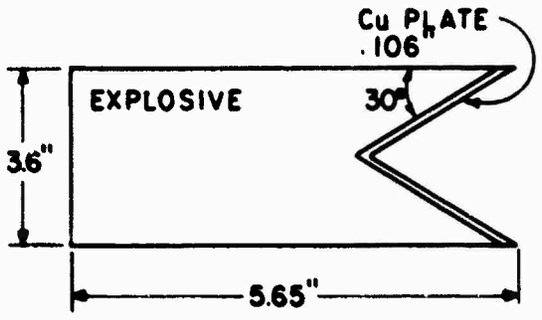



Fig 6

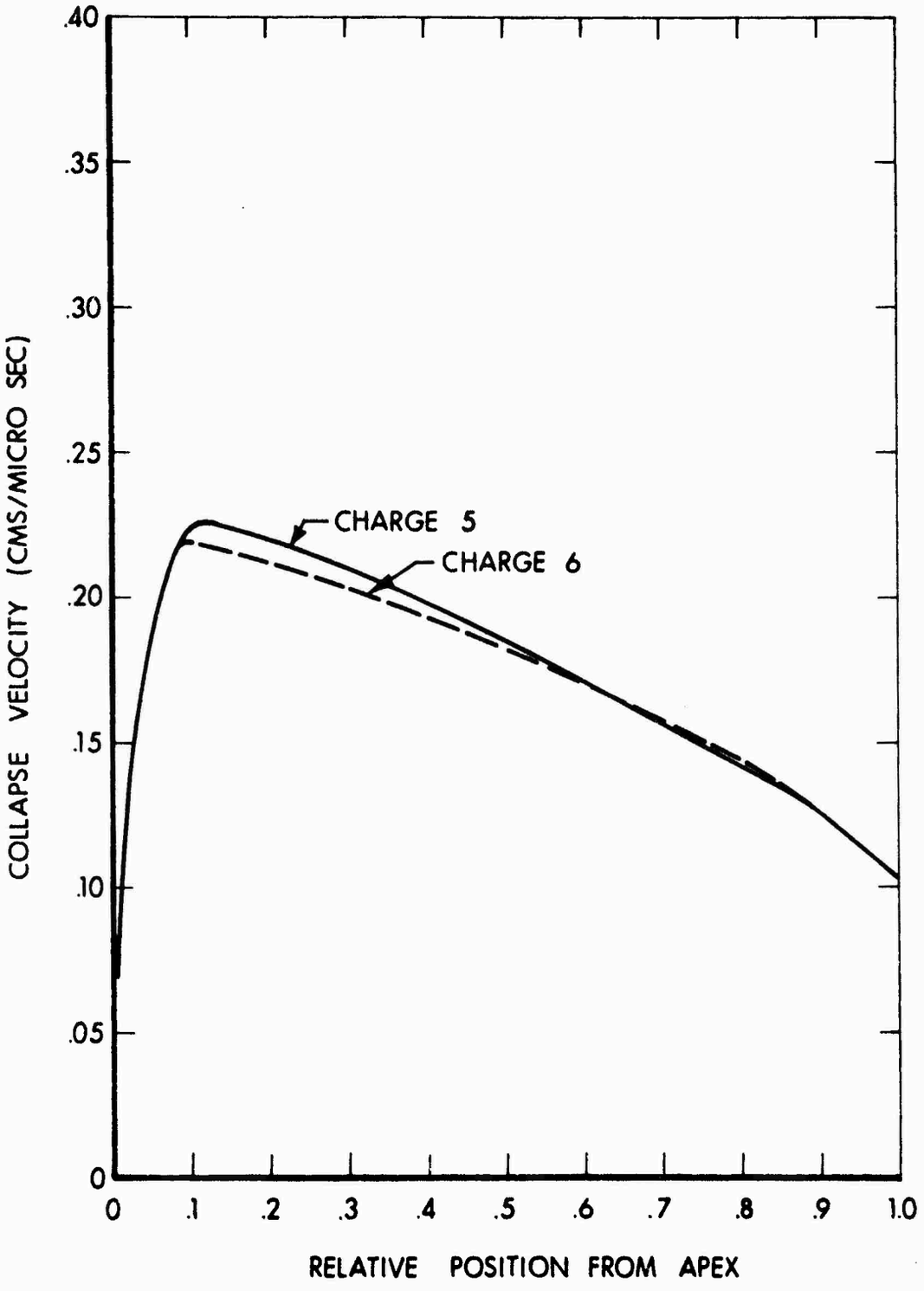
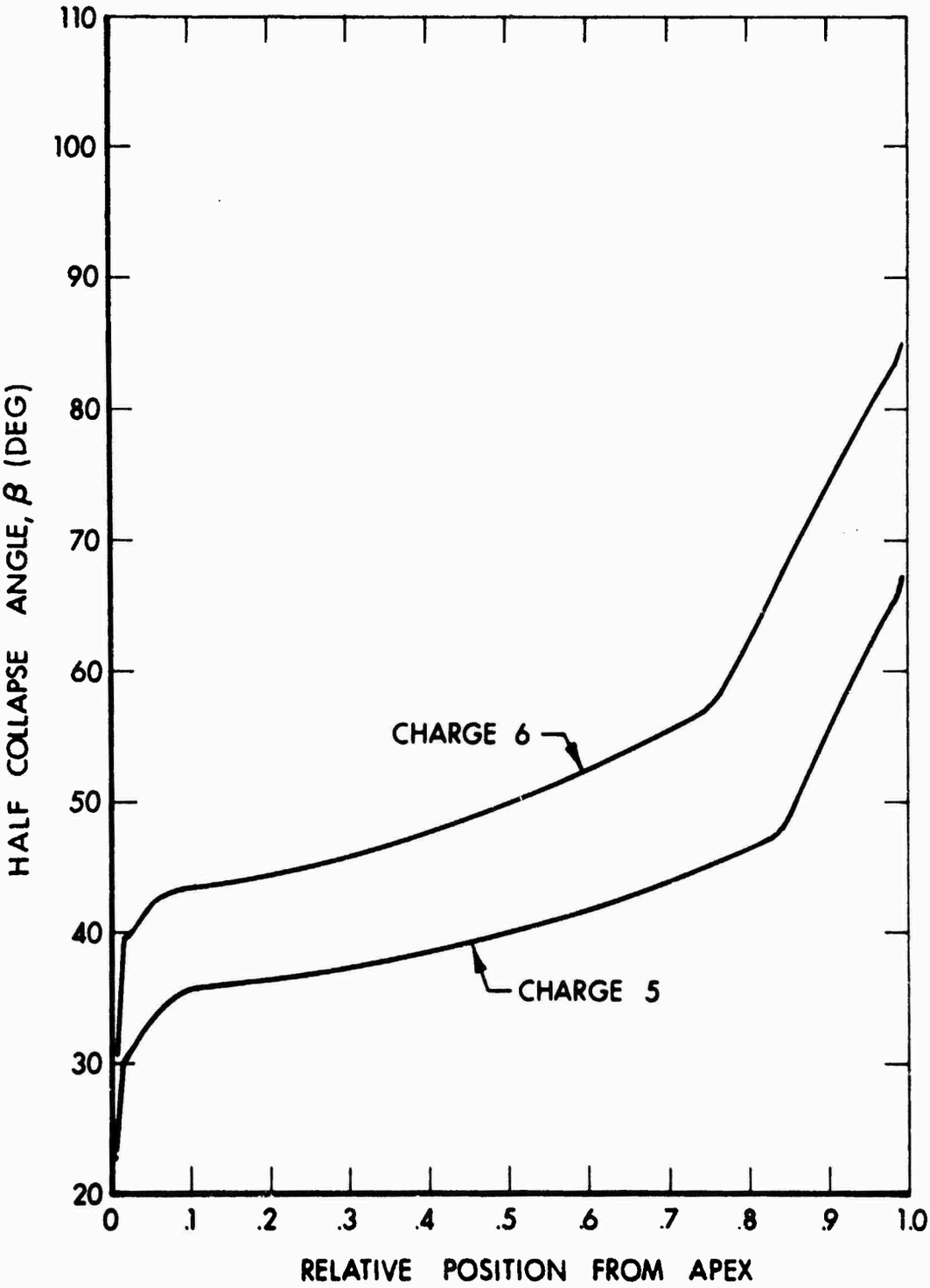

.40
.35
.30
.25
.20
.15
.10
.05
0
COLLAPSE VELOCITY (CMS/MICRO SEC)
CHARGE 5
CHARGE 6
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
RELATIVE POSITION FROM APEX

Figure 7


110
100
90
80
70
60
50
40
30
20
HALF COLLAPSE ANGLE, β (DEG)
CHARGE 6
CHARGE 5
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1.0
RELATIVE POSITION FROM APEX

Figure 8

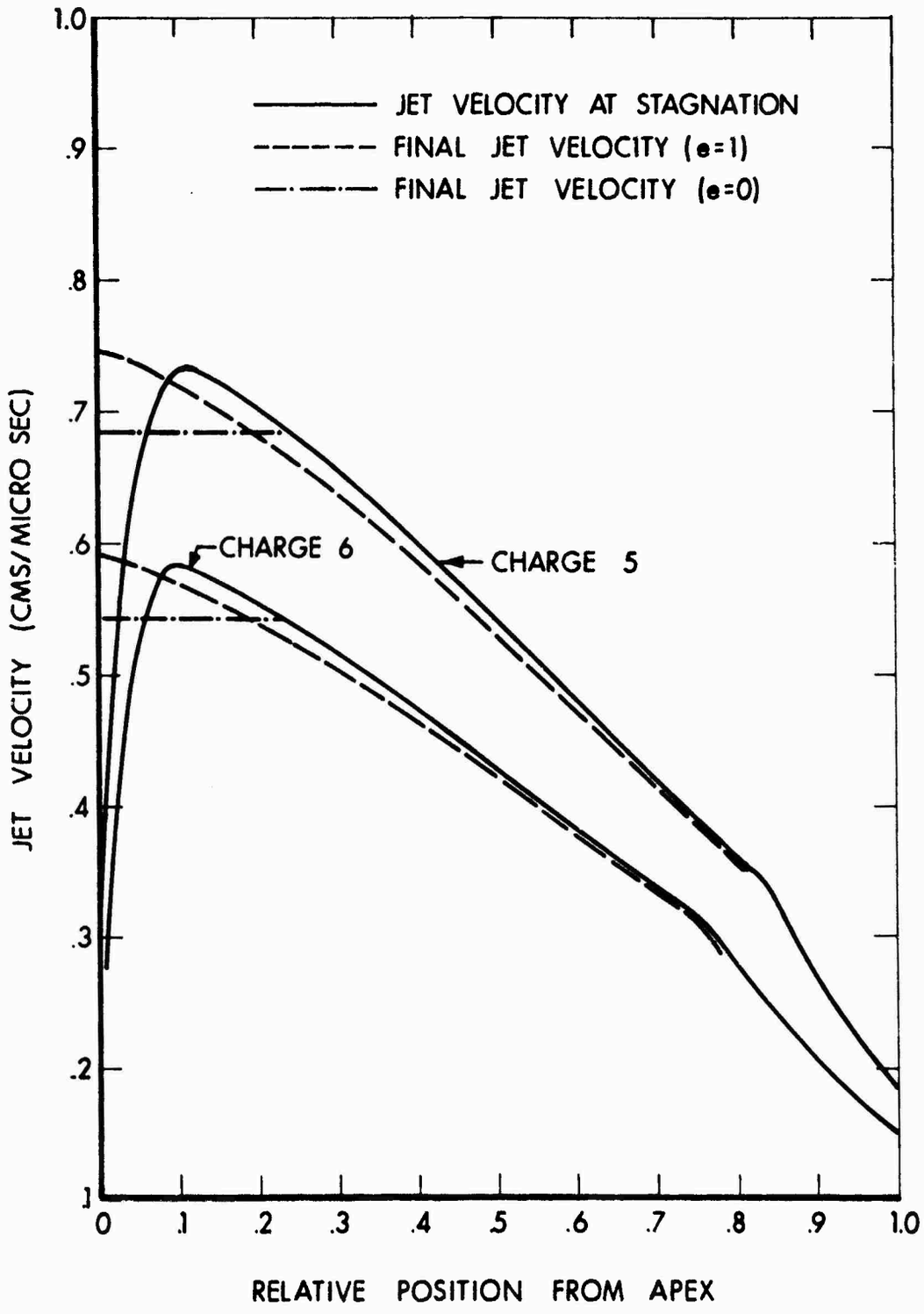
JET VELOCITY AT STAGNATION
FINAL JET VELOCITY (e=1)
FINAL JET VELOCITY (e=0)
CHARGE 6
CHARGE 5
JET VELOCITY (CMS/MICRO SEC)
RELATIVE POSITION FROM APEX
1.0
.9
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Figure 9

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A model to compute the collapse velocities of various elements of a metallic liner of a shaped charge from the known detonation properties of the explosive used and the geometrical configurations of the charge is proposed. The calculated collapse and jet velocities increase from the apex of the liner toward the base, reach a maximum, and then decrease monotonically thereafter. The calculated velocity distribution in the jet after it goes through compression agrees qualitatively and quantitatively with available experimental measurements.

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14 KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

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