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ANALYTICAL PREDICTIONS OF THE EFFECT OF WARHEAD ASYMMETRIES ON SHAPED CHARGE JETS

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February 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TECHNICAL REPORT ARBRL-TR-02214	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ANALYTICAL PREDICTIONS OF THE EFFECT OF WARHEAD ASYMMETRIES ON SHAPED CHARGE JETS		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Clifford L. Aseltine		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Ballistic Research Laboratory (ATTN: DRDAR-BLT) Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS RDT&E 1L162618AH80
11. CONTROLLING OFFICE NAME AND ADDRESS U.S.Army Armament Research and Development Command U.S. Army Ballistic Research Laboratory (ATTN: DRDAR-BL) Aberdeen Proving Ground, MD 21005		12. REPORT DATE FEBRUARY 1980
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Shaped charges
Explosives
Detonation
Phenomena

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (mba)

An analytical technique has been developed which allows the shaped charge designer to estimate the required tolerances in the final manufacturing of the device. Calculations are performed for liner, explosive, and confinement asymmetries which indicate that the rigid tolerances placed on the liner are indeed realistic. The present tolerances on explosive geometry and confinement geometry are also shown to be realistic. However, the results indicate that the explosive loading appears to be a problem in round to round variations. Less than a 2% variation in explosive composition will effect the jet more than a

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liner asymmetry at its maximum tolerance limit. Graphs, indicating transverse jet velocities as functions of liner position for various asymmetries are presented.

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I. INTRODUCTION

The development of shaped charges using conical liners has over the years generated conflicting theories as to why a large scatter in maximum penetration occurs in what appears to be identical charges. In general, blame is given to the non-uniform loading of the explosive component of the charge[1]. Various reasons are given for this non-uniformity, including separation of the components of the explosive mix; voids formed due to stresses produced by non-uniform cooling; and trapped air bubbles in the viscous melt of explosive. During the course of development of shaped charges, the Ballistic Research Laboratory (BRL) realized that significant improvements in penetration could be obtained by machining very accurately the metallic liner located in the center of the explosive charge[1,2]. This research has led to what is now considered a standard charge, referred to as the BRL 81.3mm precision charge. Details of the charge[3] are shown in Figure 1. The tolerances as indicated are, in general, adhered to accurately in the machining process. The object of this report is to present some insight into the importance of both metal and explosive tolerances, and how they might affect jet performance.

II. THEORY

The first asymmetry to be considered is the residual velocity of the jet in a transverse direction due to a liner thickness variation. Starting with the vector relationships defined in Figure 2.

$$\vec{v}_1 = v\ (t)\ [\cos \beta\ \vec{i} - \sin \beta\ \vec{j}]$$

where v(t) is evaluated just before the stagnation region. From the mirror image

$$\vec{v}_2 = v\ (t)\ [- \cos \beta\ \vec{i} - \sin \beta\ \vec{j}]\ .$$

---

[1] *J. Simon, R. DiPersio, and A. Merendino, "The Penetration Capability and Effectiveness of A Precision Shaped Charge Warhead," Ballistic Research Laboratory Report No. 1636, March 1965.* (AD #524945L)

[2] *R. DiPersio, J. Simon, A. Merendino, "Penetration of Shaped-Charge Jets into Metallic Targets," Ballistic Research Laboratory Report No. 1296, September 1965.* (AD #476717)

[3] *J. Simon, R. DiPersio, "The Evaluation of Explosive Filler on Shaped Charge Performance and Lethality Effectiveness," Ballistic Research Laboratory Report No. 1552, October 1971.* (AD #518989L)

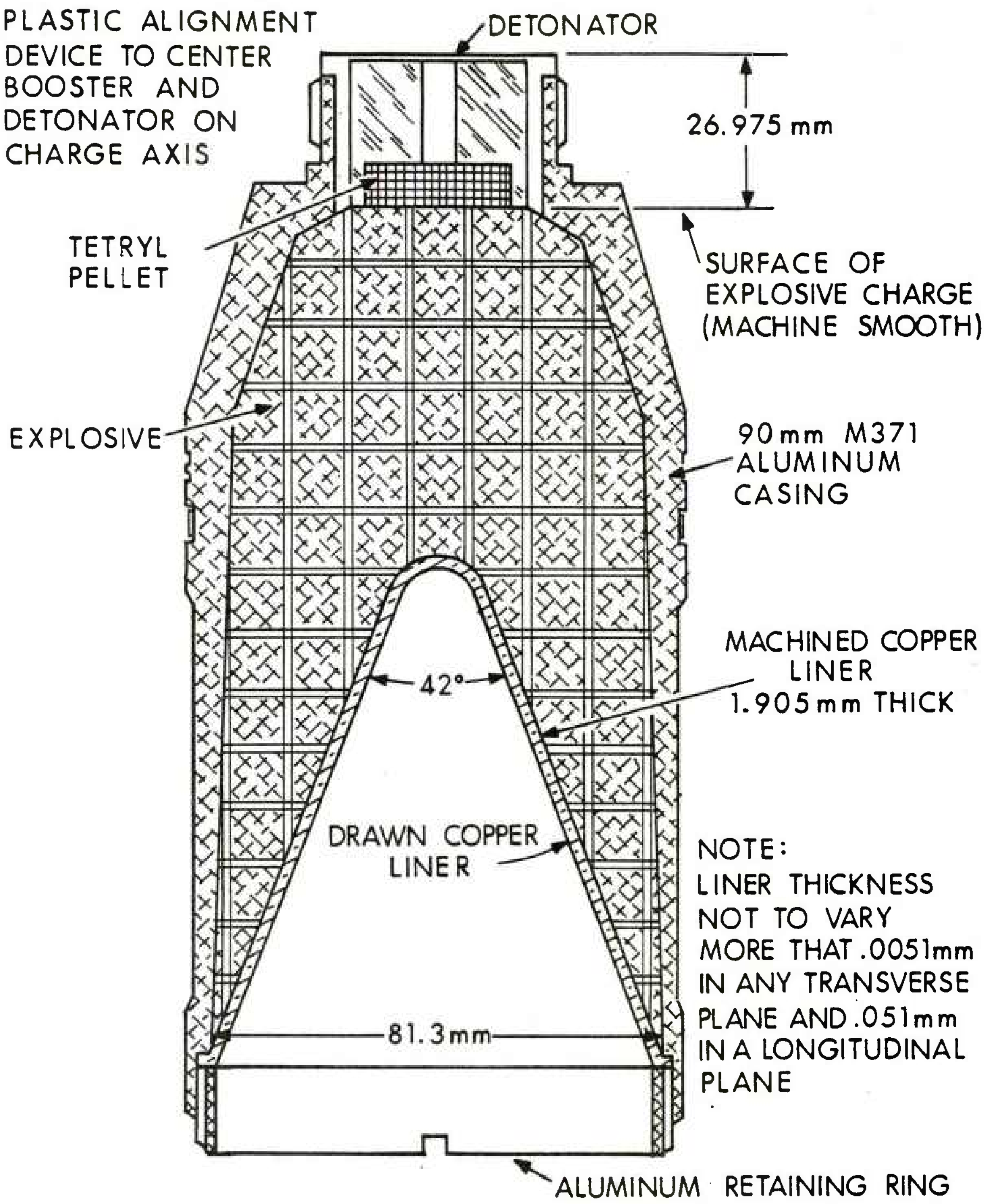


Figure 1. 81.3mm BRL Precision Charge

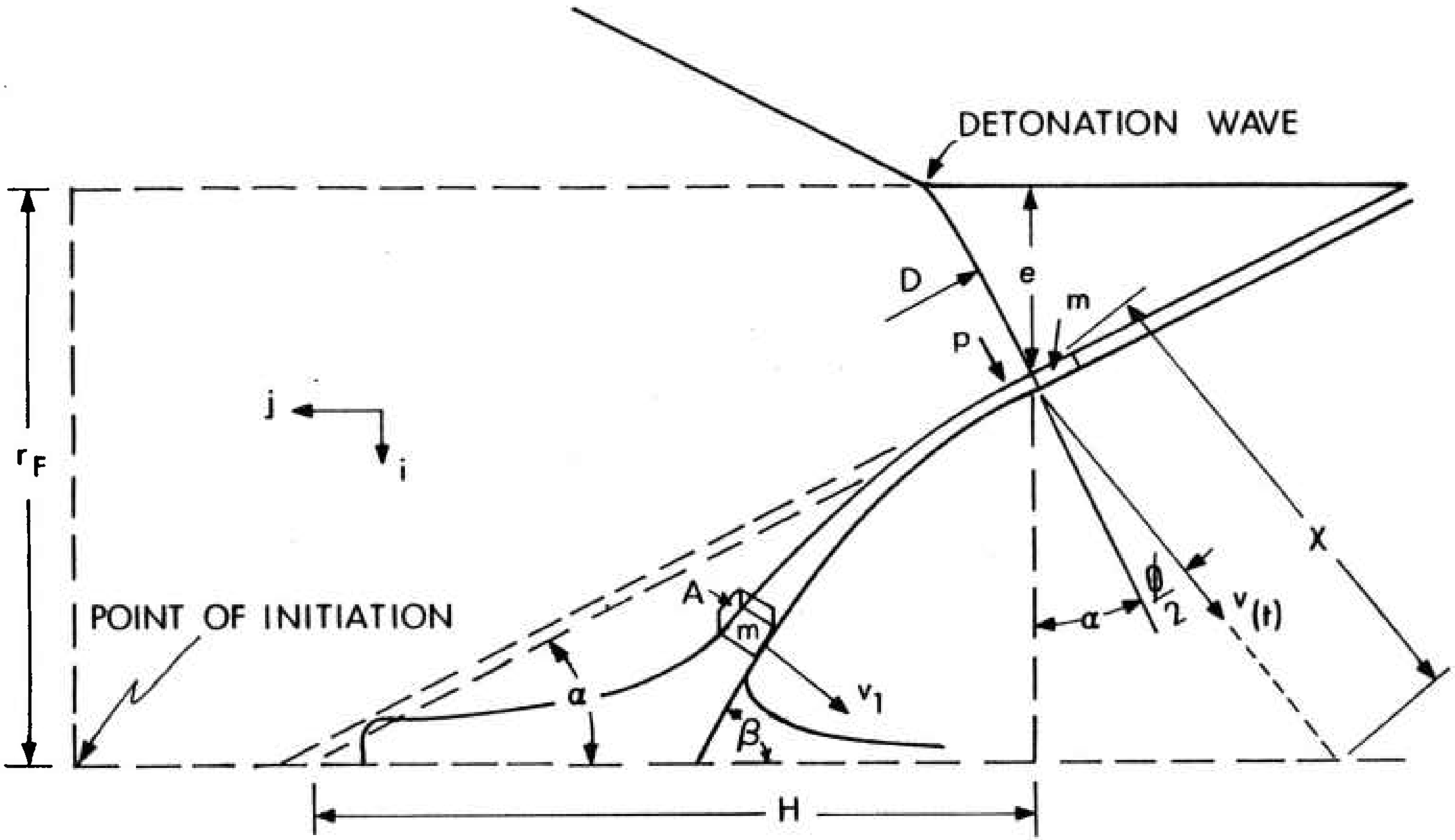


Figure 2. Schematic of Shaped Charge Cone Collapse

Assume now that a uniform liner thickness variation exists from the apex to the base of the cone. Assume also that one side of the liner is at the lower thickness limit, while the other side is at the maximum thickness limit. If two oppositely opposed mass elements $m \pm \Delta m$, having an equal cross section, A, driven by an identical pressure pulse, P, are considered, the following expression can be obtained.

$$\vec{v}^{\,i}_1 = \frac{A \cos \beta}{m - \Delta m} \int p dt \, \vec{i} \qquad \vec{v}^{\,i}_2 = - \frac{A \cos \beta}{m + \Delta m} \int p dt \, \vec{i}$$

where $\vec{v}^{\,i}$ is the velocity component of m perpendicular to the axis of cone. In order to solve equations in closed form, it is assumed that the ratio $\frac{A}{m \pm \Delta m}$ is a constant during the collapse. Thus, the residual velocity of the jet perpendicular to the axis will be

$$\begin{aligned} \vec{v}^{\,i}_j &= \left[\frac{A}{m - \Delta m} \int p dt - \frac{A}{m + \Delta m} \int p dt \right] \cos \beta \, \vec{i} \\ &= A \cos \beta \int p dt \left[\frac{1}{m - \Delta m} - \frac{1}{m + \Delta m} \right] \vec{i} \end{aligned} \qquad (1)$$

using a binomial expansion and assuming $\frac{\Delta m}{m} << 1$

$$\vec{v}^{\,i}_j \approx A \cos \beta \int p dt \left[\frac{2 \Delta m}{m^2} \right] \vec{i} \, .$$

For the purposes of obtaining a solution in closed form, let us assume a pressure pulse of the shape shown in Figure 3 where for the values of pressure and time indicated

$$a = b^2 p_o$$

$$b = 24 \times 10^{-6} \text{ sec.}$$

These values were obtained by iterating calculated collapse velocities with experimental results.

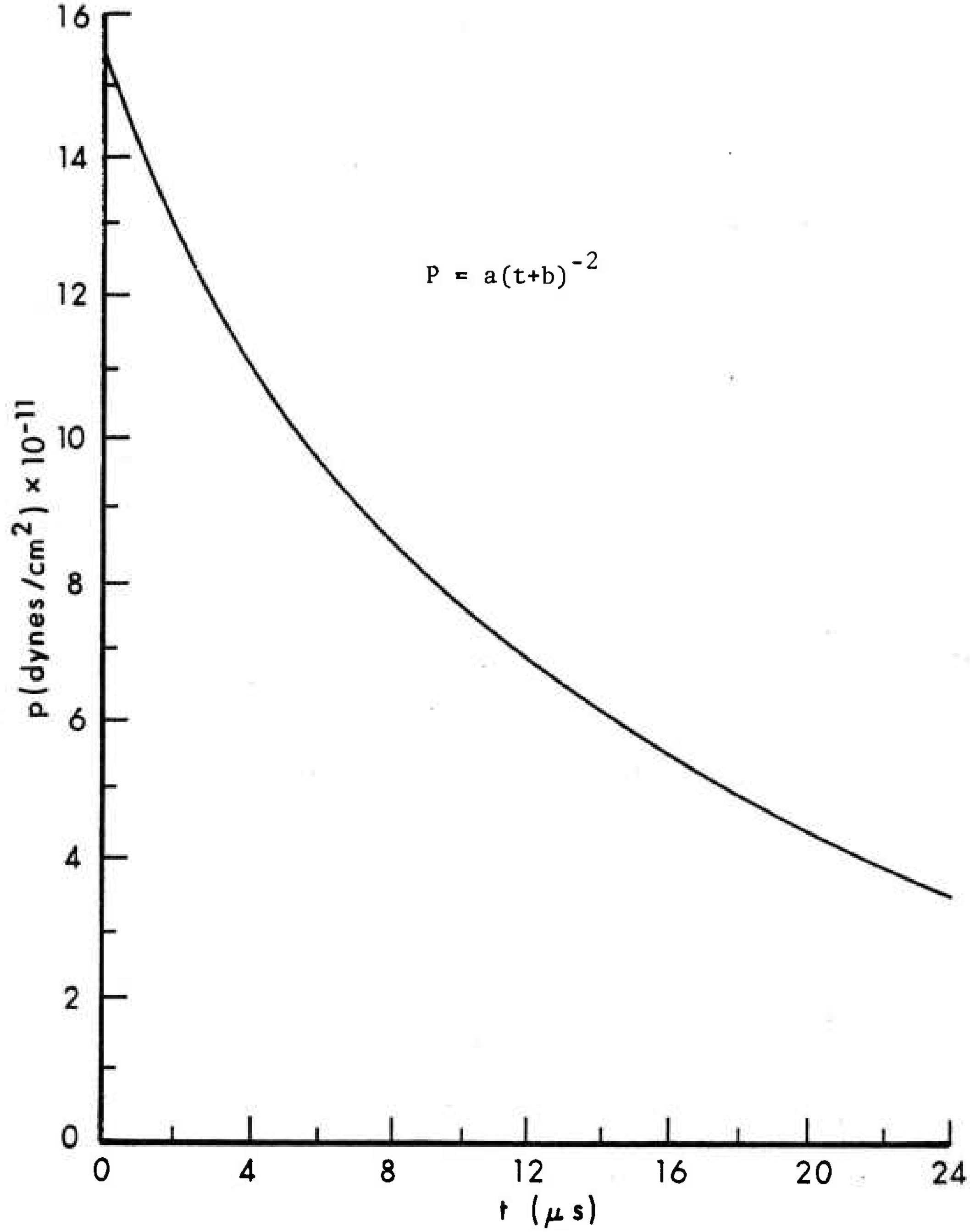


Figure 3. Pressure Function Assumed to Drive Liner

Thus,

$$\vec{v}_j^{\,i} = A \cos \beta \left[\frac{2\Delta m}{m^2}\right] \int p\,dt$$

$$= A \cos \beta \left[\frac{2\Delta m}{m^2}\right] p_o \int b^2 \, (t + b)^{-2} \, dt$$

$$\vec{v}_j^{\,i} = A \cos \beta \left[\frac{2\Delta m}{m^2}\right] b^2 p_o \left[- (t + b)^{-1} + C_1\right] . \tag{2}$$

Since at $t = 0$, $\vec{v}_j^{\,i} = 0$

$$C_1 = \frac{1}{b}$$

Therefore,

$$\vec{v}_j^{\,i} = A \cos \beta \; \frac{2\Delta m}{m^2} \; p_o b \left[1 - b \, (t + b)^{-1}\right] . \tag{3}$$

In a similar fashion the total distance traveled by the particle, m, can be shown by integration of $|\vec{v}_1|$ to be

$$X = \frac{A p_o b t}{m} - \frac{A}{m} p_o b^2 \, \ell n \, (t + b) + C_2 \, .$$

Over the region of interest

$$\ln \, (t + b) \approx \ln b + \frac{2t}{2 b + t} \, .$$

Thus,

$$X = \frac{A P_o b t}{m} - \frac{A}{m} P_o b^2 \left[\ln b + \frac{2t}{2 b + t}\right] + C_2 \, . \tag{4}$$

Now at t = 0, $\chi = 0$, therefore,

$$\chi = -\frac{Ap_o b^2}{m}\left[\frac{2t}{2\ b + t}\right] + \frac{Ap_o bt}{m}$$

by rearranging

$$\frac{Ap_o bt^2}{m} - \chi t - 2b\chi = 0 \tag{5}$$

is in the standard quadratic form and thus,

$$t = \frac{\chi + \sqrt{\chi^2 + \dfrac{8bAp_o b\chi}{m}}}{\dfrac{2Ap_o b}{m}} \ . \tag{6}$$

This can then be inserted in the equation for the transverse velocity to give

$$\vec{v}_j^{\,i} = A \cos \beta \frac{2\Delta m}{m^2} p_o b \left[1 - b\left(b + \frac{\chi + \sqrt{\chi^2 + \dfrac{8bAp_o b\chi}{m}}}{\dfrac{2AP_o b}{m}}\right)^{-1}\right] . \tag{7}$$

To get the distance, χ, at a specific position and time it can be seen in Figure 2 that

$$\chi = \frac{H \tan \alpha}{\cos\ (\alpha + \phi/2)} \ .$$

The only unknown, ϕ, in this expression can be calculated from relationship proposed by Defourneaux[4]

---

[4]*M. Defourneaux, "Energy Transfers in Explosive Propulsion," Sci and Techniques de l'Armement, Vol. 47, No. 3 (1973), pp 723-930.*

$$\frac{1}{\phi} = \frac{1}{\phi_o} + \frac{K \rho_m \varepsilon}{e}$$

where, ϕ_o is the angle obtained for infinite explosive belt;

K is an experimental constant;

ρ_m is the metal density;

ε is the metal thickness;

e is the explosive thickness.

The unknown collapse angle, β, can be calculated from another Defourneaux relationship[5],

$$\tan(\beta-\alpha) = \frac{[\sin(\alpha+\phi) - \sin\alpha] \tan\phi + H \tan\alpha \cdot \cos\alpha \frac{d\phi}{dH}}{[\sin(\alpha+\phi) - \sin\alpha] - H \tan\alpha \cos\alpha \tan\phi \frac{d\phi}{dH}} .$$

An additional correction involving the variation of impulse imparted to the liner versus explosive thickness will now be discussed. As the explosive layer becomes thinner, the impulse delivered to the liner will be reduced. Based on the release wave model of Eichelberger[6], it can be assumed the release initiates immediately after passage of the detonation wave at the charge boundary. The time at which the liner sees the release is then determined by the thickness of the explosive at the point of interest. The value of the constant, b, in the pressure time relationship was calculated only at the apex of the liner. It is possible to define a new variable, b_o, which is proportional to the radial thickness of the charge at a particular position along the liner, and having a value b at the apex. This relationship can be expressed as

$$b_o = b \; \frac{(R - H \tan\alpha)}{R} , \qquad (9)$$

where R is the radius of the cone base. The term in parenthesis will vary the value of b_o linearly from 0 to b, as a function of position, H, down the liner. Thus, the value $\vec{v_j^i}$ as given by Equation 1 can be calculated with all phenomena of interest included.

---

[5]*M. Defourneaux, "Hydrodynamic Theory of Shaped Charges and of Jet Penetration," Sciences and Techniques de l"Armement, Vol. 44, (1970), pp 293-334.*

[6]*R. Eichelberger, "Predictions of Shaped Charge Performance from The Release Wave Theory," Fundamentals of Shaped Charges Status Report No. 1, Carnegie Inst. of Tech., January 1954.*

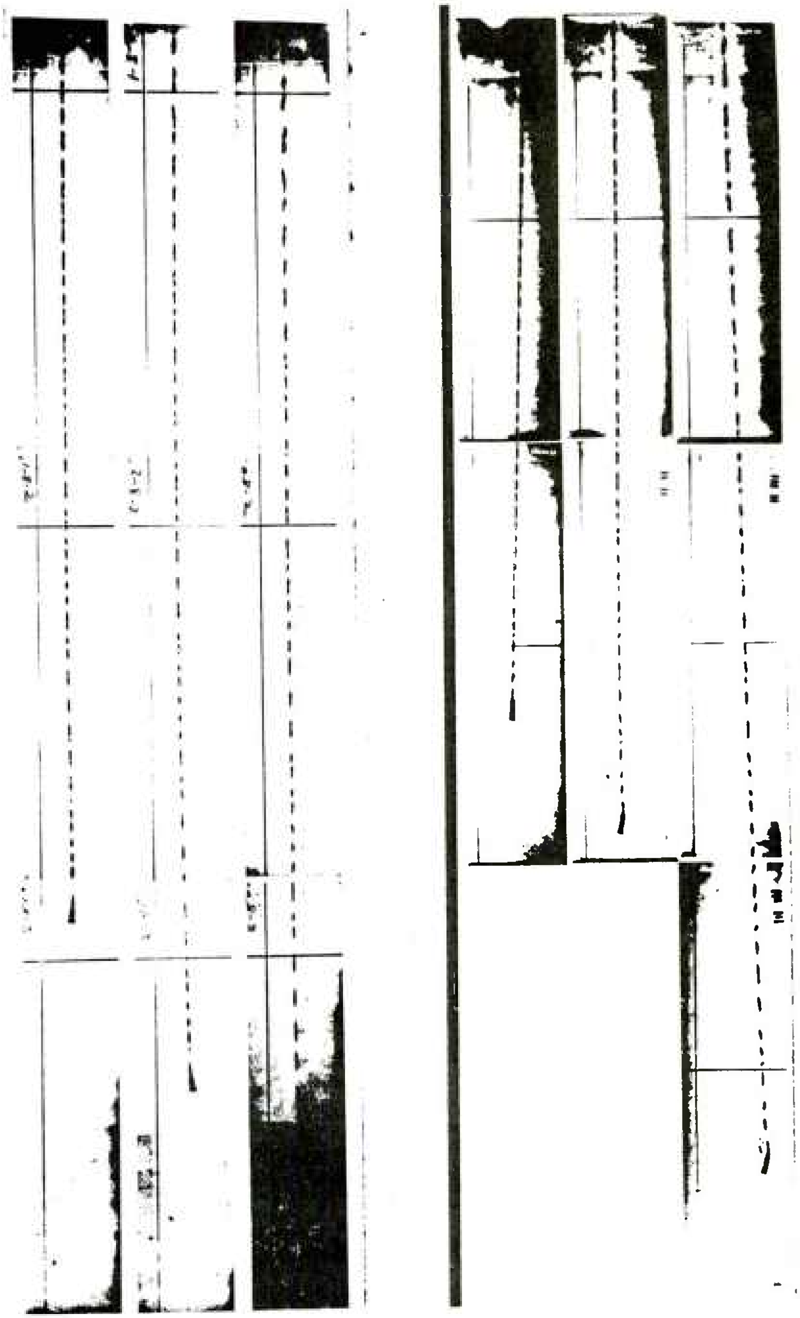
III. LINER THICKNESS VARIATIONS

We have already developed the theory for collapse problems caused by a liner thickness variation. Attention will now be turned to the effect of liner thickness tolerances on jet performance.
Figure 4 shows prints of two jet x-rays. One is perfectly straight while the other is bowed by approximately 50mm. Therefore, a good comparison can be made between jets by investigating the extent of bowing produced by an asymmetry in the charge. Consider first the effect of a liner thickness variation in a plane perpendicular to the liner axis. Also, assume as before that this variation is constant from the top to the bottom of the liner and the opposite sides are at the respective ± limit extremes in tolerance. This is then the case derived in the previous section. Thus, the transverse velocity of a jet region as a function of its original liner position can be calculated. The results of this calculation for liner thickness variations are shown in Figure 5. Note that the maximum transverse velocity occurs at the tip region of the jet and rapidly falls to zero further back in the jet. The non-linear dependence generates a jet with the front bowed away from the initial axis. Theoretically, Equation 7 indicates that this frontal bowing is caused by the cos β term which multiplies the entire transverse velocity expression. This term provides the largest contribution when β is small. This occurs for the first 1/3 to 1/2 of the cone. Thus, it would seem that in order to get a straight jet, particular attention should be paid to the tolerances on the upper half of the cone.

It would be worth digressing into possible causes of asymmetries described above. One principal cause of a non-uniformity in thickness would be the repositioning of the cone between machining the inner and outer surface. This would allow an error in the amount of the alignment gage tolerances to be introduced into the liner thickness that would extend from the top to the bottom of the cone. The use of the newly developed dual machines which machine inner and outer surfaces simultaneously should correct this problem as long as spacing between cutting tips can be held to a very high tolerance.

IV. EXPLOSIVE HOMOGENEITY

The next charge irregularity to be considered is the minute fluctuations in pressure that can occur due to a variation of composition in the explosive surrounding the charge. Equation 1 can be modified to assess the effects of a pressure difference from side to side in the amount of $\pm \Delta P$.



(A) (B)

Figure 4. Flash X-rays of (A) Precision 81.3mm Charge; (B) 2% RDX Inhomogeneity 81.3mm Charge

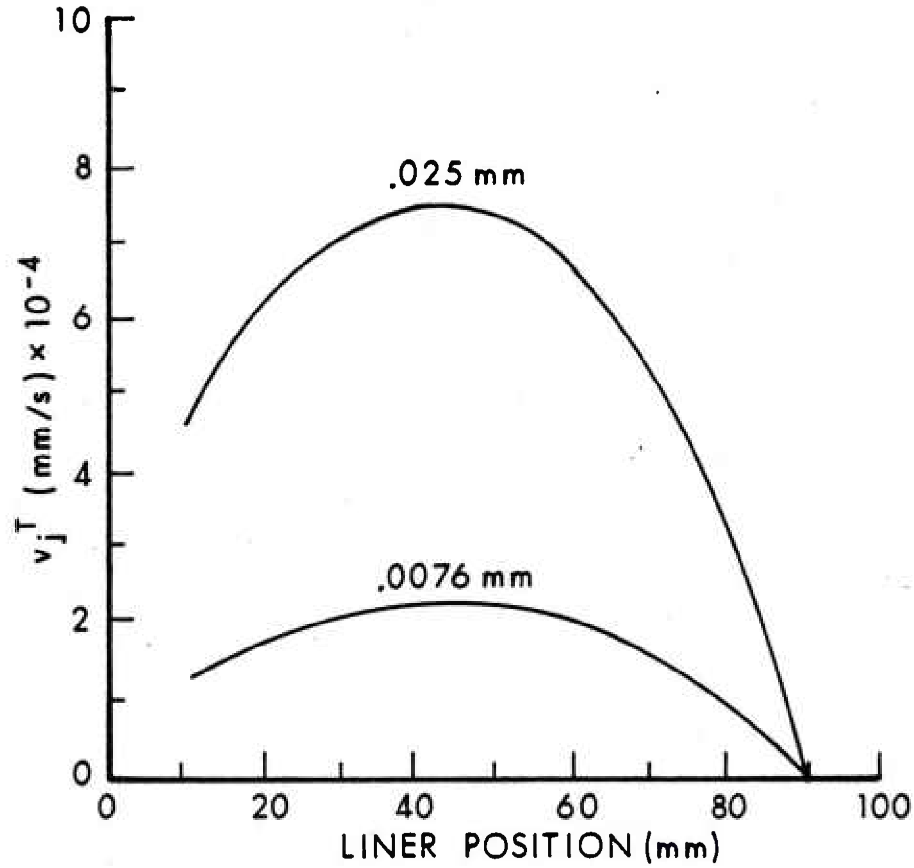


Figure 5. Transverse Jet Velocity vs. Liner Position for Different Liner Thickness Variations

$$\vec{v}_j^{\,i} = \frac{A}{m}\left[\int (p+\Delta p)\,dt - \int \left((p-\Delta p)\,dt \right)\right] \cos\beta$$

$$= \frac{2A}{m} \int \Delta p dt \cos\beta$$

$$= \frac{2\cos\beta}{\rho_m\,\varepsilon} \int \Delta p dt.$$

Now from the assumed pressure pulse, one can express Δp to first order

$$\Delta p = \Delta p_o b_o^2 \,(t + b_o)^{-2} \,.$$

Therefore,

$$\vec{v}_j^{\,i} = \frac{2\cos\beta}{\rho_m\,\varepsilon}\,\Delta p_o \int b_o^2 \,(t + b_o)^{-2}\,dt. \qquad (10)$$

The results of this calculation are presented in Figure 6 for pressure variations of 1, 2, and 3%. Again only the front portion of the jet is appreciably bowed. However, the amount of bowing produced by a 3% pressure variation is approximately 10 times larger than the bow produced by a liner thickness variation of ± .0076 mm. In an earlier work[7], Cole found 3% RDX variations in cast Comp B charges. This RDX variation can be converted by using the well known formula[8] for maximum density Comp B,

$$p = 29.5 + .157\ (\%\ \text{RDX} - 64) + 67.85\ \frac{[(\rho - 1.717)]}{\rho}\ ,\ \text{GPa}$$

where ρ is the density of the resulting explosive. For an increase in RDX percentage to 67% the pressure increase will be 2.24%. Table I illustrates the dependence of % Δp vs % RDX composition with 64% being $\Delta p = 0$. These asymmetries observed by Cole are well within the range to produce an observable effect on the jet.

---

[7]*J. E. Cole, "The Quality of Explosive Loading of Shaped Charges at The Ballistic Research Laboratory," Ballistic Research Laboratory Report 1927, July 1968.* (AD #A030357)

[8]*B. Dobratz, "Properties of Chemical Explosives and Explosive Simulants," Lawrence Livermore Laboratory Report No. UCRL-51319, Rev. 1, July 1974.*

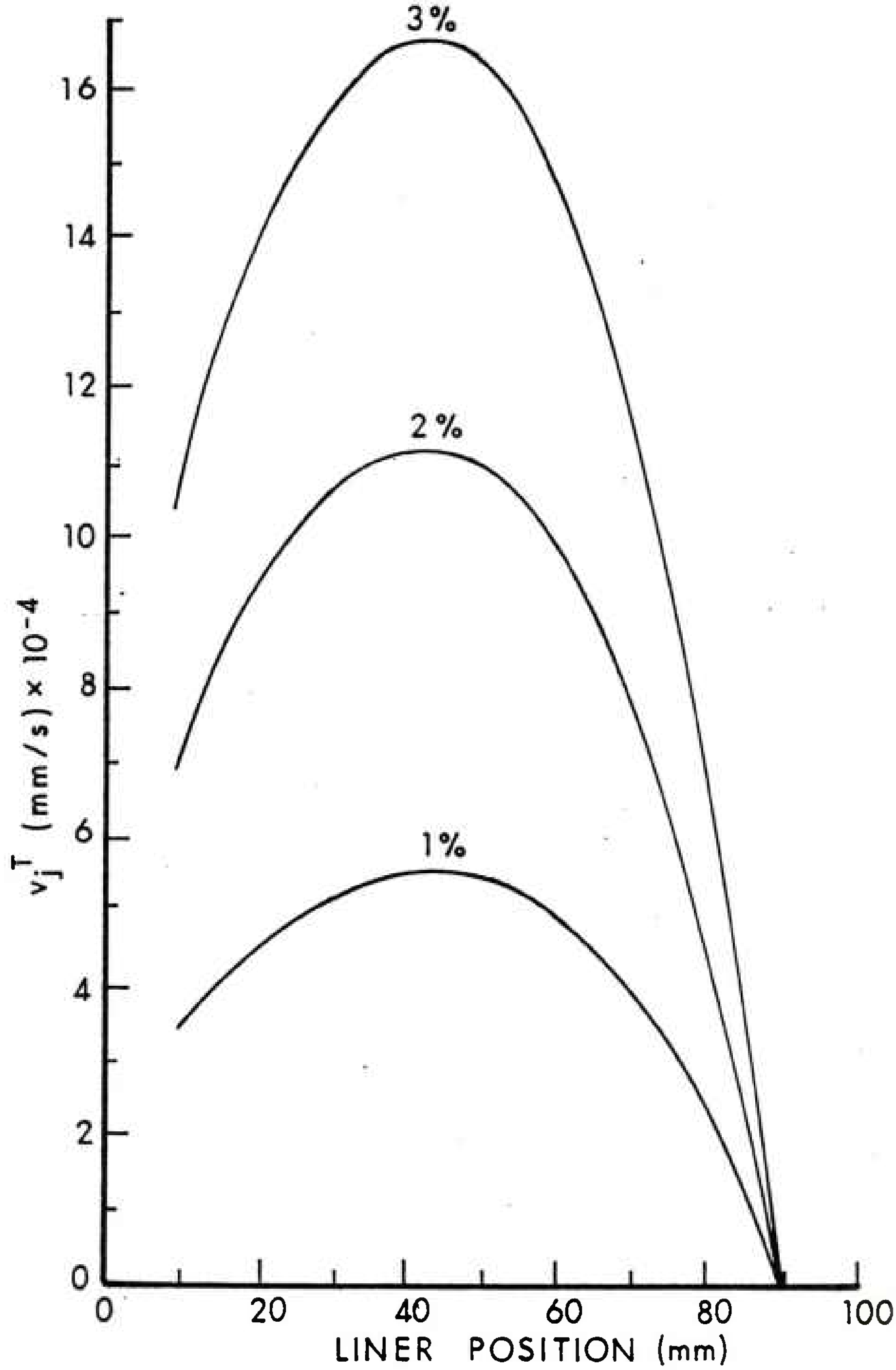


Figure 6. Transverse Jet Velocity vs. Liner Position for Pressure Variation Across Liner

Table I

% RDX	Δp (%)
60	-2.8
61	-2.1
62	-1.3
63	- .6
64	0
65	+ .8
66	+1.5
67	+2.24
68	+2.95

V. EXPLOSIVE ASYMMETRY

From the pressure function,

$$p = p_o\, b^2_o (t + b_o)^{-2} , \qquad (11)$$

a determination can be made of the effect of the explosive asymmetry on the transverse velocity. The factor which varies is the term b_o. Thus,

$$\Delta p = [2p_o b_o (t + b_o)^{-2} - 2\, p_o b^2_o (t + b_o)^{-3}]\ \Delta b_o .$$

The value of Δb_o, for an explosive asymmetry can be found in the following way. Equation 9 gives

$$b_o = b \left(\frac{R - H \tan \alpha}{R}\right) ,$$

where (R - H tan α) is the thickness of explosive, e, remaining between the liner and the outside of the charge. Thus,

$$b_o = b\ \frac{e}{R} ,$$

and

$$\Delta b_o = b\ \frac{\Delta e}{R} .$$

Therefore,

$$\Delta P = \left[2p_o b_o (t + b_o)^{-2} + (-2)\ p_o b_o^2\ (t + b_o)^{-3}\right] \frac{b\ \Delta e}{R}$$

$$v^{\vec{i}}_{jet} = \frac{4 \cos \beta}{\rho_m \varepsilon} \int \frac{b\ \Delta e}{R} \left[p_o b_o (t + b_o)^{-2} - p_o b_o^2\ (t + b_o)^{-3}\right] dt \ . \qquad (12)$$

The results of this calculation are presented in Figure 7 for Δe = .025mm and Δe = .13mm. Note the relative insensitivity of this asymmetry upon jet quality. In this example any bowing that exists occurs near the last 1/3 of the jet, where the influence of the asymmetry is more capable of effecting the collapse process.

VI. CONFINEMENT ASYMMETRY

In order to investigate the effect of confinement tolerances, a different approach must be followed. Not knowing the effect of confinement on the value of b in Equation 11, it is necessary to determine the tolerance limit in a different fashion. The well known Gurney relationships can provide insight into the relative importance of various portions of the charge. Since cylindrical Gurney formulae are not available we will use the results of the explosive layer system which have been shown to be acceptable for shaped charges[9]. For a metal-explosive-tamper sandwich the velocity of the metal surface is given by[10].

$$v_m = \sqrt{2E} \left(\frac{1 - A + A^2}{3} + \frac{n}{c} A^2 + \frac{m}{c} \right)^{-1/2}$$

$$A = \frac{1 + 2\frac{m}{c}}{1 + 2\frac{n}{c}} \ .$$

where m is metal mass, n is tamper mass, and c is charge mass, and E = the Gurney energy. The change in velocity of the metal layer with respect to a change in thickness of any layer of the sandwich can be found by taking the derivative of v_m with respect to the layer of interest.
The results are,

---

[9] *Private communication BRL, Shaped Charge Branch personnel.*

[10] *J. E. Kennedy, "Gurney Energy of Explosives: Estimation of The Velocity and Impulse Imparted to Driven Metal," Sandia Report No. SC-RR-70-790, December 1970.*

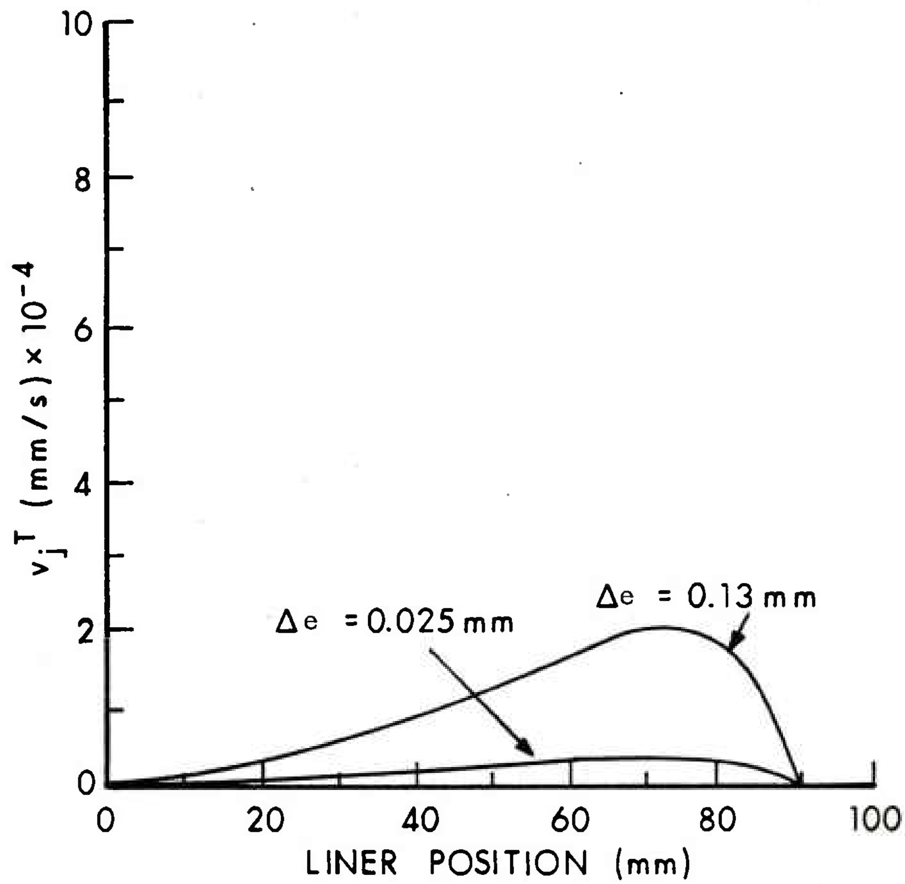


Figure 7. Transverse Jet Velocity vs. Liner Position for Different Explosive Centering Asymmetries Around Liner

$$\frac{c}{\sqrt{2E}} \frac{dv_m}{dm} = -1/2 \left[\frac{1-A+A^2}{3} + \frac{n}{c} A^2 + \frac{m}{c}\right]^{-3/2}$$

$$\times \left[\frac{(2A-1)\,\bar{A}}{3} + \frac{2nA\bar{A}}{c} + 1\right]$$

where

$$A = \frac{1 + 2\,\frac{m}{c}}{1 + 2\,\frac{n}{c}}$$

$$\bar{A} = \frac{2}{1 + 2\,\frac{n}{c}}$$

$$\frac{c}{\sqrt{2E}} \frac{dv_m}{dc} = -1/2 \left[\frac{1-A+A^2}{3} + \frac{n}{c} A^2 + \frac{m}{c}\right]^{-3/2}$$

$$\times \left[\frac{(2A-1)\,\dot{A}}{3} + \frac{2nA\dot{A}}{c} - \frac{nA^2}{c} - \frac{m}{c}\right]$$

where

$$\dot{A} = \frac{-2\,\frac{m}{c}}{1 + 2\,\frac{n}{c}} - \frac{(1 + 2\,\frac{m}{c})\,(-2\,\frac{n}{c})}{\left(1 + 2\,\frac{n}{c}\right)^2}$$

$$\frac{c}{\sqrt{2E}} \frac{dv_m}{dn} = -1/2 \left[\frac{1-A+A^2}{3} + \frac{n}{c} A^2 + \frac{m}{c}\right]^{-3/2}$$

$$\times \left[\frac{(2A-1)\,A'}{3} + A^2 + \frac{2n}{c} AA'\right]$$

where

$$A' = -2\,(1 + \frac{2m}{c})\,(1 + \frac{2n}{c})^{-2}.$$

These equations can be plotted as shown in Figures 8, 9, and 10. Thus for a given $\frac{n}{c}$ in the shaped charge, the relative importance of each layer can be assessed assuming a cylindrically confined shaped charge as shown in Figure 11. The values of $\frac{m}{c}$ and $\frac{n}{c}$ can then be found by inspection to be,

$$\frac{m}{c} \approx \frac{2\,\rho_m\, r_m\, t_m}{\rho_c\,(r_n^2 - r_m^2)},$$

and

$$\frac{n}{c} \approx \frac{2\,\rho_n\, r_n\, t_n}{\rho_c\,(r_n^2 - r_m^2)}$$

Assuming the jet tip originates 1/3 of the way down from the apex to the base. The values of $\frac{m}{c}$ and $\frac{n}{c}$ for the values shown in Figure 11 are

$$\frac{m}{c} = .18 \text{ and } \frac{n}{c} = .64.$$

Then referring to the graphs of Figures 8, 9, and 10 the following values can be obtained

$$\frac{dv_m}{dm} = \frac{\sqrt{2E}}{c}\ (1.6)$$

$$\frac{dv_m}{dt_m} \approx \frac{2\pi\,\rho_m\, r_m\,\sqrt{2E}}{c}\quad (1.6)$$

$$\frac{dv_m}{dc} = \frac{\sqrt{2E}}{c}\quad (.22)$$

$$\frac{dv_m}{dt_c} \approx \frac{2\pi\,\rho_c\, r_n\,\sqrt{2E}}{c}\quad (.22)$$

$$\frac{dv_m}{dn} = \frac{\sqrt{2E}}{c}\quad (.05)$$

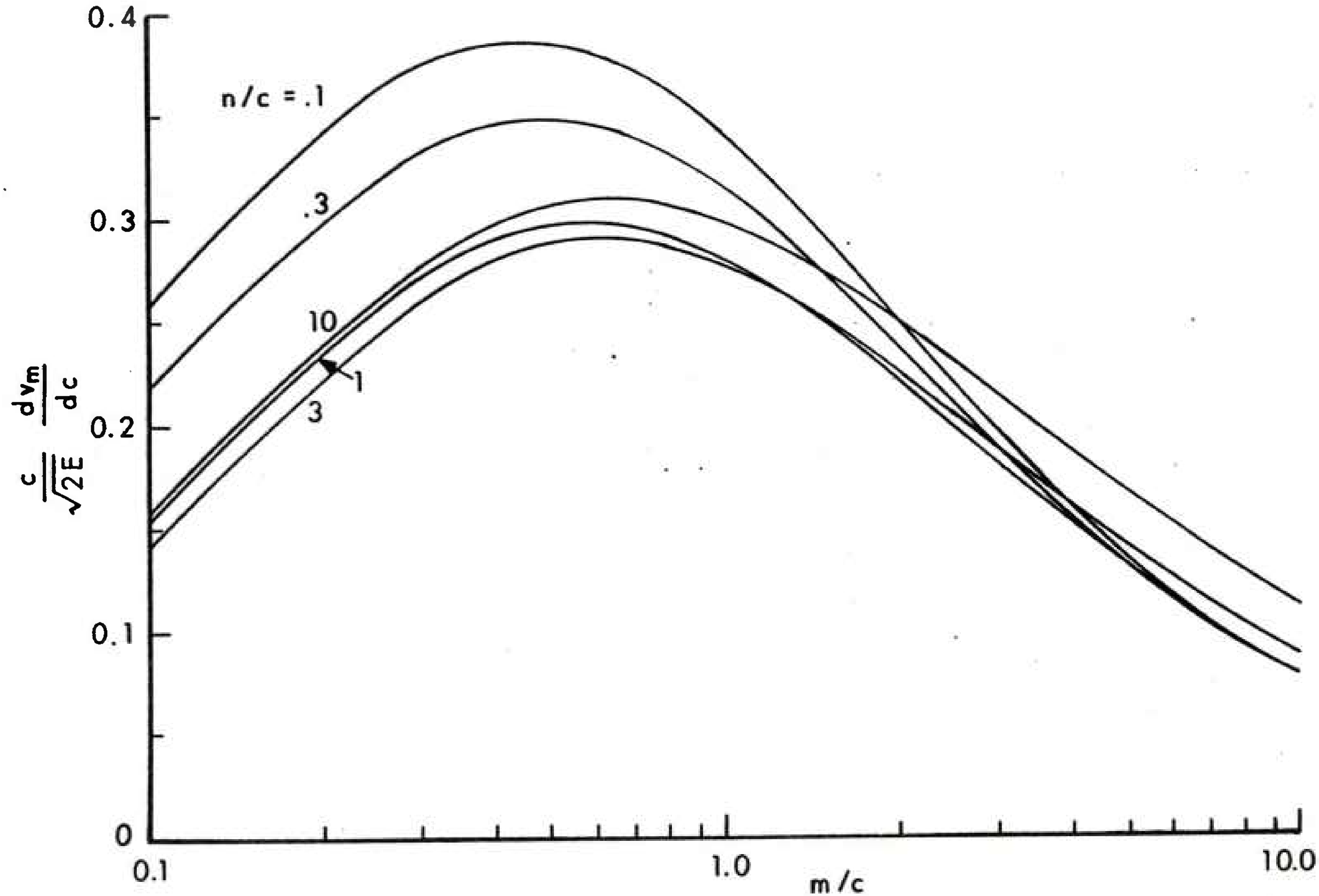


Figure 8. Gurney Estimates of Metal Velocity Variation vs. Charge Thickness Variation (Metal-Explosive-Tamper Sandwich)

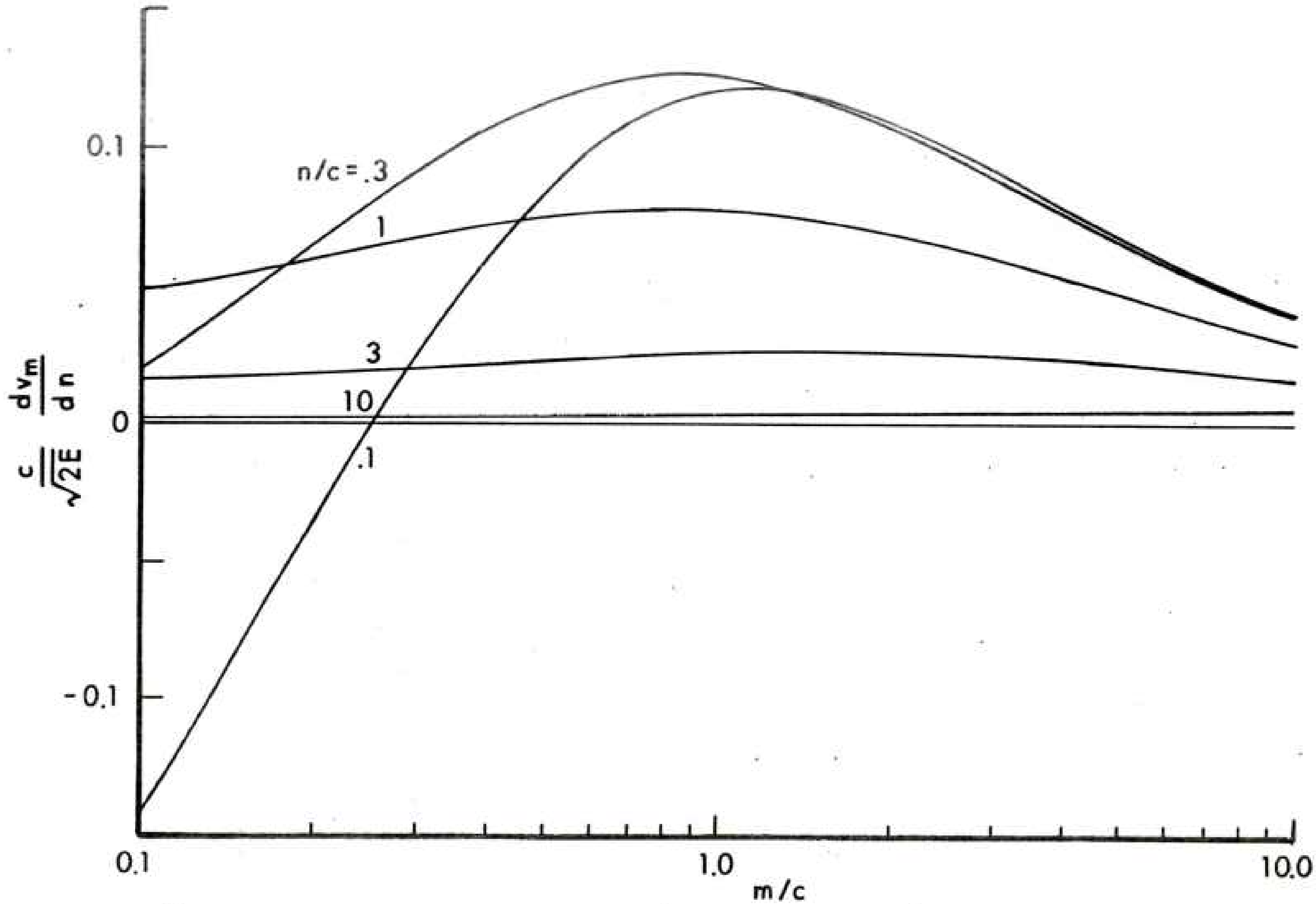


Figure 9. Gurney Estimates of Metal Velocity Variation vs. Tamper Thickness Variation (Metal-Explosive-Tamper Sandwich)

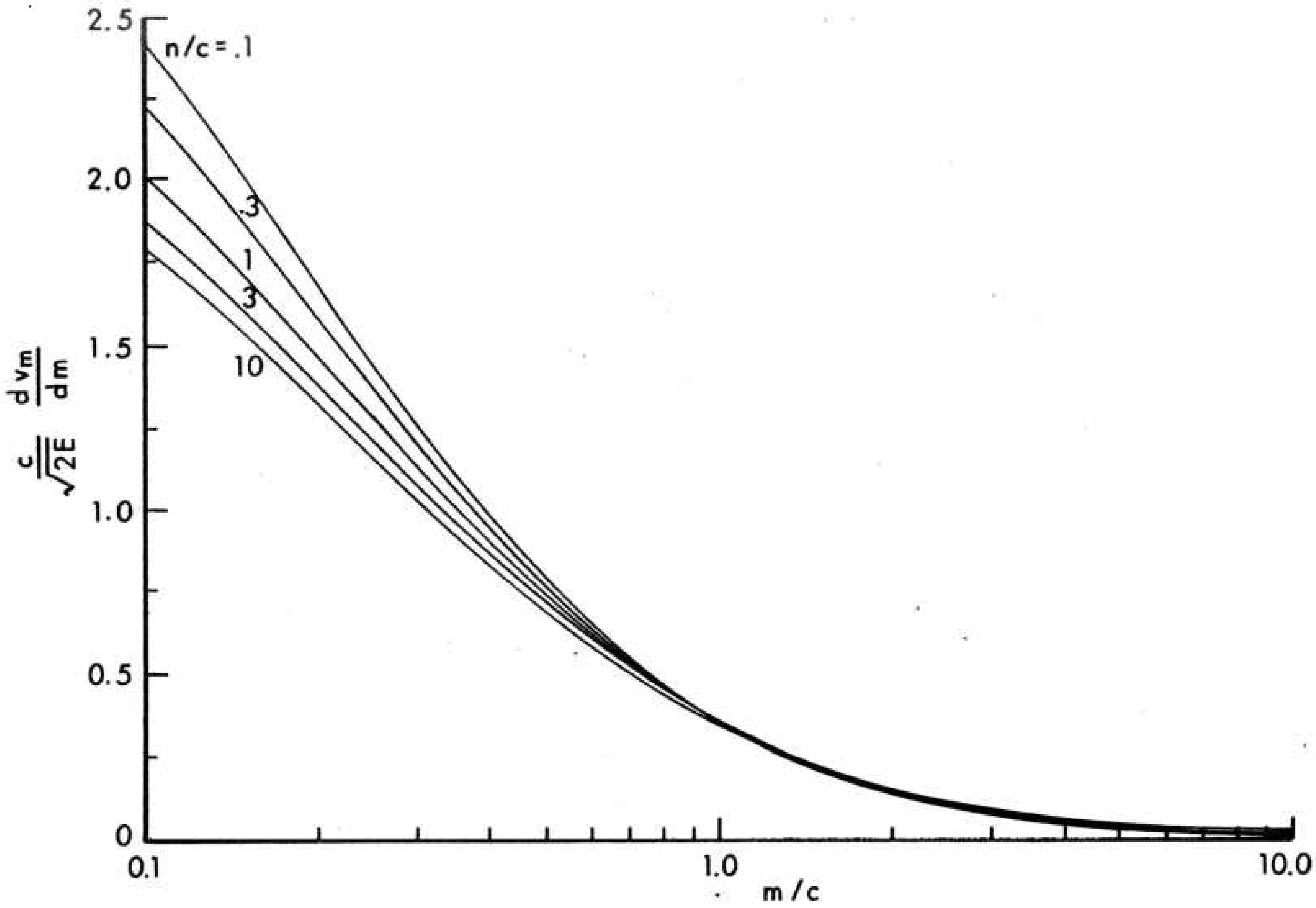


Figure 10. Gurney Estimates of Metal Velocity Variation vs. Metal Thickness Variations (Metal-Explosive-Tamper Sandwich)

t_m = 1.9 mm

t_n = 3.175 mm

ρ_c = 1.717 gm/cm^3

ρ_m = 8.9 gm/cm^3

ρ_n = 7.85 gm/cm^3

r_n = 40.6 mm

r_m = 13.6 mm

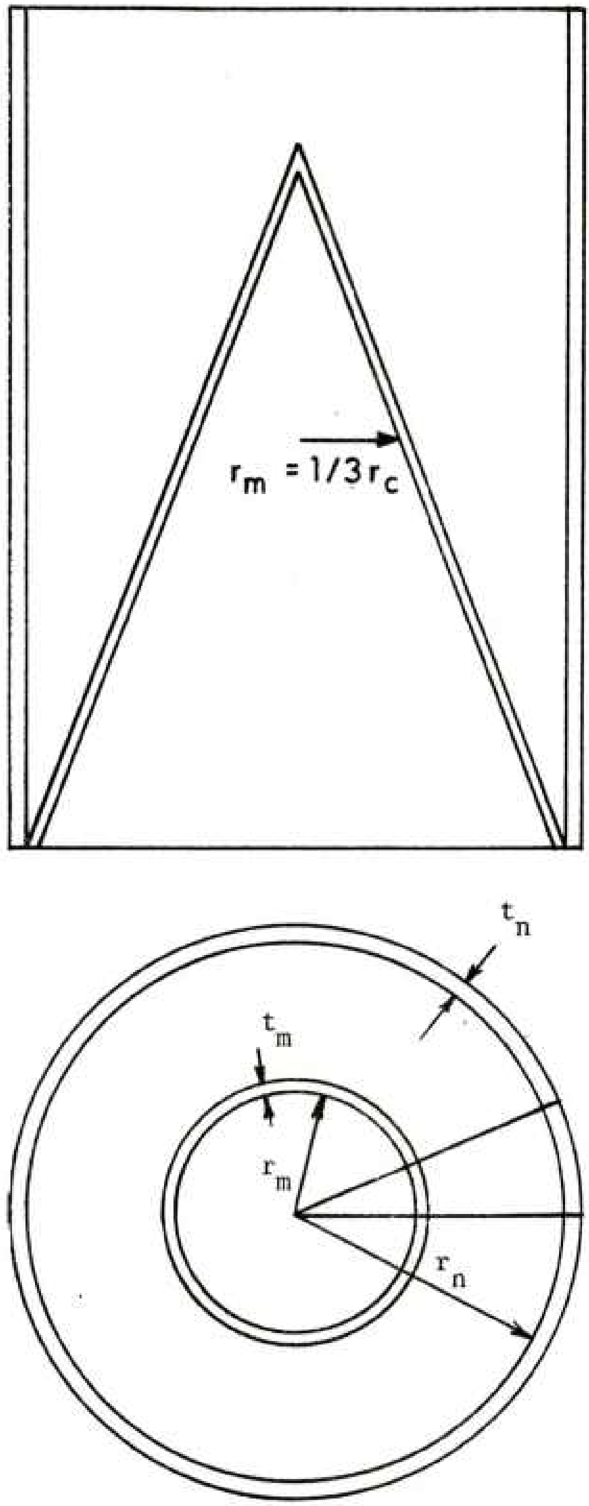


Figure 11. Charge Geometry Used to Estimate Relative Importance of Gurney Estimates

$$\frac{dv_m}{dt_n} \approx \frac{2\pi \rho_n r_n \sqrt{2E}}{c} \quad (.05)$$

where t_m, t_c, t_n refer to the thickness of the liner, charge, and tamper respectively. Thus, as would be expected the variation in the liner dimensions is the most critical. The relative importance is the following:

$$\frac{\text{RELATIVE LINER IMPORTANCE}}{\text{RELATIVE CHARGE IMPORTANCE}} \approx \frac{\rho_m \, r_m \, (1.6)}{\rho_c \, r_n \, (.22)} = 12.6$$

$$\frac{\text{RELATIVE LINER IMPORTANCE}}{\text{RELATIVE TAMPER IMPORTANCE}} \approx \frac{\rho_m \, r_m \, (1.6)}{\rho_n \, r_n \, (.05)} = 12.1$$

Thus, it would seem that the tolerance placed on the thickness of the tamper layer can be 12.6 times less rigid than the tolerance placed on the metal liner. For most charges this would be ± .064mm in any transverse plane. For this charge the explosive tolerance can be 12.1 times less rigid than the liner tolerance or ± .061mm.

VII. CONCLUSION

In the manufacture of shaped charges, certain minimum requirements have been experimentally determined for fabrication of the individual pieces making up the charge. This report develops a simple calculational scheme which can test the validity of the requirements and make estimates for those mechanical parameters not assessed previously. A modified shaped charge collapse theory was used to determine the transverse jet velocities arising from non-uniform collapse of the liner. Results indicate more precision is required over the upper one-half of the liner-explosive system than anywhere else in the charge.

LIST OF SYMBOLS

$v(t)$	speed of liner element
$\vec{v}_1$, $\vec{v}_2$	velocity vectors of two opposing liner elements
β	collapse angle of conventional shaped charge
A	cross sectional area of liner element
m	mass of liner element
Δm	variation in mass of liner element
p_o	initial pressure of explosive behind detonation
$p(t)$	pressure in explosive gases at liner interface
Δp	variation in initial pressure, p_o
b, b_o	constant appearing in pressure function $p(t)$
χ	distance liner element travels to cone axis
α	half angle of conical liner
H	height of cone
ϕ	initial bending angle of liner after passing of detonation wave
ε	metal liner thickness
ρ	density of Composition B for a given % RDX
R	radius of cone base
e	explosive thickness at a point along charge
v_m	velocity of metal liner as determined by Gurney formulae (G.F.)
m/c	metal mass to charge mass ratio used in G.F.
n/c	tamper mass to charge mass ratio used in G.F.
ρ_m	density of metal liner used in G.F.
ρ_n	density of tamper used in G.F.

LIST OF SYMBOLS

ρ_c	density of charge used in G.F.
r_m	radius of metal liner used in G.F.
r_n	radius of tamper used in G.F.
t_c	thickness of explosive used in G.F.
t_m	thickness of liner used in G.F.
t_n	thickness of tamper used in G.F.
c	charge mass used in G.F.

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