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A LINK BETWEEN SHAPED CHARGE PERFORMANCE AND DESIGN

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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It is illustrated that the penetration performance of a shaped charge determines "best" values of parameters in the DiPersio, Simon, and Merendino theory of penetration by shaped-charge jets and that it is possible to relate these penetration parameters to design parameters such as cone angle and liner thickness.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

DiPersio, Simon, and Merendino[1] presented equations to determine the penetration depth and hole volume associated with a shaped charge jet impacting a given target. In particular, given jet and target material densities, ρ_j and ρ_t, jet break-up time, t_1, initial jet tip velocity, V_j^o, minimum penetration velocity*, U_{min}, the penetration depth, as a function of the virtual stand-off distance, Z_o, can be computed. In addition, if given average jet diameter, d_j, and an energy constant, C, DiPersio, et al provide equations which enables one to calculate the hole volume associated with the penetrating jet. DiPersio, et al obtained values of t_1, U_{min}, and V_j^o from experimental measurements for a precision shaped charge, with a 42° conical liner, and calculated the total penetration depth as a function of stand-off distance for this particular charge. They obtained favorable agreement with experimental measurements of penetration depth at various stand-off distances where the stand-off distance is the distance from the base of the liner to the target.

A question raised by one of the authors (J.T.H.) was, "Under what conditions does the experimental penetration depth - stand-off data and hole volume - stand-off data determine or infer the values of C, U_{min}, and t_1?", i.e., the parameters utilized in the DiPersio, Simon, and Merendino (DSM) equations.

A partial answer to this question was given earlier by Majerus and Scott[2], who utilized a modified form of the DSM equations and investigated the round-to-round variability of C and U_{min}. Majerus and Scott provided a computational method of determining C and U_{min} from experimental penetration and hole volume - stand-off data. In their method, they required, in addition to target and material properties, location of virtual origin, jet break-up time, t_1, jet tip velocity, jet diameter, etc.

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[1] *R. DiPersio, J. Simon, and A. Merendino, "Penetration of Shaped Charge Jets into Metallic Targets," BRL R-1296, September 1965, (UNCLASSIFIED).* (AD #476717)

* *Also called an interaction parameter; see Reference 2.*

[2] *J. Majerus and B. Scott, "CUMIN: A Computer Code for Determining Certain Jet/Target Parameters from Experimental Data," ARBRL-TR-02129, December 1978, (UNCLASSIFIED).* (AD #B035331L)

In the following, we show that functions of the DSM parameters, t_1, U_{min}, and C, can be determined from experimental penetration and hole volume-stand-off data or, in fact, from desired penetration performance data. These functions, together with specification of V_j^o and jet diameter d_j yield estimates of t_1, U_{min}, and C. Since V_j^o and d_j are readily determined from the BASC[3] code and only require knowledge of material densities, some explosive properties, liner thickness, ϵ, and cone angle, α, the methodology provided herein enables one to calculate these DSM parameters without additional experimentation. Such a procedure may be useful in shaped charge design problems.

II. DETERMINATION OF U_{MIN} AND t

Letting $x = V_j^o t_1$, and $y = U_{min} t_1$ then the total penetration of the jet into the target is given by*

$$P_T = Z_o \left[\{ x/(1+\gamma)y \}^{1/\gamma} - 1 \right] \tag{1}$$

whenever

$$0 \leq Z_o \leq (1+\gamma)y \, [(1+\gamma)y/x]^{1/\gamma} \tag{2}$$

where $\gamma = \sqrt{\rho_t/\rho_j}$, or by

$$P_T = [(1+\gamma)x^{1/(\gamma+1)} Z_o^{\gamma/(1+\gamma)} - \sqrt{(1+\gamma)yx^{1/(\gamma+1)} Z_o^{\gamma/(1+\gamma)}}]/\gamma - Z_o \tag{3}$$

whenever

$$(1+\gamma)y[(1+\gamma)y/x]^{1/\gamma} \leq Z_o \leq x \tag{4}$$

or

$$P_T = [x - \sqrt{y(x+\gamma Z_o)}\,] / \gamma \tag{5}$$

whenever

$$x \leq Z_o \leq x\,(x/y - 1) / \gamma \tag{6}$$

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[3] *J. Harrison, "Improved Analytical Shaped Charge Code: BASC", ARBRL-TR- 02300, March 1981.* (AD #A100275)

* *Equations (23)-(25) of reference 2.*

Equations (1) - (6) enable one to calculate the total jet penetration as a function of stand-off from the virtual origin, Z_o, whenever x and y are known. We note from (2), (4), and (6) that the boundary of each region is also a function of x and y. Thus if x^* and y^* are known values of x and y, then this specification determines a partition such that given a value of Z_o one can determine the corresponding value of P_T.

If we are given $\{ (P_{T,i}, Z_{o,i}) \}$ for i = 1, ..., N and where $P_{T,i}$ is either the observed value of P_T at $Z_o = Z_{o,i}$ or is the desired performance at $Z_o = Z_{o,i}$ then we can obtain "best" values of x and y, i.e., x^*, y^* as follows. We note that the boundary between each region of validity for equations (1), (3), and (5) is a function of x and y, thus for each value of x and y, we can compute the value of $P_T = f(x,y,Z_o)$ for any given value of Z_o. If not, then the values of x and y lie outside the feasible region. We let

$$H(x,y) = \sum_{i=1}^{N} [P_{T,i} (Z_{o,i}) - f(x,y,Z_{o,i})]^2 \tag{7}$$

and we determine x^*, y^* such that

$$H(x^*,y^*) \leq H(x,y) \text{ for all } x,y. \tag{8}$$

If V_j^o is known, then t_1 and U_{min} follow from the definition of x and y.

III. AN EXAMPLE

Experimental data for the BRL Standard-Shaped charge are provided by DSM. Included within this data are total penetration vs. stand-off, jet break-up time, initial jet tip velocity, and minimum penetration velocity U_{min}. We have utilized the penetration stand-off data for stand-off distances through 20 cone diameters (we did not use the penetration depth at 25 cone diameters) in equation (7), i.e., we obtained the solution x^*, y^* from obtaining

$$\underset{x,y}{\text{MIN}} \sum_{i=1}^{N} [P_{T,i} (Z_{o,i}) - f(x,y,Z_{o,i})]^2 \tag{9}$$

from which we found

$$x^* = 85.905 \text{ cm} \tag{10}$$
$$y^* = 11.41 \text{ cm}$$

DSM reported that $V_j^o = 0.830$ cm/μsec thus since $x^* = V_j\ t_1^*$ and $y^* = U_{min}\ t_1^*$ we have

$$\begin{aligned} t_1^* &= 103.5\ \mu\text{sec} \\ U_{min}^* &= 0.110\ \text{cm}/\mu\text{sec} \end{aligned} \tag{11}$$

as compared to DSM experimental values of

$$\begin{aligned} t_1 &= 103\ \mu\text{sec} \\ U_{min} &= 0.10\ \text{cm}/\mu\text{sec} \end{aligned} \tag{12}$$

It is appropriate at this point to recall that V_j^o can be calculated from the BASC code, thus the above calculation can be performed without knowledge of the experimental value of V_j^o.

Since the determination of x^* and y^* also results in the determination of the corresponding region of penetration, i.e., $Z_{c,i}$ corresponds to a region in x - y space, the penetration is also calculated - and required in the minimization of (9). The calculated penetration vs virtual stand-off distance is shown in Figure 1 along with the experimental values of the penetration depth. The agreement is excellent.

The minimization of (9) was accomplished by utilizing the "Complex Method" due to M. J. Box[4]. This method requires only function evaluations and not derivatives; thus the method is ideal for this particular application.

IV. *VIRTUAL ORIGIN APPROXIMATION*

In the above example, the penetration depth was given as a function of the virtual stand-off distance. In the DSM report, the authors obtained the location of the virtual origin from flash radiograph measurements; however, in many other reports, the virtual origin is either not given or is approximated by a "rule of thumb". For example, DiPersio, Jones, et al[5] use, *from past experience*, the rule "the

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[4] *M. J. Box, "A New Method of Constrained Optimization and a Comparison with Other Methods," Computer J.,* 8 *42-52 (1965).*

[5] *R. DiPersio, W. Jones, A. Merendino, and J. Simon, "Characteristics of Jets from Small Caliber Shaped Charges with Copper and Aluminum Liners," BRL MR-1865, September 1967 (UNCLASSIFIED).* (AD #823839)

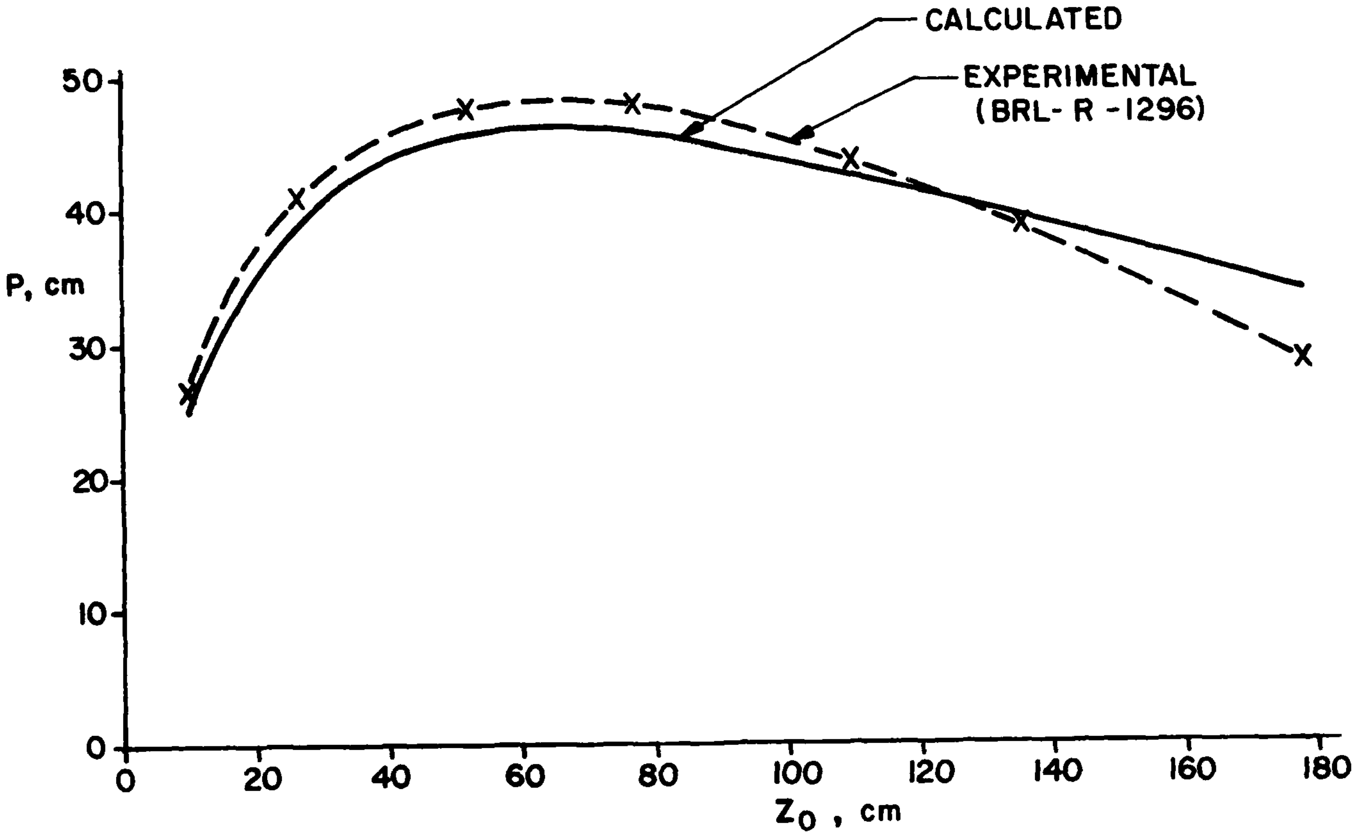

FIGURE 1. CALCULATED AND EXPERIMENTAL PENETRATION DEPTH VS STANDOFF DISTANCE FROM VIRTUAL ORIGIN FOR THE BRL PRECISION SHAPED CHARGE

approximate location of the virtual origin of a highly confined charge, ..., is three-fourths of the liner height ...". In attempting to determine t and U_{min} from the data of reference 5, we found that the above rule did not result in adequate agreement between computed and experimental values. Therefore, we modified our computational procedures and let

$$Z_o = B + S. \tag{13}$$

where B is the distance from the base of the liner, along the cone axis, to the apparent origin of the jet, and S is the stand-off distance. Thus equation (7) becomes

$$H(x,y,B) = \sum_{i=1}^{N} [P_{T,i} (S_i, B) - f(x,y,B,S_i)]^2 \tag{14}$$

so that we now seek x*, y*, and B* such that

$$H(x^*,y^*,B^*) \leq H(x,y,B) .$$

Utilizing the penetration data of reference 5, equation (14) was minimized. In this minimization process, we constrained B to lie in the interval

$$0 \leq B \leq B_{max}$$

where B_{max} = height of cone + distance allowed for liner retainer ring ($\doteq$ 1.4 cm). For the 20°, 60°, and 90° conical liners, the resulting agreement of calculated and experimental jet break-up time was excellent. For the 40° copper liner, we found that if B_{max} was taken to be twice the liner height, then good agreement could also be attained for this case. In Table 1, we present calculated break-up times t_1^* and observed values $\hat{t}_1$, calculated minimum penetration velocity U^*_{min} and the calculated location of virtual origin B*.

In obtaining the jet break-up times, t_1^*, listed in Table 1, we used, in each case, the corresponding experimental jet tip velocity reported in reference 5; however, it is noted again that the jet tip velocity can be calculated from the BASC code utilizing liner thickness, ε, apex angle, α, and explosive and liner material properties. In Table 2, we compare the BASC-code generated values with the experimental values for some of the 3.81 cm copper and aluminum liners of reference 5.

Table 1. Some Calculated and Observed Jet Data for the 3.81 cm Copper Liner Shaped Charge (asterisk denotes calculated value)

Cone Angle	t_1^*, μsec	$\hat{t}_1$, μsec	U^*_{min}, cm/μsec	B^*, cm
20°	41.5	40.8	0.18	12.2
40°	62.5	63.9	0.16	10.0
60°	65.3	66.7	0.14	4.4
90°	63.4	64.3	0.11	0.0

Table 2. Experimental and BASC-Code Generated Values of Jet Tip Velocity for Selected 3.81 cm Aluminum and Copper Liners

Cone Angle	Material	$\hat{V}_j^o$, cm/μsec	V_j^o, cm/μsec (BASC)
20°	Cu	0.99	1.03
20°	Al	1.12	1.08
40°	Cu	0.82	0.84
40°	Al	0.93	0.91
60°	Cu	0.67	0.74
60°	Al	0.81	0.82

In Figures 2-5, we have plotted the "best" penetration - virtual stand-off curves generated by minimizing (14) for each of the 3.8 cm (1.5") copper liners of reference 5. In each case, we used the average penetration values for each liner and we have plotted these average values, for comparison, on each figure. With the exception of the 20^o liner, the agreement is satisfactory.

In Figure 6, we have plotted the computed "best" value B^* of the virtual origin location as a function of cone angle for the 3.81 cm copper liner and the 42° BRL precision shaped charge of reference 1. The plot indicates that the virtual origin location is approximately linear with respect to cone angle.

Finally, in Figure 7, we have plotted "best" values of U^*_{Min} as a function of cone angle for the 1.91 and 3.81 cm copper conical liners of reference 5. It appears that for the liner, explosive, and target complex of reference 5 that U^*_{Min} is approximately linear with respect to cone angle and does not depend greatly upon the cone base diameter for these scaled liners. Also, on Figure 7 we have plotted U^*_{Min} which was calculated from the penetration stand-off data of reference 1. We note that both the explosive and target properties have changed for this case.

V. DETERMINATION OF THE ENERGY CONSTANT

The hole volume produced by the penetrating jet can be calculated for each region of penetration by the equations (38), (40), and (42) of the DSM report. For example, for region 1$^+$

$$\tau_T = \xi\, x\, \{\, 1 - [\frac{(1+\gamma)y}{x}]^3 \,\}$$

where

$$\xi = \frac{\pi d_j^{\,2}}{24C}\, \rho_j\, (V_j^{\,o})^2 \qquad (15)$$

For each of the other regions, each equation is a function of ξ, x, Z_o, and y. We have shown previously that x and y, i.e., x^*, and y^* can be obtained by minimizing (7) or (14), and have noted that d_j and V_j^o can be obtained from the BASC-code, thus if we denote the calculated hole volume, in its appropriate stand-off region by g (Z_o, x^*, y^*, ξ) we obtain ξ^* by minimizing

$$G(\xi) = \sum_{i=1}^{N} [\, \tau_T(Z_{o,i}) - g(Z_{o,i}, x^*, y^*, \xi)\,]^2 \qquad (16)$$

$^+$See equations (2), (4), and (6) for corresponding boundary relations.

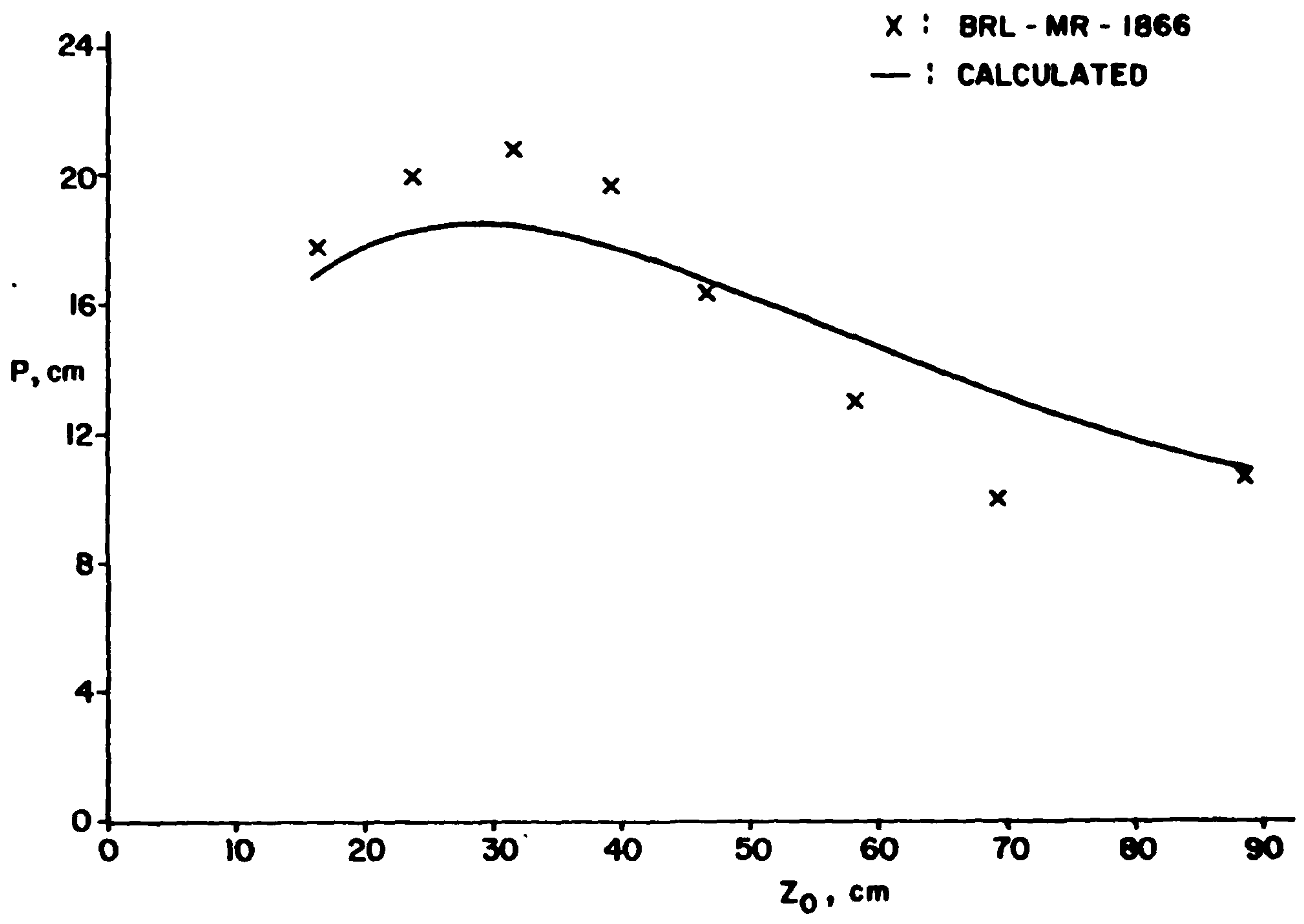

FIGURE 2. PENETRATION DEPTH VS VIRTUAL STANDOFF DISTANCE FOR THE 3.81 CM., CU., CONICAL LINER. CONE ANGLE = 20° .

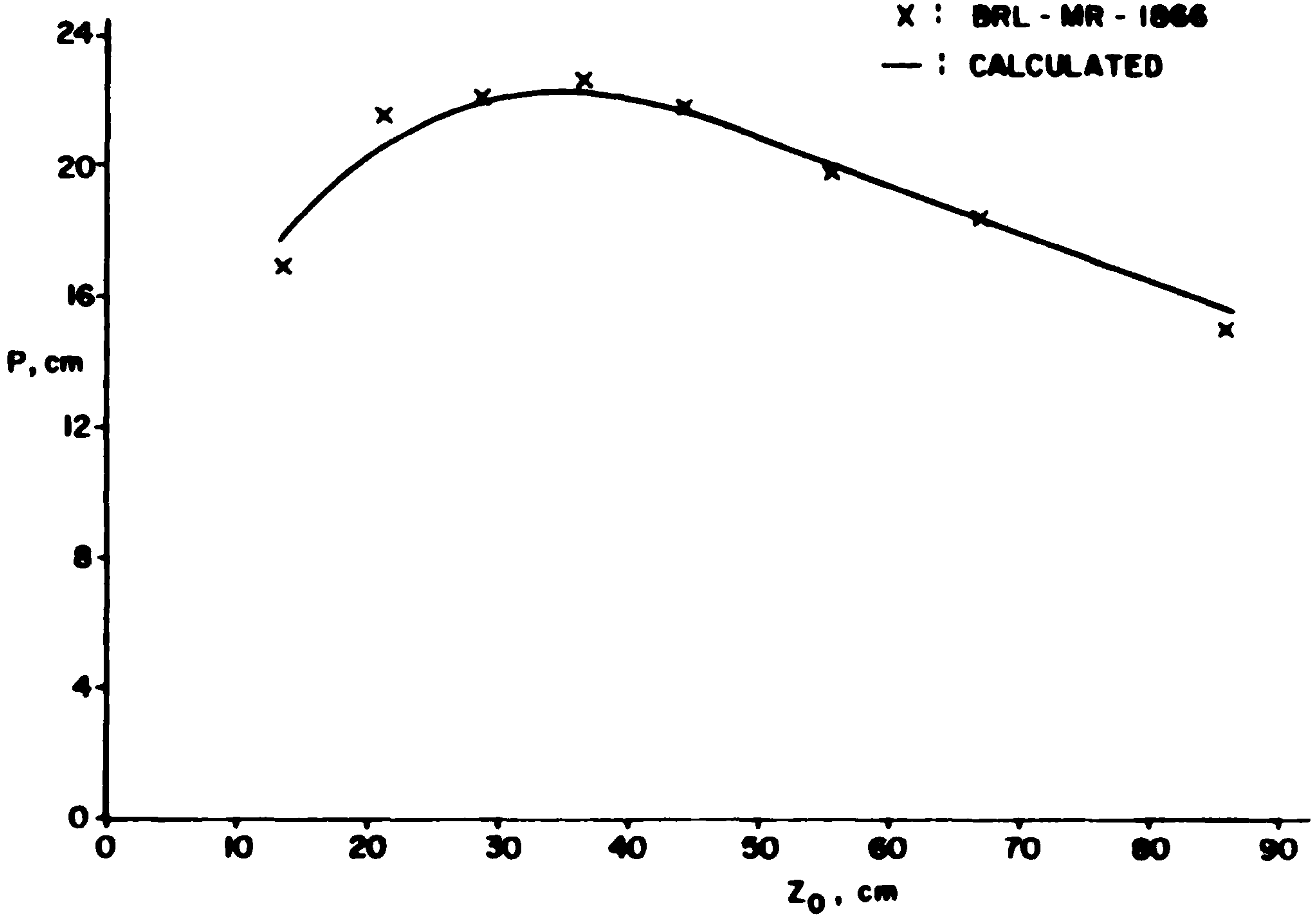

FIGURE 3. PENETRATION DEPTH VS VIRTUAL STANDOFF DISTANCE FOR THE 3.81 CM., CU., CONICAL LINER. CONE ANGLE = 40°.

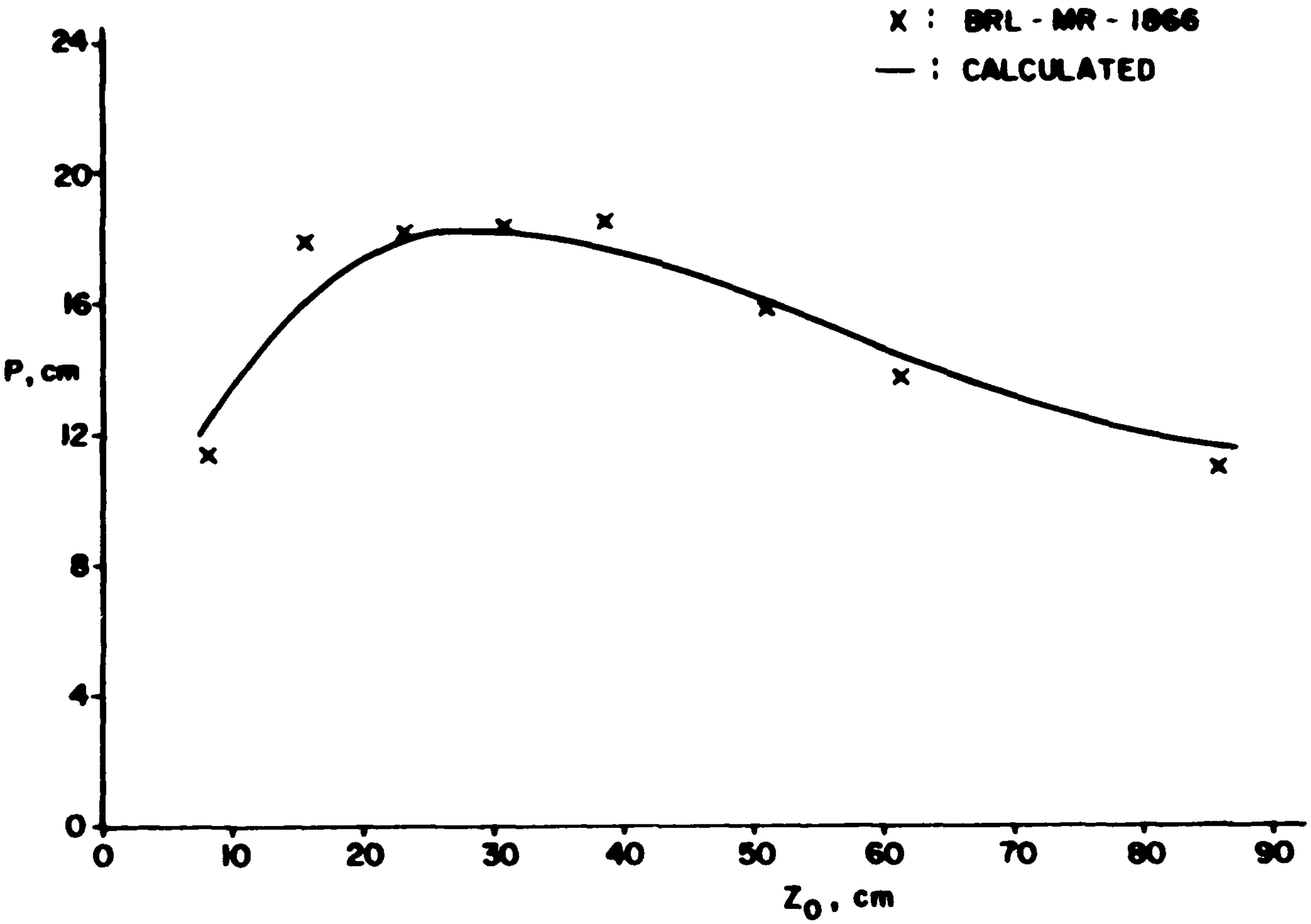

FIGURE 4. PENETRATION DEPTH VS VIRTUAL STANDOFF DISTANCE FOR THE 3.81 CM., CU., CONICAL LINER. CONE ANGLE = 60° .

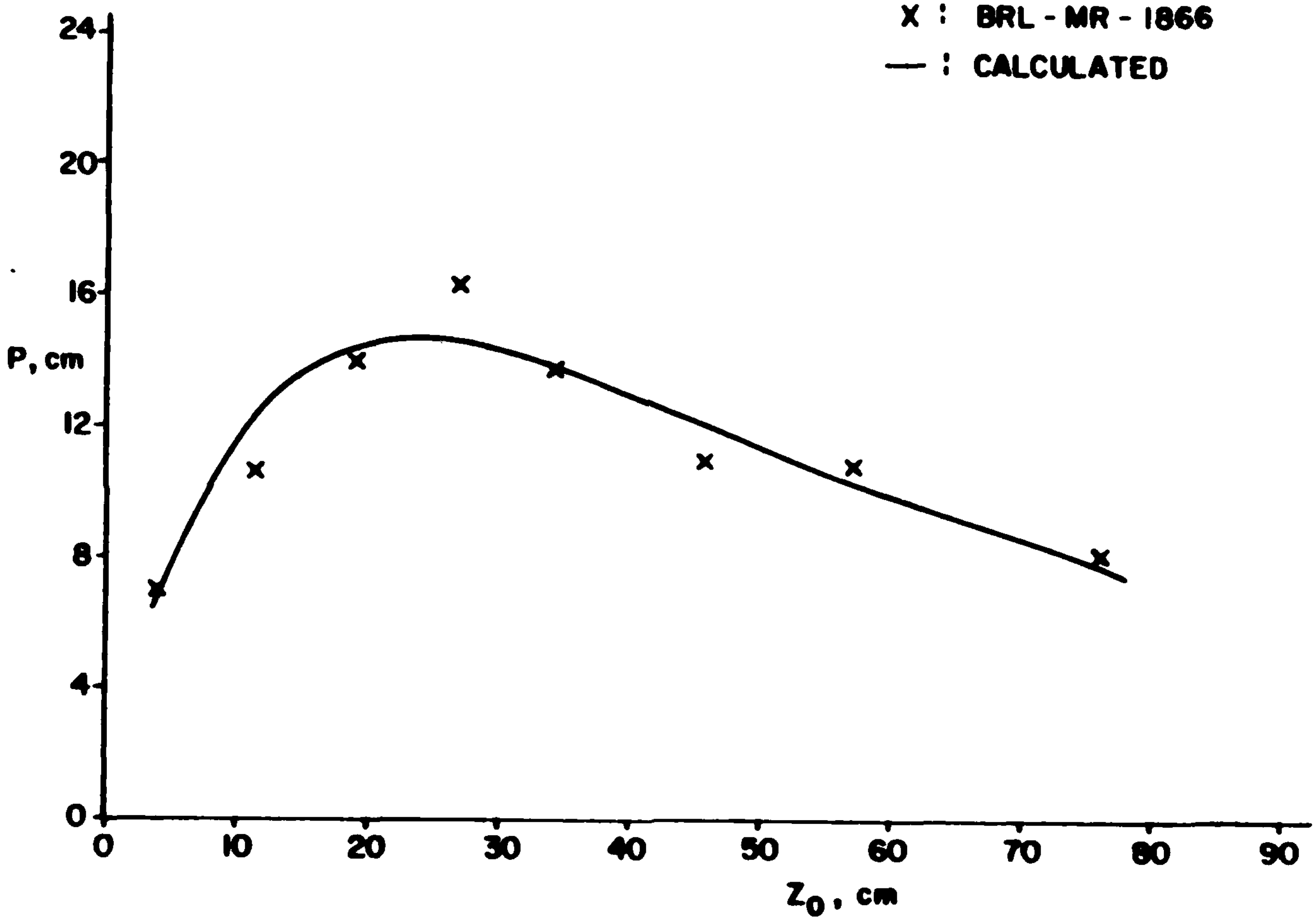

FIGURE 5. PENETRATION DEPTH VS VIRTUAL STANDOFF DISTANCE FOR THE 3.81 CM., CU., CONICAL LINER. CONE ANGLE = 90°.

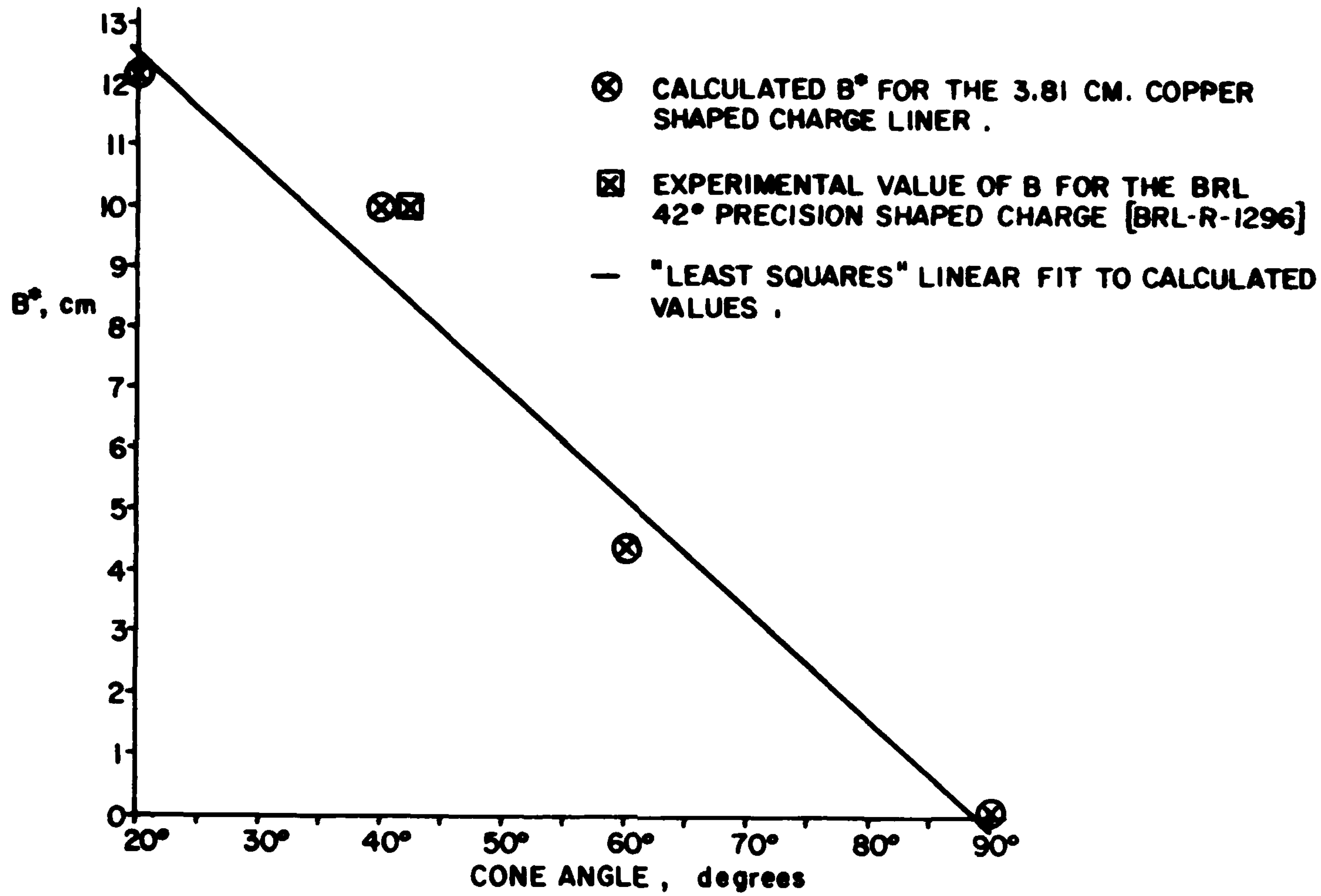

FIGURE 6. CALCULATED VIRTUAL ORIGIN VS CONE ANGLE .

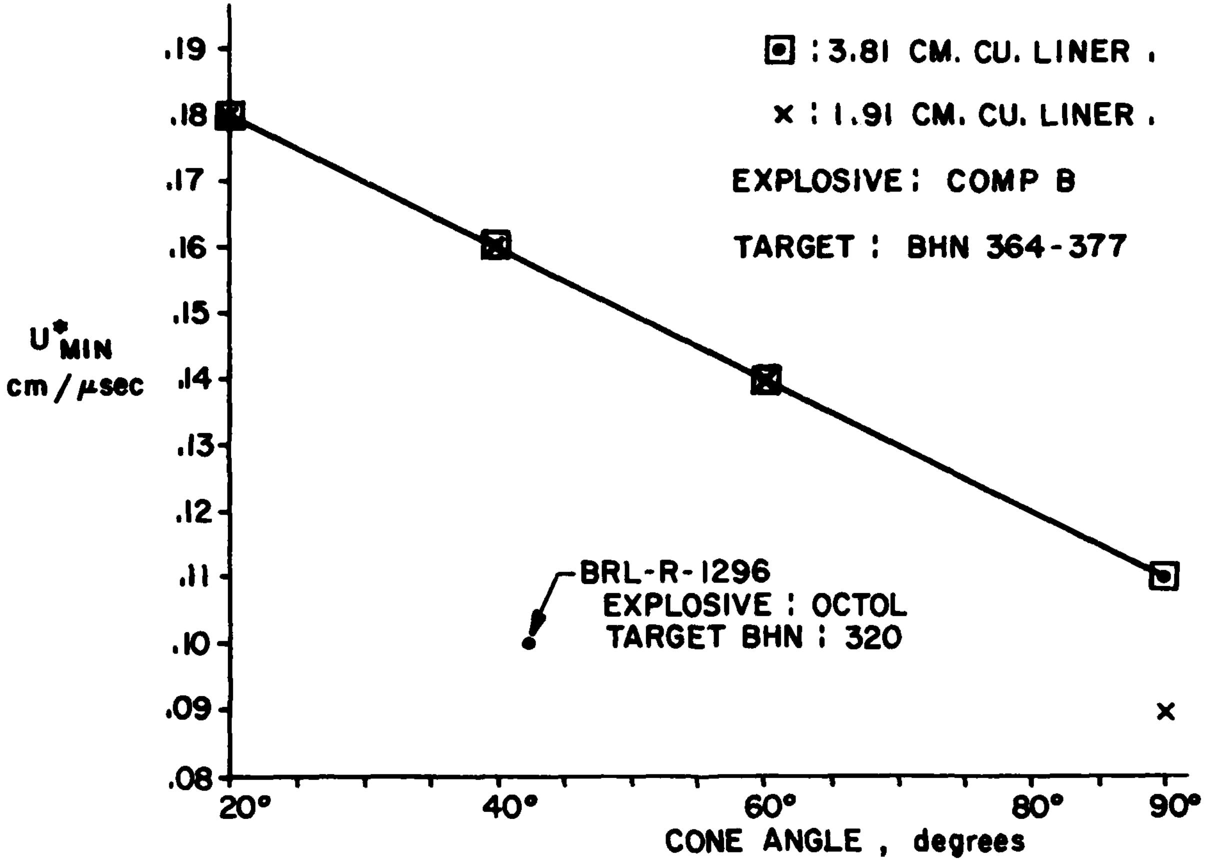

FIGURE 7. CALCULATED U_{MIN} VS CONE ANGLE .

The value of $\xi = \xi^*$ which minimizes (16) can then be used to determine the energy constant C whenever V_j^o and d_j are known. Since both d_j and V_j^o can be determined with BASC then a "best" value, C^*, of the energy constant can be determined.

VI. SUMMARY

We have shown how penetration performance - stand-off data and hole volume - stand-off data can be utilized to determine values of specific functions of the DiPersio, Simon, Merendino shaped-charge parameters C, U_{min}, and t_1, and that specification of the initial jet tip velocity V_j^o determines "best" values of t_1 and U_{min}. If, in addition, the jet diameter d_j is known, then the energy constant C is readily determined. It is of interest to note that V_j^o and d_j are readily determined from Harrison's BASC code and are functions of the liner thickness and cone angle. The implication of this is that since x^* and y^* are determined from penetration performance data one may then search for "best" values of cone angle, α, and liner thickness, ε, which maximizes the jet break-up time t_1. From the definition of x we see that one should choose α and ε such that V_j^o is a minimum.

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4. Has the information in this report led to any quantitative savings as far as man-hours/contract dollars saved, operating costs avoided, efficiencies achieved, etc.? If so, please elaborate.

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