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ANALYTICAL MODEL FOR HIGH EXPLOSIVE MUNITIONS STORAGE

H. L. Schreyer
L. E. Romesberg

Mechanics Research, Inc.
Albuquerque, New Mexico

TECHNICAL REPORT NO. AFWL-TR-70-20

June 1970

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This report was prepared by Mechanical Research, Inc., Albuquerque, New Mexico, under Contract F29601-69-C-0034. The research was performed under Project 1597, Task 12.

Inclusive dates of research were February 1969 through March 1970. The report was submitted 24 March 1970, by the Air Force Weapons Laboratory Project Officer, Captain Jacob C. Armstrong (WLCT).

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This report has been reviewed and is approved.

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ABSTRACT

Analytical models and subsequent computer codes have been developed for predicting peak overpressure, positive unit impulse, the distribution and impact velocity of bomb fragments, crater dimensions and ejecta thickness from the detonations of typical bomb stacks used by the Air Force. These models consider aboveground barricaded stacks with an equivalent net weight high-explosive range of 10 to 500 tons of TNT. The peak overpressure and impulse from a detonation are obtained by modifying the known results of a bare hemispherical charge to take into account the stack and barricade geometries and the interaction effect of bombs. Fragment dispersion patterns are predicted by combining experimental results for single bombs and using the trajectory equations for the motion of a steel fragment in air. By using basic principles and experimental data, crater and ejecta dimensions are predicted. Based on output from the computer codes, illustrative examples are given together with recommendations for future tests to obtain needed data. Programs for optimizing munition storage areas are also suggested.

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ABBREVIATIONS AND SYMBOLS

A
Cross-sectional area of fragment perpendicular to the direction of propagation, ft.$^2$

B
Region defined by geometry of explosive charge

$B_L$
Bottom half of region of explosive charge

$B, C, D$
Coefficients for $(P/P_{sphere})$ polynomial in FAR

$C_D$
Drag coefficient

$C_F$
Cratering factor

$C_{Fo}$
Crater factor for a reference charge

$C_F/C_{Fo}$

$C_0, C_1,...$
Coefficients for $B, C, D, F, G, \text{ and } H$ polynomials

$D_a$
Apparent depth of crater, ft.

$E_D$
Energy dissipated in the form of heat

$E_G$
Total kinetic energy of the earth elements, ft. lb.

$E_s$
Kinetic energy delivered to earth surface, ft. lb.

$E^D$
Energy dissipation ratio

$E_T$
Total kinetic energy of a charge, ft. lb.

EFNB
Effective number of bombs in a stack

$F_D$
 Drag force on fragment, lbs.

$F_{Dx}$
Drag force in X-direction, lbs.
$F_Y$ Drag force in Y-direction, lbs.

$F_G$ Force of gravity, lbs.

$F$, $G$, $H$ Coefficients for $(I/I_{sphere})$ polynomial in FAR

FAR Face area ratio

$H$ Vertical distance from centroid of crater volume element to centroid of ejecta volume element, ft.

$H_e$ Height of ejecta, ft.

$I$ Scaled positive impulse, psi-ms/lb. $^{1/3}$

$K$ Ratio of energy at surface for a yield $W$ divided by energy at surface for a reference charge $\text{yield } W_0$

$L$ Distance to horizontal plane through center of mass, ft.

$[L]$ *ital* length dimension

$[M]$ Fundamental mass dimension

$N_{\theta_1, \theta_2}^{\beta_1, \beta_2}$ Number of fragments in the region $\theta_1 \leq \theta \leq \theta_2$, $\beta_1 \leq \beta \leq \beta_2$

$P$ Peak overpressure, psi

$R$ Distance from burst point, ft.

$R_a$ Apparent radius of crater, ft.

$R_c$ Radius to center of mass of crater volume element, ft.

$R_e$ Radius to center of mass of ejecta volume element, ft.
<table>
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<td>$R_{j-1,j}, R_{j,j+1}$</td>
<td>Lower and upper boundaries of impact area $A_j$</td>
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<td>$R_1, R_2, ...$</td>
<td>Ordered impact ranges for nearest, next nearest, etc., impact points</td>
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<td>$\tilde{R}_1, \tilde{R}_2, \tilde{R}_3$</td>
<td>Distance from burst point to points of barricade, ft.</td>
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<tr>
<td>SD</td>
<td>Stack depth, ft.</td>
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<td>SH</td>
<td>Stack height, ft.</td>
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<td>SL</td>
<td>Stack length, ft.</td>
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<tr>
<td>T</td>
<td>$W/W_0$</td>
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<tr>
<td>$[T]$</td>
<td>Fundamental time dimension</td>
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<tr>
<td>V</td>
<td>Speed of fragment, ft./sec.</td>
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<tr>
<td>$\dot{V}$</td>
<td>Time rate change of velocity, ft./sec.</td>
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<td>$V_e$</td>
<td>Volume of ejecta, ft.</td>
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<td>$V_L$</td>
<td>Volume of bottom half of charge, ft.</td>
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<td>$\mathbf{V}_0$</td>
<td>Velocity vector at time = zero, ft./sec.</td>
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<td>W</td>
<td>Weapon yield, equivalent weight of TNT</td>
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<td>$W_L$</td>
<td>Weapon yield for a charge shape with center of mass at $L$, lbs. of TNT</td>
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<td>$W_0$</td>
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<td>Scaled distance, ft./lb.$^{1/3}$</td>
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<tr>
<td>$Z_1, Z_2, Z_3$</td>
<td>Height of barricade at $\tilde{R}_1, \tilde{R}_2, \tilde{R}_3$ respectively, ft.</td>
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a  Coefficient in polynomial $x$

$a_o$  Acceleration in vertical direction, ft./sec.$^2$

$a_o, a_1, \ldots$  Coefficients for polynomial $\ln P$

$b$  Coefficient in polynomial $\hat{x}$

$b_0, b_1, \ldots$  Coefficients for polynomial $\ln I$

$c$  Ballistic coefficient, 1/ft.

$c_0, c_1, \ldots$  Coefficients for polynomials $B, C, D, F, G,$ and $H$

$d_0, d_1, \ldots$  Coefficients for polynomial EDGE PRESSURE/FACE PRESSURE

$e$  Kinetic energy per unit mass, ft./lb.

$\bar{e}_B$  Unit vector in direction of center line out of nose of bomb

$e_s$  Energy per unit mass delivered at earth surface, ft./lb.

$e_o$  Initial kinetic energy per unit mass, ft./lb.

$\bar{e}_o$  Unit vector in direction $\vec{V}_o$

$e_o, e_1, \ldots$  Coefficients for polynomial EDGE IMPULSE/FACE IMPULSE

$\bar{e}_1, \bar{e}_2, \bar{e}_3$  Unit vectors in directions $X, Y,$ and $Z$ respectively.

$f$  Non-dimensional function of $\phi$

$f'$  Unknown function

$f_0, f_1, \ldots$  Coefficients for polynomial for pressure ratio for barricade effect

$g$  Gravity constant, ft./sec.$^2$

$i_s$  Positive unit impulse, psi-ms

xiv
\( k \)  
Constant

\( l \)  
Length of sides for a steel cube, ft.

\( m \)  
Mass of fragment, slugs

\( t \)  
Time, sec.

\( v \)  
Velocity in vertical direction, ft./sec.

\( v_0 \)  
Initial speed of particles in charge, ft./sec.

\( w_f \)  
Weight of fragment, lb.

\( W_{FG} \)  
Weight of fragment, grams

\( x \)  
Distance along X-direction, ft.

\( \ddot{x} \)  
Acceleration in X-direction, ft./sec\(^2\)

\( x_c \)  
Crater depth as a function of \( R \), ft.

\( y \)  
Distance along Y-direction, ft.

\( \ddot{y} \)  
Acceleration in Y-direction, ft./sec\(^2\)

\( y_0 \)  
Height of bomb above impact point, ft.

\( z \)  
Distance above earth surface, ft.

\( \ddot{z} \)  
Acceleration in vertical direction, ft./sec\(^2\)

\( z_{CG} \)  
Vertical distance to center of mass of explosive, ft.

\( z_{CG}^0 \)  
Height of center of mass of reference charge, ft.

\( z_0 \)  
Vertical position at time = 0, ft.
\( \alpha \quad \) Angle between horizontal line and tangent to trajectory, radians

\( \dot{\alpha} \quad \) Time rate change of \( \alpha \), radians/sec.

\( \alpha_{\text{impact}} \quad \) Impact angle for fragment, degrees

\( \beta \quad \) Departure angle from burst point measured from horizontal, degrees

\( \hat{\beta} \quad \) Soil parameters

\( \beta_1, \beta_2 \quad \) Lower and upper bounds on a region of \( \beta \) respectively

\( \gamma \quad \) Angle between centerline out nose of bomb and initial velocity of fragment, degrees

\( \gamma_A \quad \) Weight density of air, lb./ft.\(^3\)

\( \delta \quad \) Angle between azimuth angle \( \theta \) and barricade wall

\( \Delta V_c \quad \) Element of volume of the crater, ft.\(^3\)

\( \Delta V_e \quad \) Element of volume of the ejecta, ft.\(^3\)

\( \Delta x \quad \) Incremental change in \( x \)

\( \Delta y \quad \) Incremental change in \( y \)

\( \Delta \alpha \quad \) Incremental change in \( \alpha \)

\( \Delta \beta \quad \) Increment of \( \beta \)

\( \Delta \theta \quad \) Increment of \( \theta \)

\( \varepsilon \quad \) Strain rate

\( \zeta \quad \) Constant

\( \theta \quad \) Angle between line out center of barricade opening and horizontal direction of fragment

\( \theta_B \quad \) Angle between line out center of barricade opening and centerline out nose of bomb
\( \theta_1, \theta_2 \)  
Lower and upper bound on a region of \( \theta \) respectively

\( w \)  
Constant for energy computations

\( \nu \)  
Non-dimensional variable, generalized viscosity

\( \nu' \)  
Soil viscosity

\( \rho \)  
Mass density of soil

\( \rho_A \)  
Density of air, slugs/ft.\(^3\)

\( \sigma \)  
Soil parameter

\( \tau \)  
Stress

\( \phi \)  
Angle between \( R_2 \) and barricade wall

\( \psi \)  
Angle between \( R_1 \) and barricade wall

\( \psi(y) \)  
Number of fragments per steradian

\( \psi_{1,2} \)  
Average number of fragments per steradian in a solid angle
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SECTION I
INTRODUCTION

One of the major problems at many Air Force installations is the storage of large quantities of munitions. Safety considerations for protection of personnel and material in the event of accidental detonation, although overriding, are in direct conflict with economics, i.e., large clear zones require considerable real estate with resulting long roads and utility lines. If munitions storage clearance requirements could be reduced without endangering safety requirements, significant economic gains could be realized.

Full-scale tests of munitions storage concepts have been conducted and have yielded valuable information leading toward more rational munitions storage criteria. Such tests are, however, expensive and exceedingly time consuming. Availability of analytical procedures which could be used with some confidence to predict the effects of detonation of a stack of munitions would be invaluable in analyzing new storage concepts, or in rational, effective planning of such future full scale tests as may be required. This study is a step toward development of such procedures.

The most significant parameters in determining munitions detonation hazards include peak overpressure, unit impulse, mass and velocity of projectiles formed from bomb fragments and their distribution, crater dimensions, and the probable ejecta distribution. This report outlines an analytical model that adequately
predicts these parameters for the range of 25,000 to 500,000 pounds net weight of high explosives. Associated with the report are computer programs that perform the numerical analysis required for the models. Even though the most recent sources have been consulted, it was considered advisable to construct the model and the computer programs in a manner that would easily allow alterations as new experimental and theoretical work became available.

Section II considers the peak overpressure and unit impulse emanating from bomb stacks, both barricaded and unbarricaded. Section III handles fragmentation while Section IV discusses cratering. The corresponding computer programs are listed and described in Appendices I, II and III respectively. Examples of results obtained from the computer programs are presented in Section V. As a result of the extensive literature survey that was conducted and from the formation of the analytical models, it became apparent that further investigations, both experimental and analytical, in certain critical areas would be highly beneficial. Such a program is outlined in Section VI.

Throughout the report, an attempt has been made to use a judicious combination of basic principles and results from small and full-scale tests. Such an approach is considered necessary if the results are to be used for typical situations that currently confront the Air Force. Furthermore, the use of fundamental concepts implies that new situations can be handled with some degree of confidence. However, it should always be kept in mind that soil conditions, for example, can change with time and
accordingly, even well designed experiments produce data with a considerable amount of scatter. Accordingly, a certain amount of engineering judgment is required in connection with the results of this study.
SECTION II
BLAST EFFECTS

1. INTRODUCTION

The objective of this section is to develop an analytical model which will predict the environment produced by the air blast from a high explosive detonation. The primary parameters to be investigated are the peak overpressure and positive impulse experienced at all points on the surface surrounding a high-order surface detonation. The effects to be investigated include: a) the effect of substituting conventional Air Force bombs for TNT in the explosive stack; b) the effect on the peak overpressure-scaled distance $P-Z$ and scaled positive impulse-scaled distance $I-Z$ relationships produced by the explosive stack geometry, and c) the effect on the $P-Z$ and $I-Z$ relationships produced by a barricade surrounding the explosive stack on three sides (standard open-end barricade). The scaled distance $Z$ is defined to be the distance $R$ from the point of detonation divided by the equivalent charge weight in pounds of TNT to the one-third power $W^{1/3}$

$$ Z = R/W^{1/3} \tag{1} $$

The scaled positive impulse $I$ is defined to be the positive unit impulse $i_s$ divided by the equivalent charge weight in pounds of TNT to the one-third power $W^{1/3}$

$$ I = i_s/W^{1/3} \tag{2} $$
The general approach followed is to develop a model to predict the P-Z and I-Z relationships for a surface detonation of a hemispherical stack of high explosive TNT, and then to modify these relationships to account for the individual effects listed above. The effect produced by changing the point of detonation in the stack is assumed to be negligible. (See Reference 1).

2. BARE CHARGE PARAMETERS

The initial task in the development is to model the environment produced by a surface detonation of a bare, i.e., unbarri-caded, hemispherical stack of TNT, with respect to peak overpressure and scaled positive impulse. Curves describing the peak overpressure-scaled distance relationship for high explosive surface detonations are available throughout the literature. These relationships have been developed through many years of full scale testing and are widely accepted. Discrepancies do appear in the literature when comparing the relationships published by one testing agency with those published by another; however, these discrepancies are of a relatively small order. The relationships selected for the model development (See Figure 1) are published in Reference 2.

To carry out the objectives of this section, it is necessary to have these results available in a numerical form. The procedure used in modeling the P-Z and I-Z relationships is as follows: a) Points on the P-Z and I-Z curves are selected; b) the coordinates (P, Z) and (I, Z) of these points are transformed
Figure 1. Shock Wave Parameters for Hemispherical TNT Surface Explosion at Sea Level
by computing the natural logarithm of each coordinate so that
the coordinates \((\ln P, \ln Z)\) and \((\ln I, \ln Z)\) are obtained;
c) the coordinates \((\ln P, \ln Z)\) and \((\ln I, \ln Z)\) are used in a
least squares polynomial curve fit program to obtain relation-
ships of the form

\[
\ln P = a_0 + a_1 (\ln Z) + a_2 (\ln Z)^2 + \ldots \quad \text{and} \quad (3)
\]

\[
\ln I = b_0 + b_1 (\ln Z) + b_2 (\ln Z)^2 + \ldots \quad \text{and} \quad (4)
\]
d) the polynomial coefficients obtained from the curve fit pro-
gram are then used to evaluate the value of peak overpressure \(P\)
and scaled positive impulse \(I\) at the desired values of scaled
distance \(Z\).

This procedure yields results which are in very close
agreement with the original relationships (curves). The maxi-
mum error in the predicted peak overpressure-scaled distance
relationship is less than 7\% for \(0.5<Z<10 \text{ ft/}lb^{1/3}(P>10 \text{ psi})\),
less than 3\% for \(10<Z<45 \text{ ft/}lb^{1/3}(1.0>P>10 \text{ psi})\) and less than
5.0\% for \(45<Z<500 \text{ ft/}lb^{1/3}(P<1.0 \text{ psi})\). The maximum error in
the predicted scaled positive impulse-scaled distance relation-
ship is less than 6\% for \(0.5<Z<10 \text{ ft/}lb^{1/3}(I>10.0 \text{ psi-ms/}lb^{1/3})\),
less than 5\% for \(10<Z<75 \text{ ft/}lb^{1/3}(10.0>I>1.0 \text{ psi-ms/}lb^{1/3})\) and
less than 15\% for \(75<Z<500 \text{ ft/}lb^{1/3}(I<1.0 \text{ psi-ms/}lb^{1/3})\).

The resulting coefficients for determining the overpressure
and scaled positive impulse according to Equations (3) and (4)
are given in Table I.
<table>
<thead>
<tr>
<th>TABLE I</th>
</tr>
</thead>
</table>

**POLYNOMIAL COEFFICIENTS FOR DETERMINING PEAK OVERPRESSURE AND SCALED POSITIVE IMPULSE FOR A BARE HEMISPHERICAL CHARGE**

\[
\begin{align*}
    a_0 &= 10.7036810 \times 10^1 \\
    a_1 &= -0.1663724 \times 10^1 \\
    a_2 &= -0.2516481 \times 10^0 \\
    a_3 &= -0.1137714 \times 10^0 \\
    a_4 &= +0.3818405 \times 10^{-1} \\
    a_5 &= +0.5035198 \times 10^{-1} \\
    a_6 &= -0.2756970 \times 10^{-1} \\
    a_7 &= +0.5557968 \times 10^{-2} \\
    a_8 &= -0.5108014 \times 10^{-3} \\
    a_9 &= +3.1795565 \times 10^{-4} \\
\\
    b_0 &= +0.3129288 \times 10^1 \\
    b_1 &= -0.1295979 \times 10^0 \\
    b_2 &= +0.4112452 \times 10^0 \\
    b_3 &= -0.7687394 \times 10^0 \\
    b_4 &= +0.4969224 \times 10^0 \\
    b_5 &= -0.1684197 \times 10^0 \\
    b_6 &= +0.2805656 \times 10^{-1} \\
    b_7 &= -0.1791292 \times 10^{-2}
\end{align*}
\]
3. BOMB EFFECT

The effect produced by substituting conventional Air Force bombs for TNT in the explosive stack has been studied by several authors for many years. This effect is accounted for in the model development through the use of a bomb factor. This factor is multiplied by the total explosive weight in the bomb stack to yield an equivalent weight of TNT. The bomb factor includes the confined explosion effect, the surface reflectivity effect, and the individual bomb geometry effect. Typical bomb factors can be found in Reference 3. No attempt has been made to account for the explosion confinement effect caused by stacking bombs. There will be some confinement effect caused by surrounding a bomb by other bombs. However, since there apparently is no empirical or theoretical data available, this effect cannot be accounted for in the present model.
4. STACK GEOMETRY EFFECT

It is a well accepted fact that the geometry of the explosive stack has a great effect on the peak overpressure and positive impulse at positions "close" to the stack. This effect diminishes with distance from the stack. Even though this fact is well known and accepted, there is very little data available in the current literature which quantitatively describes such a variation.

Apparently Reference 4 describes one of the few attempts to measure the effect of the geometry of charges on peak overpressure and positive impulse. The report is composed basically of peak overpressure and positive impulse measurements using eight charge shapes composed of 50 pounds of RDX composition C-3 explosive which is equivalent to 54.5 pounds of TNT.

It will be assumed that a "standard" high explosive bomb stack can be approximated by a solid stack of explosives with a rectangular solid shape. Therefore, the only shapes considered by the above mentioned report which are pertinent to the model development are the cubical shaped charge and the plate shaped charge. The length of a side of the cubical shaped charge used in the test was 9.6 in. x 9.6 in. while the plate dimensions were 54.1 in. x 9.0 in. x 1.8 in. Pressure and impulse measurements were made at 35 ft., 45 ft., 60 ft., 70 ft., and 80 ft., from the center of the charges, along lines perpendicular
to each face and through the charge center for the cube and the plate, and along lines through the edge and the charge center in a horizontal plane for the cube. These distances from the charge center correspond to scaled distances of 9.22, 11.85, 15.80, 18.43, and 21.06 ft/1b$^{1/3}$, respectively. The average peak overpressures and positive impulses measured at the above locations for the sphere, cube and plate are shown in Tables II and III, respectively (See Tables 1a, 1b, 2a, 2b, 7a, and 7b of Reference 4).

The author of Reference 4 commented that the accuracy of the data did not warrant an attempt at curve fitting. Since the development of the geometry effect portion of the model is based solely on the data from this one report, steps were taken to smooth out some of the inaccuracies of the test data. To reduce the effect on readings by individual differences in recording instruments, system circuitry, and drift from zero calibration point before testing, the ratio of measurements for shaped charges divided by measurements from spherical charge rather than actual measurements was used. In other words, the model development deals with the effect of going from a spherical charge to a rectangular charge (i.e., cube and plate) rather than dealing with the rectangular charges at face value.

A parametric study performed on the data revealed that a reasonable approach to the model development would be to analyze the data with respect to an "area ratio" scheme. The reasons
<table>
<thead>
<tr>
<th>Distance From Charge Center (ft)</th>
<th>Sphere (1)</th>
<th>Cube Face Horizontal</th>
<th>Largest Face Vertical (1) Long Axis (4)</th>
<th>Largest Face Horizontal (1) Long Axis (7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>10.7</td>
<td>11.8</td>
<td>13.6</td>
<td>11.2</td>
</tr>
<tr>
<td>45</td>
<td>7.7</td>
<td>7.5</td>
<td>9.6</td>
<td>8.1</td>
</tr>
<tr>
<td>60</td>
<td>4.8</td>
<td>3.9</td>
<td>5.7</td>
<td>5.1</td>
</tr>
<tr>
<td>70</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>4.0</td>
</tr>
<tr>
<td>80</td>
<td>2.9</td>
<td>2.1</td>
<td>3.1</td>
<td>3.4</td>
</tr>
</tbody>
</table>
### TABLE III

**POSITIVE IMPULSE (PSI-MS) YIELDED BY 50-LB RDX COMPOSITION C-3 CHARGES**

<table>
<thead>
<tr>
<th>Distance From Charge Center (ft)</th>
<th>Sphere (1)</th>
<th>Cube Face Horizontal</th>
<th>Largest Face Vertical</th>
<th>PLATE</th>
<th>Largest Face Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Face (2)</td>
<td>Edge (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>30.2</td>
<td>29.0</td>
<td>37.8</td>
<td>31.4</td>
<td>40.3</td>
</tr>
<tr>
<td>45</td>
<td>28.7</td>
<td>21.1</td>
<td>30.2</td>
<td>34.1</td>
<td>37.3</td>
</tr>
<tr>
<td>60</td>
<td>20.8</td>
<td>14.8</td>
<td>22.8</td>
<td>21.3</td>
<td>24.4</td>
</tr>
<tr>
<td>70</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>23.2</td>
<td>21.2</td>
</tr>
<tr>
<td>80</td>
<td>15.0</td>
<td>20.4</td>
<td>17.2</td>
<td>17.0</td>
<td>18.2</td>
</tr>
</tbody>
</table>
for adopting this scheme for a rectangular charge are as follows:

a. The total energy released to the surrounding atmosphere by a charge resting on a surface should be proportional to the total surface area exposed to the atmosphere (this excludes the face of the charge which is in contact with the surface),

b. The energy experienced by a point, which lies on a line perpendicular to one of the exposed faces of the charge and through the charge center, should be proportional to the total energy released by the detonation of the charge times the ratio of the charge face area nearest to the point to the total charge surface area exposed to the atmosphere. This ratio is hereafter referred to as the "face area ratio" (FAR), and is computed as follows (See Figure 2):

\[
\text{FAR}_{P_1} = \frac{SH \times SD}{2(SH \times SD) + 2(SH \times SL) + (SL \times SD)} \quad (5a)
\]

\[
\text{FAR}_{P_2} = \frac{SH \times SL}{2(SH \times SD) + 2(SH \times SL) + (SL \times SD)} \quad (5b)
\]
Figure 2. Bomb Stack Dimensions
The values of FAR, which correspond to the charge orientations and measurement directions for the cube and plate data of Tables II and III, are \( \text{FAR}_2 = 0.20 \), \( \text{FAR}_4 = 0.0147 \), \( \text{FAR}_5 = 0.440 \), \( \text{FAR}_6 = 0.0227 \), and \( \text{FAR}_7 = 0.1365 \), where the subscripts correspond to the numbered columns of both Tables. The magnitude of FAR will always be greater than 0.00 and less than 0.50. The data in columns 4 and 6 of Tables II and III are ignored in the analysis because it is felt that the values of FAR, for these conditions, are much lower than will ever be experienced in an actual bomb stack. Figure 3 shows the product of overpressure ratios (face overpressure from rectangular stacks divided by overpressure from spherical stack) and FAR plotted against distance from stack center. Figure 4 shows similar curves for impulse ratios. Note that for large distances from charge center these curves approach the value of FAR in each case. These curves not only vary with the value of FAR, but also with the distance from the charge center. At each value of \( R \), or the corresponding value of scaled distance \( Z \), however, a relationship between pressure ratio or impulse ratio and FAR can be established for the three curves shown in each figure. These relationships can be expressed in the form

\[
\frac{P}{P_{\text{sphere}}} = B + C (\text{FAR}) + D (\text{FAR})^2 \tag{6a}
\]

\[
\frac{I}{I_{\text{sphere}}} = F + G (\text{FAR}) + H (\text{FAR})^2 \tag{6b}
\]
Figure 3. Overpressure Ratio x FAR vs. Distance from Charge Center
Figure 4. Impulse Ratio x FAR vs. Distance from Charge Center
where B, C, D, F, G, and H are coefficients which can be solved exactly for any fixed value of \( Z \) since in each case there are three unknowns and three equations.

In these relations data from charge shapes with different equivalent amounts of TNT can be used since the scaled distance \( Z \) can be used.

The solutions to these equations for the values of \( R \) or \( Z \) given in Tables II and III are shown in Table IV which indicates that B, C, D, F, G, and H vary with the value of \( Z \). It was assumed that fifth order polynomials would adequately describe this variation in \( Z \). A least squares polynomial curve fit program was used to fit the available data from Reference 4. Also, the geometry effect must vanish for large \( Z \). Hence there were six data points available for the curve fitting routine (Table IV).

Denote the general form of these polynomials by

\[
B, C, D, F, G, H = C_0 + C_1 Z + C_2 Z^2 + C_3 Z^3 + C_4 Z^4 + C_5 Z^5
\]  

(7)

The computed values of the coefficients are given in Table V.

Figure 5 gives the overpressure and impulse ratios based on Equations (6) and (7) for points along a line perpendicular to the center of one of the vertical faces of a cubical shaped explosive stack, that is, \( \text{FAR} = 0.2 \). Note that the predicted curves fit the data of Reference 4 quite accurately as well as approaching the value 1 for large \( Z \). This is to be
<table>
<thead>
<tr>
<th>Z</th>
<th>PRESSURE RATIO</th>
<th>IMPULSE RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>9.22</td>
<td>0.6867</td>
<td>1.5682</td>
</tr>
<tr>
<td>11.85</td>
<td>0.7166</td>
<td>0.5313</td>
</tr>
<tr>
<td>15.80</td>
<td>1.5938</td>
<td>-6.7473</td>
</tr>
<tr>
<td>(large)</td>
<td>1.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>$C_0$</td>
<td>$C_1$</td>
</tr>
<tr>
<td>---</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>B</td>
<td>19.9156</td>
<td>-5.4922</td>
</tr>
<tr>
<td>C</td>
<td>-161.9033</td>
<td>47.4129</td>
</tr>
<tr>
<td>D</td>
<td>272.6186</td>
<td>-77.9697</td>
</tr>
<tr>
<td>F</td>
<td>5.9069</td>
<td>-1.7159</td>
</tr>
<tr>
<td>G</td>
<td>-1.3016</td>
<td>4.6739</td>
</tr>
<tr>
<td>H</td>
<td>-8.1686</td>
<td>-4.9228</td>
</tr>
</tbody>
</table>
Figure 5. Comparison of Predicted Overpressure and Impulse Ratios to BRL Data for Cubical Shaped Explosive Stack.
expected since these points were used in determining the coefficients. A similar conclusion holds when FAR = 0.44 and FAR = 0.1365. The polynomial expressions are necessary for determining the overpressure and impulse ratios for values of Z and FAR not given explicitly by Reference 4.

Reasonable results for extrapolations to values of Z in the region Z > 9 can be expected because of the experimental data that is available. However, for values of Z less than 9 the predicted values may not be very accurate.

To obtain approximate values for the actual peak overpressure and positive impulse for positions along a line perpendicular to the center of a vertical stack face, the overpressure and positive impulse ratios are multiplied by the peak overpressure and positive impulse respectively. These are obtained from the polynomial fit for curves associated with the surface detonation of a hemispherical stack at the same values of scaled distance Z. Although the overpressure and impulse ratios involve spherical charges, the results from a hemispherical detonation are used to convert these ratios to true peak overpressures and positive impulses. The basic reason for using data associated with a hemispherical charge is that the positive impulse is larger than that associated with a spherical charge for the same value of Z. Presumably this would yield conservative values of positive impulse, which is especially needed in the region Z < 9 where no experimental data is available.
It is assumed that there is very little difference in peak overpressure and positive impulse between the center line mentioned above and the corresponding line on the surface vertically below the center line. Such an assumption will be implicitly assumed from now on for all other horizontal lines emanating from the center of a rectangular stack.

Now that the overpressure and impulse at positions out from the center of a vertical face of a rectangular stack have been modeled, the next step is to predict these parameters out from the vertical edges. The only data available on which this development can be based are the data shown in column 3 in Table II and Table III.

The technique employed in the development of the edge peak overpressure and scaled impulse versus scaled distance was to establish edge to face peak overpressure and edge to face positive impulse relationships as functions of scaled distance. This was achieved by dividing the values in column 3 of Tables II and III by the values in column 2 of the corresponding tables, thereby establishing coordinates for five points for the ratio relationships. These coordinates were put into a least squares polynomial curve fit program to obtain the polynomial coefficients for the polynomials in 2 to describe the ratio relationships. Table VI shows the polynomial coefficients for the relationships that yield the ratio of edge peak overpressure to face peak overpressure and edge impulse to face impulse. Figure 6 shows these relationships as functions of scaled distance.
TABLE VI

POLYNOMIAL COEFFICIENTS FOR THE RATIOS
EDGE PRESSURE/FACE PRESSURE AND
EDGE IMPULSE/FACE IMPULSE

\[
\frac{\text{EDGE PRESSURE}}{\text{FACE PRESSURE}} = \sum_{i=0}^{6} d_i z^i
\]

\[
d_0 = -0.5442047 \times 10^{-1}
\]
\[
d_1 = -0.3279577 \times 10^{-2}
\]
\[
d_2 = 0.3172064 \times 10^{-1}
\]
\[
d_3 = -0.2700095 \times 10^{-2}
\]
\[
d_4 = 0.8668014 \times 10^{-4}
\]
\[
d_5 = -0.1294399 \times 10^{-5}
\]
\[
d_6 = 0.7019624 \times 10^{-8}
\]

\[
\frac{\text{EDGE IMPULSE}}{\text{FACE IMPULSE}} = \sum_{i=0}^{4} e_i z^i
\]

\[
e_0 = -0.3879756 \times 10^{0}
\]
\[
e_1 = 0.2953776 \times 10^{0}
\]
\[
e_2 = -0.1519496 \times 10^{-1}
\]
\[
e_3 = 0.2943603 \times 10^{-3}
\]
\[
e_4 = -0.1946069 \times 10^{-5}
\]

25
These relationships were established from data for a cubical shaped charge where the pressures and impulses off of the faces as functions of $Z$ are equal. The technique employed in the model for predicting edge overpressures and impulses for stacks which are not cubical (i.e., face pressure and impulse as functions of $Z$ are not equal for adjoining faces) is to multiply the ratios, at a given value of $Z$, by the average face value of peak overpressure and impulse at the same value of $Z$.

Now that the peak overpressure and positive impulse relationships as functions of $Z$ have been established along lines perpendicular to the stack faces through the stack center, and along lines extending from the stack center through the stack edges (all lines in a horizontal plane) the parameter values along intermediate lines through the stack center can be established by linear interpolation. This technique is illustrated in Figure 7.

5. BARRICADE EFFECT

It is a well known and accepted fact that a barricade in close proximity to an explosive detonation will significantly affect the peak overpressure and positive impulses at positions "close" to the barricade. Although there has been considerable study dealing with qualitative (i.e., amount of destruction) effects produced by barricaded explosive charges, there has not been much study concerning quantitative (i.e., actual pressure and impulse measurement) effects produced by barricaded explosive charges in the current literature.
OVER Pressures AND POSITIVE IMPULSES KNOWN AS FUNCTIONS OF Z OUT OF STACK FACE

\[
P_i = \frac{\theta}{\theta_E} (P_E - P_{F1}) + P_{F1}
\]

\[
l_i = \frac{\theta}{\theta_E} (l_E - l_{F1}) + l_{F1}
\]

Figure 7. Geometry Effect and Interpolation Technique
The only reference revealed by the literature search which deals directly with the effects produced by a standard (i.e., three adjoining walls perpendicular to each other) barricade is Reference 2. This report gives incident pressures as a function of scaled distance (See Figure 8) for various directions of propagation from a three sided barricade. The barricade length to depth ratio is approximately one (1) and the weight of charge to volume of structure ratio \((W/V)\) (pounds of TNT/ft.\(^3\)) is in the range 0.2 to 2.0. For very large or small \(W/V\) values, the incident pressure versus scaled distance in all directions of propagation from a barricade will be very nearly equal to the results for an unharricaded charge. Results of barricade effects on positive impulse versus scaled distance for various directions of propagation from the barricade considered are not reported here or elsewhere in the literature.

The technique employed in the development of this portion of the model was to establish peak overpressure ratio relationships for the four directions from the barricade center shown in Figure 8 as functions of scaled distance. This was accomplished by dividing the pressure values from the curve for an unconfined surface burst shown in Figure 8 by the pressure values from the curves for the four directions from the barricade center at selected values of scaled distance. These point coordinates were then put into a least squares polynomial curve fit program to obtain coefficients for fourth order polynomials in terms of scaled distance \(Z\) which describe the overpressure ratios for
Figure 8. Exterior Leakage Pressure vs Scaled Distance
each of the four directions from the barricade center shown in Figure 8. The polynomial coefficients are shown in Table VII.

Pressure ratio relationships for directions between those shown are established through linear interpolation as was done in the geometry effects model development.

Since the barricade effect on positive impulse cannot be established because of the lack of reliable data, the model assumes that positive impulse is affected in the same way as is the pressure. Therefore, the above developed overpressure ratio relationships are reused as positive impulse ratio relationships.

The technique to establish the peak overpressure and positive impulse produced by a barricaded explosive detonation is to evaluate the above ratio relationships at the desired direction and scaled distance from the barricade and multiply the computed ratio value by the overpressure and impulse of the bare charge at the same value of scaled distance. If geometry effects are included in the problem, the computed ratio value is multiplied by the peak overpressure and positive impulse which has been previously modified to account for the stack geometry effect.

It should be emphasized that this approach assumes that the explosive stack and barricade are rectangular with stack and barricade sides parallel to each other, that the same vertical line passes through the center of the stack and the barricade, that the ratio of barricade length to barricade depth is approximately equal to one, and that the ratio of the weight of charge to the volume of barricade (lbs/ft^3) is in the range of 0.2 to 2.0.
### TABLE VII

**POLYNOMIAL COEFFICIENTS FOR PRESSURE RATIO VS. Z POLYNOMIALS FOR BARRICADE EFFECT**

<table>
<thead>
<tr>
<th>Direction From Barricade Center</th>
<th>$f_0$</th>
<th>$f_1$</th>
<th>$f_2$</th>
<th>$f_3$</th>
<th>$f_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out Barricade Open End (Line A Figure 7)</td>
<td>$0.1569062 \times 10^1$</td>
<td>$-0.2554407 \times 10^{-1}$</td>
<td>$0.5148503 \times 10^{-3}$</td>
<td>$-0.4569341 \times 10^{-5}$</td>
<td>$0.1281275 \times 10^{-7}$</td>
</tr>
<tr>
<td>Out Barricade Side (Line B Figure 7)</td>
<td>$0.3327308 \times 10^0$</td>
<td>$0.4917871 \times 10^{-1}$</td>
<td>$-0.1202383 \times 10^{-2}$</td>
<td>$0.1121702 \times 10^{-4}$</td>
<td>$0.3175593 \times 10^{-7}$</td>
</tr>
<tr>
<td>Out Barricade Corner (Line C Figure 7)</td>
<td>$0.8900162 \times 10^{-1}$</td>
<td>$0.6300556 \times 10^{-1}$</td>
<td>$-0.1518243 \times 10^{-2}$</td>
<td>$0.1415396 \times 10^{-4}$</td>
<td>$-0.4012012 \times 10^{-7}$</td>
</tr>
<tr>
<td>Out Barricade Back (Line D Figure 7)</td>
<td>$0.1533164 \times 10^0$</td>
<td>$0.3944894 \times 10^{-1}$</td>
<td>$-0.7604483 \times 10^{-3}$</td>
<td>$0.6033857 \times 10^{-5}$</td>
<td>$-0.1556003 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Pressure Ratio = \( \sum_{i=0}^{4} f_i z^i \)
6. SUMMARY

This section has outlined the theory, experimental data and assumptions that have been utilized in developing a workable model for predicting peak overpressures and positive impulses associated with a barricaded HE detonation. The basic approach was to use well known results from detonations of bare hemispherical TNT charges and to modify these results to account for the effects of bombs, rectangular stack configurations and barricades. For those areas where a certain amount of uncertainty prevailed, a conservative approach was adopted so that the predicted values would be larger than what might be actually experienced in practice.

The computer program which follows the theory outlined in this section is described in Appendix I.
SECTION III
FRAGMENTATION

1. INTRODUCTION
The purpose of the fragmentation portion of the program is to formulate an analytical model to describe the fragment dispersion pattern resulting from the explosion of barricaded munitions. The model must consider the dispersions and patterns in terms of fragment velocities, weights, trajectories and ranges.

2. STATEMENT OF PROBLEM
The fragment dispersion pattern of a barricaded explosion is affected primarily by the parameters: a) initial fragment velocity, b) fragment mass, c) spatial position on the bomb, d) initial departure angle, e) fragment trajectories, f) bomb stack geometry, g) and barricade geometry. The analytical model developed with these parameters must yield fragment dispersion patterns that are at least comparable to dispersion data from barricaded explosive tests. The model must be able to yield the range and the striking velocity of the fragments in order to determine the danger of sympathetic detonation of adjacent bomb stacks.
3. SCOPE OF INVESTIGATION

The basic approach for predicting the above parameters for the explosion of a barricaded bomb stack is to proceed from known fragment behavior for a single bomb. Representative single bomb fragment data that are available (References 5-7) for a large variety of bombs is shown in Figure 9. These data consist of: a) the number of fragments per steradian (solid angle), b) the average fragment mass (grams), as a function of the polar angle measured from the nose of the bomb.

Once the initial fragment velocity and fragment weight are known, the trajectory range and striking velocity may be predicted for various angles of departure. These data are first generated for the explosion of a barricaded single bomb and is then correlated with fragment survey data from experimental bomb stack tests such as the "BIG PAPA" tests (Reference 1). The correlation with experimental fragment survey data yields interaction coefficients which indicate the number of single bombs required to yield the fragment data from the stack tests.
Figure 9. Representative Fragmentation Data
For The Explosion of a Single Bomb.
4. ANALYTICAL FRAGMENT MODEL FOR A SINGLE BOMB

a. Fragment Parameters

To develop a model for a bomb stack, it is necessary to first consider the dispersion pattern for a single bomb. The parameters that are required include the mass and initial velocity of the fragments and the number of fragments per steradian that are emitted from the bomb.

Gurney's Theory and Mott and Shapiro's Theory (Reference 7) are available for predicting the initial fragment velocity and mass distribution respectively. Both of these theories have been favorably correlated with experimental data. A significant disadvantage of these theories is that there is no method for predicting how the mass of the fragments vary along the length of the bomb. Hence, a distribution would have to be assumed or the average fragment mass determined from Mott's equation could be used.

Since experimental fragment data for several bombs are available in the literature, as shown in Figure 9, it was considered appropriate to use this information as needed in the model instead of using an exclusively theoretical approach.

By using the data from fragment tests on single bombs, the following parameters are known as functions of the polar angle $\gamma$ (Figure 10): a) fragment mass, b) fragment initial velocity, c) fragment mass distribution along the
$0 \leq \gamma \leq \pi$

$-\pi/2 \leq \beta \leq \pi/2$

Figure 10. Polar and Departure Angles for a Bomb Fragment.
bomb, d) and number of fragments per steradian or solid angle. It is assumed that each fragment initially departs along the line through the bomb center and the point on the bomb casing at which the fragment is located. The angle that this line makes with the horizontal plane is denoted as the departure angle $\beta$.

**b. Fragment Trajectories**

The trajectory equations are necessary to: a) determine if fragments clear the barricade, b) predict the fragment range and impact velocity, c) predict the number of fragments/unit area and mass/unit area as a function of azimuth angle and range from blast. It will be assumed in the model that if fragments do not clear the barricade, they are stopped and no longer considered.

The range and impact velocity will be predicted by using basic equations of mechanics for the trajectory in a finite difference form.

The trajectory of a fragment is shown in Figure 11. The equations below are taken from References 8 and 9 and modified for purposes of this study.
Figure 11. Trajectory of a Fragment.
The forces that act on a body in flight are the drag $F_D$ and the force of gravity $F_g$. Assume that the magnitude of the drag force, acting in the direction opposite to the velocity, is given by

$$F_D = \frac{1}{2} \rho A C_D V^2$$

where

- $\rho_A$ = density of air, slugs/ft.$^3$
- $A$ = cross-sectional area perpendicular to the direction of propagation, ft.$^2$
- $C_D$ = drag coefficient which is a function of shape
- $V$ = speed of fragment, ft./sec.

The components of the drag force in the X and Y directions are given respectively by

$$F_D^X = -F_D \cos \alpha$$
$$F_D^Y = -F_D \sin \alpha$$

where $\alpha$, as shown in Figure 11, is the angle between the horizontal line and the tangent to the trajectory and varies such that

$$\beta \geq \alpha \geq -\alpha_{\text{impact}}$$
The magnitude of the force due to gravity is given by

\[ F_g = mg \]  

(11)

where

\[ m = \text{mass of fragment, slugs} \]
\[ g = \text{gravitational constant, ft./sec}^2 \]

Newton's law yields the following equations of motion:

\[ m\ddot{x} = F_D X \]  

(12a)

\[ m\ddot{y} = F_D Y - F_g \]  

(12b)

where

\[ \ddot{x} = \text{acceleration in X-direction} \]
\[ \ddot{y} = \text{acceleration in Y-direction} \]

If the ballistic coefficient \( c \) is defined by

\[ c = \frac{\rho A C_D}{2m} \]  

(13)

then Equations (12a) and (12b) become

\[ \ddot{x} = -cv^2 \cos\alpha \]  

(14a)

\[ \ddot{y} = -cv^2 \sin\alpha - g \]  

(14b)
Since
\[
\frac{dx}{dt} = v \cos \alpha \tag{15a}
\]
\[
\frac{dy}{dt} = v \sin \alpha \tag{15b}
\]

Equations (14a) and (14b) become
\[
\frac{d(v \cos \alpha)}{dt} = -cv^2 \cos \alpha \tag{16a}
\]
\[
\frac{d(v \sin \alpha)}{dt} = -cv^2 \sin \alpha - g \tag{16b}
\]

By performing the indicated time derivatives, these equations can be written in the form
\[
\dot{v} \cos \alpha - v \dot{\alpha} \sin \alpha = -cv^2 \cos \alpha \tag{17a}
\]
\[
\dot{v} \sin \alpha + v \dot{\alpha} \cos \alpha = -cv^2 \sin \alpha - g \tag{17b}
\]

By multiplying Equation (17b) by \(\cos \alpha\) and Equation (17a) by \(-\sin \alpha\) and adding, we get the following equation
\[
v \ddot{\alpha} = -g \cos \alpha \tag{18}
\]
or
\[
d\alpha = \frac{-g \cos \alpha}{v} \, dt \tag{19}
\]

Inverting this equation yields
\[
dt = \frac{-v}{g \cos \alpha} \, d\alpha \tag{20}
\]

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By combining Equations (16a) and (20), we get

\[ d(v \cos \alpha) = \frac{c v^3}{g} \, d\alpha \]  

(21)

Multiply Equation (20) on the left hand side by \( \frac{dx}{dt} \) and on the right by its equivalent \( (V \cos \alpha) \) from Equation (15a)

\[ dx = -\frac{v^2}{g} \, d\alpha \]  

(22)

Similarly from Equations (15b) and (20)

\[ dy = -\frac{v^2}{g} \tan \alpha \, d\alpha \]  

(23)

In summary, the governing equations for the time, velocity and coordinates of the fragment, with \( \alpha \) chosen to be the independent variable, are

\[ dt = \frac{V}{g \cos \alpha} \, d\alpha \]  

(24a)

\[ d(v \cos \alpha) = \frac{c v^3}{g} \, d\alpha \]  

(24b)

\[ dx = -\frac{v^2}{g} \, d\alpha \]  

(24c)

\[ dy = -\frac{v^2}{g} \tan \alpha \, d\alpha \]  

(24d)

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The initial conditions are

\[ a \big|_{t=0} = b \quad (25a) \]
\[ v \big|_{t=0} = v_0 \quad (25b) \]
\[ x \big|_{t=0} = 0 \quad (25c) \]
\[ y \big|_{t=0} = y_0 \quad (25d) \]

For a numerical solution of \( V, x \) and \( y \) in terms of \( \alpha \), Equations (24b), (24c) and (24d) are written in a finite difference form as follows:

\[ \Delta V = V(\tan \alpha + \frac{cV^2}{g \cos \alpha}) \Delta \alpha \quad (26a) \]
\[ \Delta x = -\frac{V^2}{g} \Delta \alpha \quad (26b) \]
\[ \Delta y = -\frac{V^2}{g} \tan \alpha \Delta \alpha \quad (26c) \]

After each increment in \( \alpha \), the coordinates of the fragment can be determined and the computation stopped once the particle strikes the barricade or the ground.

c. Fragment Ballistic Coefficients

In order to integrate the trajectory equations of the previous section, the ballistic coefficient \( c \) must
be determined for each fragment. It is more convenient
to express Equation (13) in the form
\[ c = \frac{\gamma_A C_D A}{2w_F} \quad (27) \]

where

\[ \gamma_A = \text{weight density of air, lb./ft.}^3 \]
\[ w_F = \text{weight of fragment, lb.} \]

The weight density of air is assumed known. \( C_D \) is
expected to take on values ranging from 0.3 to 2.0 and
will be assumed constant for any fragment. Reference 10
indicates a value of 0.6 for the drag coefficient, \( C_D \),
as most appropriate for random steel fragments from an
exploded bomb case. The remaining term that is needed
is the ratio \( A/V_p \).

Since there is some disagreement as to appropriate
values for this ratio, consider, for purposes of illustration
only, a steel cube where the length of any edge is \( l \).
Then the cross-sectional area \( A \) must lie in the region
\[ l^2 \leq A \leq 3l^2 \cos(54^\circ 44') \]
If the density is taken to be 500 lb./ft.\(^3\), then
\[ w_F = 500l^3 \]
and
\[ l = \left[ \frac{w_F}{500} \right]^{1/3} \]
The range for the area to weight ratio is then given by

\[
\frac{0.0159}{\frac{w}{W}} \leq \frac{A}{W} \leq \frac{0.0275}{\frac{w}{W}} \quad (\text{ft}^2),
\]

For irregular fragments such as those formed by the rupture of a bomb case, the area to weight ratio would be expected to be larger. An average value of

\[
\frac{A}{\frac{w}{W}} = \frac{0.0345}{\frac{w}{W}^{1/3}} \quad (\text{ft}^2) \quad (28a)
\]

or

\[
\frac{A}{\frac{w}{W}} = \frac{0.232}{\frac{w}{W}^{1/3}} \quad (\text{ft}^2) \quad (28b)
\]

has been suggested by Reference 11 where \( \frac{w}{W} \) is the weight of the fragment in grams. This average value has been used in connection with the numerical analysis for the trajectory portion of the program in which case the fragment ballistic coefficient becomes

\[
c = \frac{0.00532}{\frac{w}{W}^{1/3}} \quad (29)
\]
d. Coordinate System

Most typical bomb stack barricades are rectangular with three closed sides and one open as shown in Figure 12. For convenience, we adopt the coordinate system shown in Figure 13 where $\theta = 0$ corresponds to the line coming from the center of the bomb out the open side of the barricade. As before, $\beta$ is the angle that a given line makes with the horizontal plane. The bomb is assumed to be horizontal and $\theta_B$ denotes the orientation of the polar axis of the bomb.

The number of fragments per steradian that are emitted from a bomb (Figure 9) is given as a function of the polar angle $\gamma$. Since the analysis will be performed using the coordinates $\theta$ and $\beta$ it is necessary to obtain a relation which expresses $\gamma$ in terms of these two coordinates. This is easily handled using vector algebra.

In connection with Figure 13, let $\vec{e}_1$, $\vec{e}_2$, and $\vec{e}_3$ be unit base vectors in the directions $X$, $Y$, and $Z$ respectively. Denote a unit vector in the direction of $\vec{V}_0$ by $\vec{e}_0$ and a unit vector out the nose of the bomb by $\vec{e}_B$. Then

$$\vec{e}_0 = \cos\beta \cos\theta \vec{e}_1 + \cos\beta \sin\theta \vec{e}_2 + \sin\beta \vec{e}_3 \quad (30a)$$

$$\vec{e}_B = \cos^2\theta \vec{e}_1 + \sin\theta \vec{e}_2 \quad (30b)$$
Figure 12. Typical Bomb Stack Barricade.
Figure 13. Coordinate System for a Regular Barricade Enclosing a Single Bomb.
Using the definition of the cross-product,

\[ |\vec{e}_0 \times \vec{e}_B| = |\vec{e}_0| |\vec{e}_B| \sin \gamma \quad (31) \]

Since the magnitudes of \( \vec{e}_0 \) and \( \vec{e}_B \) are both one, this relation yields

\[ \gamma = \arcsin (\cos^2 \theta + \sin^2 \beta \sin^2 (\theta - \theta_B))^{1/2} \quad (32) \]

Let \( \Psi(\gamma) \) denote the number of fragments per steradian ejected by the bomb. Then the total number of fragments ejected out an arbitrary region is given by

\[ N = \int \Psi(\gamma) \, d\omega \quad (33) \]

where the element of steradian \( d\omega \) is given by

\[ d\omega = \cos \beta \, d\beta \, d\theta \quad (34) \]

For the region bounded by the coordinates \( \theta = \theta_1, \theta = \theta_2, \beta = \beta_1 \) and \( \beta = \beta_2 \), the total number of fragments would be

\[ N_{\theta_1, \theta_2, \beta_1, \beta_2} = \int_{\beta_1}^{\beta_2} \int_{\theta_1}^{\theta_2} \Psi(\gamma) \cos \beta \, d\theta \, d\beta \quad (35) \]

If the average number of fragments per steradian over this region is denoted by \( \Psi_{12} \), then the total number of fragments would be

\[ N_{\theta_1, \theta_2, \beta_1, \beta_2} = \Psi_{12} (\theta_2 - \theta_1) (\sin \beta_2 - \sin \beta_1) \quad (36) \]
Usually the coordinates of a region such as the one defined above are given by

\begin{align*}
\theta_2 &= \theta + \frac{\Delta \theta}{2} \\
\theta_1 &= \theta - \frac{\Delta \theta}{2} \\
\beta_2 &= \beta + \frac{\Delta \beta}{2} \\
\beta_1 &= \beta - \frac{\Delta \beta}{2}
\end{align*}

(37a) – (37d)

If \( \Delta \theta \) and \( \Delta \beta \) are small enough, it would be reasonable to choose as average values for the initial velocity, number of fragments, and fragment mass, those values given in Figure 9 for the polar angle \( \gamma(\theta, \beta) \). These parameters could then be used in connection with the trajectory equations derived previously to determine probable impact velocities and coordinates.

e. **Barricade Geometry Considerations**

To include barricade geometry affects, a more general barricade composed of straight wall segments was considered. This introduces very little additional complicating features and allows some flexibility so that optimization of barricade design could be considered in the future.

The geometry of the wall segments of the barricade is described in terms of cylindrical coordinates \( R, \theta, \) and \( Z \) with the origin placed at the bomb center. It is
assumed that the wall remains intact as far as the fragments are concerned so that if the fragment strikes a barricade wall, it stops. Thus, for particular azimuth and departure angles, the existence of a wall for that azimuth must first be determined; if a wall is present its height must be known so that the question of whether or not the fragments have cleared that portion of the barricade can be answered.

The problem to be solved is illustrated in Figure 14. For a given azimuth angle of trajectory $\theta$, the distance to the wall $R_3$ must be determined. The known quantities are $R_1$, $R_2$, $\theta_1$, $\theta_2$, and the height of the barricade $z_1$, $z_2$, and $z_3$. Since two sides $(R_1, R_2)$ and the included angle ($\Delta\theta$) are known, the law of tangents can be used to find $\phi$ and $\psi$:

\[
\phi = \frac{1}{2} (180 - \Delta\theta) + \tan^{-1} \left\{ \frac{R_1 - R_2}{R_1 + R_2} \tan \frac{1}{2} (180 - \Delta\theta) \right\} \quad (38a)
\]

\[
\psi = \frac{1}{2} (180 - \Delta\theta) - \tan^{-1} \left\{ \frac{R_1 - R_2}{R_1 + R_2} \tan \frac{1}{2} (180 - \Delta\theta) \right\} \quad (38b)
\]

The included angle between $R_3$ and the barricade wall is then

\[
\delta = 180 - (\phi + (\theta_2 - \theta)) \quad (39)
\]
Figure 14. General Barricade Configuration
The law of sines for a plane triangle can then be used to obtain the required distance to the barricade

$$R_3 = R_2 \frac{\sin\phi}{\sin\gamma} \quad (40)$$

f. Distribution of Fragments

The previous sections have outlined a method for computing the impact point and velocity for a group of fragments which are assumed to have identical mass and velocity. The total number of fragments in this group depend on the azimuth angle $\theta$, departure angle $\beta$ and the size of the region defined by $\theta_1$, $\theta_2$, $\beta_1$ and $\beta_2$. In actual fact all of these fragments will not land at one spot but in general, they will be distributed over some area. The following discussion presents a method that should give reasonable results that can be compared with experimental data.

For a given $\theta$, a series of impact ranges will be determined together with corresponding values of mass, number of fragments and impact velocities. The number of impact ranges will correspond directly to the number of increments used to cover the range of $\beta$. Suppose the ranges are ordered in an increasing sequence

$$0 \leq R_1 \leq R_2 \leq \ldots \leq R_j \leq \ldots \leq R_N.$$  

To illustrate the procedure, consider the fragment parameters associated with the range $R_2$. A reasonable approximation

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is to distribute these fragments over the area bounded by the coordinates $R_{1,2}$, $R_{2,3}$, $\theta_1$ and $\theta_2$ (See Figure 15) where

$$\theta_1 = \theta - \frac{\Delta \theta}{2}$$  \hspace{1cm} (41a)  

$$\theta_2 = \theta + \frac{\Delta \theta}{2}$$  \hspace{1cm} (41b)  

$$R_{1,2} = \frac{R_1 + R_2}{2}$$  \hspace{1cm} (41c)  

$$R_{2,3} = \frac{R_2 + R_3}{2}$$  \hspace{1cm} (41d)  

The area $A_2$ covered by such a segment is

$$A_2 = \frac{1}{2} (R_{2,3}^2 - R_{1,2}^2) \Delta \theta$$  \hspace{1cm} (42)  

Similarly, the area associated with the range $R_J$ would be

$$A_J = \frac{1}{2} (R_{J,J+1}^2 - R_{J-1,J}^2) \Delta \theta$$  \hspace{1cm} (43)  

where

$$R_{J-1,J} = \frac{1}{2} (R_{J-1} + R_J)$$  \hspace{1cm} (44a)  

$$R_{J,J+1} = \frac{1}{2} (R_J + R_{J+1})$$  \hspace{1cm} (44b)
Figure 15. Approximate Impact Areas.
For the furthest impact point $R_N$, choose

$$R_{N-1,N} = \frac{1}{2} (R_{N-1} + R_N) \quad (45a)$$

$$R_{N,N+1} = 2R_N - R_{N-1,N} \quad (45b)$$

With the impact areas defined by Equation (43), both the number of fragments and the total weight per unit area can be determined by dividing the total number of fragments and the total weight landing at a particular range by the corresponding area, that is,

$$\left( \frac{\text{Number}}{\text{Unit Area}} \right)_J = \frac{(\text{Number of fragments landing at } R_J)}{A_J} \quad (46a)$$

$$\left( \frac{\text{Weight}}{\text{Unit Area}} \right)_J = \frac{(\text{Number})}{(\text{Unit Area})_J} \text{ (Average weight of fragment landing at } R_J) \quad (46b)$$
5. ANALYTICAL FRAGMENT MODEL FOR A STACK OF BOMBS

The fragmentation model developed in the preceding discussion will yield fragment dispersions for a single bomb. The theory is expected to hold for a stack of bombs where the origin of the coordinate system is placed at the center of the stack. However, interaction effects should produce a number of fragments for a given impact area somewhat less than the product of the number of bombs and the number of fragments produced by a single bomb. The exact effect must be determined experimentally.

An illustration of the fragment survey areas from Phase II of the BIG PAPA Tests is shown in Figure 16. For each one of the fragment survey areas, fragments were counted and weighed. By computing the number of fragments and their weights for the same area, a "correlation" or "effective number of bombs" factor may be computed for each area. Hopefully, the variation of the correlation factor from survey area to survey area would lie within a tolerable limit. With the "effective number of bombs" EFNB, determined, the fragment distribution for a single bomb can be multiplied by EFNB to obtain the distribution pattern for the stack of bombs.
Figure 16. Fragmentation Survey Plan for Phase II of the Big Papa Tests.
6. SUMMARY

This section has presented a model that predicts the impact velocity and distribution of fragments for a barricaded or unbarri-caded bomb stack.

Data in the form of initial fragment velocity, size and distribution for each bomb, which is available in References 5 and 6, is used. The fragments that are ejected within a small area of the bomb case are assumed to have identical initial conditions as far as the trajectory equations are concerned. Average values for the mass and initial velocities of the fragments are used together with a ballistic coefficient that was determined experimentally. If the group of fragments clear the barricade then the point and velocity of impact can be determined. For comparison with experimental data, this group of fragments is assumed to be distributed over an adjacent area determined by the increments in azimuth angles and points of impact of other groups of fragments along the same azimuth angle.

The same procedure is used for a stack of bombs except that the total number of bombs must be modified to account for interaction effects. The degree of modification must be determined experimentally from existing experimental data.

The computer program that follows the theory of this section is described in Appendix II.
SECTION XV
CRATERING

1. INTRODUCTION

A considerable amount of data have been accumulated that relate the size of craters to the yield of explosives, primarily for bare spherical and hemispherical charges. Most of the work accomplished prior to 1961 has been summarized in Reference 12. Crater measurements of later detonations of major importance have been made and include "Operation Snow Ball" (Reference 13), "Operation Distant Plain" (References 14 and 15) and "Operation Sailor Hat" (Reference 16). These shots cover a wide range of explosive yield and soil types, a fact which produced a considerable amount of diversity in crater sizes.

Predicting the shape of explosion-produced craters and the distribution of the ejected material has been a matter of some concern for several years (References 17-20). Generally, the approach has been to assume a non-dimensional relation between characteristic dimensions of the crater and the explosive yield raised to some power. The resulting relation, called a scaling law, is then used to extrapolate to new regions of interest.

These scaling laws, even though set up to form a "best possible" fit for existing data, must be modified for changes in earth media. Furthermore, it has become rather apparent from the shots at the Suffield Experimental Station and from
"Operation Sailor Hat" that any one scaling law will produce reasonable results over a limited yield range.

The charge shapes in the tests mentioned above are exclusively spherical or hemispherical. Results for other shapes such as rectangular parallelepipeds that would be of more significance for this report are almost non-existent except for the "BIG PAPA" test (Reference 1).

In light of the almost total absence of analytical work in this area and because of the different shaped charge of interest in this project, specifically that associated with bomb stacks, it seemed appropriate to develop an elementary model using basic principles of mechanics. Although the approach adopted in this section freely uses past empirical relations, such an analysis could form the basis of a more rigorous development in the future if experiments could be devised to adequately determine the governing parameters.

As for the past sections, all charges will be assumed to be resting on the surface.
2. THE EFFECT OF CHARGE SHAPE

a. Preliminary Comments

When an explosion is detonated, the total available energy is divided into various categories: blast wave, heat, and kinetic energy of the material itself to mention the most obvious ones. Apparently the blast wave does not contribute to cratering, but rather, it causes a shock wave to be instigated in the earth (Reference 21). The major source of cratering action must then be the kinetic energy of the explosive material. By momentum transfer, energy is transferred to the earth media elements located on the surface and adjacent to the explosive, and by propagation within the neighboring region, earth particles are ejected and a crater is formed.

Because of the confining effect of the explosive material on itself, it seems plausible that the initial direction of propagation of explosive elements would be towards the surface of the explosive. Furthermore, because of air friction, interaction with other elements and so forth, the velocity of each element would decrease with time. Hence, those elements closest to the earth would be the most effective as far as cratering is concerned.

b. Basic Assumptions

The above observations suggest that it is appropriate to make several simplifying assumptions to make an investi-
gation of charge shape amenable to analysis. Because of the preliminary nature of this work, the following assumptions are made with the full knowledge that they may be unjustified; however, the resulting analysis should yield a reasonable approximation:

(1) Assumption 1

Just the bottom half of the charge contributes to the cratering phenomenon.

(2) Assumption 2

The velocities of all elements in the bottom half of the charge are the same immediately after detonation and are directed vertically downward. This implies that if $v_0$ is the initial speed of all elements in the charge, then the initial kinetic energy per unit mass

$$ e_o = \frac{1}{2} v_o^2 $$

is independent of position.

(3) Assumption 3

The friction force is constant and is the same within and outside the original outline of the charge.

Such an assumption yields a couple of interesting results. First it can be shown that the kinetic energy/unit mass $e$ decays linearly with distance by letting $z$ denote the distance of an element above the surface at any time $t$ (See Figure 17). From Newton's Law, the acceleration is constant

$$ \ddot{z} = a_o $$

(48)
Figure 17. Notation for Typical Charge Shape
so that the velocity and position respectively become

\[ v = \dot{z} = a_0 t - v_0 \]  
\[ z = \frac{a_0 t^2}{2} + v_0 t + z_0 \]

(49a) (49b)

By a series of substitutions

\[ e = \frac{1}{2} v^2 \]
\[ = \frac{1}{2} v_0^2 - a_0 z_0 + a_0 z \]

(50)

and hence, \( e \) decreases as \( z \) decreases.

Secondly, if an element is initially at the critical distance \( L \) above the surface where

\[ L = \frac{v_0^2}{2a_0} \]

(51)

then \( v \) (and hence, \( e \)) is zero when that particular element reaches the surface. In other words, all elements above the plane \( z=L \) and in the bottom half of the charge will not contribute to the cratering action.

(4) Assumption 4

For the range of explosive yield considered in this report, the height of the center of gravity of the charge \( z_{CG} \) is below the plane \( z=L \) so that all parts of the bottom half of the charge will contribute to cratering.
(5) Assumption 5

At the interface between the surface of the earth and the explosive, the loss of kinetic energy is negligible.

c. Cratering Factor

The energy \( e_s \) per unit mass delivered at the surface of the earth by elements originally at a distance \( z_0 \) above the surface is obtained from Equation (50):

\[
e_s = e \bigg|_{z=0} = \frac{1}{2} \frac{v_o^2}{z_0^2} \left( 1 - \frac{2z_0}{v_o^2} \right) \tag{52a}
\]

or, after using Equation (51)

\[
e_s = e_o \left( 1 - \frac{z_0}{L} \right) \tag{52b}
\]

The total kinetic energy of the charge is

\[
E_T = \int_B e_o \, dm = Me_o \tag{53}
\]

where \( M \) denotes the total mass of the charge and \( B \) the region occupied by the total charge. On the other hand, the kinetic energy delivered to the surface of the earth is

\[
E_s = \int_{B_L} e_s \, dm = \frac{M}{2} e_o \left( 1 - \frac{z_{CG}}{2L} \right) \tag{54}
\]
where $B_L$ denotes the bottom half of the charge and $z_{CG}$ is the distance to the center of mass of the total charge.

A cratering factor $C_F$ can be defined as the ratio of the kinetic energy reaching the earth's surface to the total kinetic energy, that is

$$C_F = \frac{E_S}{E_T}$$

$$= \frac{1}{2} \left[ 1 - \frac{z_{CG}}{2L} \right]$$  \hspace{1cm} (55)

According to assumption 4, the cratering factor must lie in the range

$$\frac{1}{4} \leq C_F \leq \frac{1}{2}$$  \hspace{1cm} (56)

Equation (55) implies that for two charges with the same total kinetic energy, the charge with the lowest center of mass will be the most effective as far as cratering is concerned.

d. Charge Shapes and Non-dimensional Variables

If $W$ denotes the yield of an explosion in terms of an equivalent weight of TNT, then immediately after detonation, assume that the total kinetic energy of the explosive is directly proportional to $W$ and is independent of the charge shape, that is

$$E_T = \mu W$$  \hspace{1cm} (57)
where \( u \) is a constant. The energy delivered to the surface is then

\[
E_s = C_F uW
\]  \hspace{1cm} (58)

To eliminate the unknown factor \( u \), reference charges can be introduced. For each charge shape, let \( W_o \) denote a reference yield and define

\[
E^o_s = C_{Fo} uW_o
\]  \hspace{1cm} (59)

where

\[
C_{Fo} = \frac{1}{2} \left( 1 - \frac{z^o_{CG}}{L} \right)
\]  \hspace{1cm} (60)

and \( z^o_{CG} \) is the height of the center of mass of the reference charge.

If the following non-dimensional variables are introduced:

\[
T = \frac{W}{W_o}
\]  \hspace{1cm} (61a)

\[
K = \frac{E_s}{E^o_s}
\]  \hspace{1cm} (61b)

\[
C^F_o = \frac{C_F}{C_{Fo}}
\]  \hspace{1cm} (61c)

then

\[
K = C^F_o T
\]  \hspace{1cm} (62)
and the factor \( \mu \) is not present. If \( z_{CG} \) and \( z_{CG}^0 \) are both much smaller than \( L \), then \( C_0^e \) is approximately equal to one.

For a given class of charge shapes, the total yields can be used rather than the dimensions \( L, z_{CG} \) and \( z_{CG}^0 \). One such set is illustrated in Figure 18 and is characterized by the fact that the volume is proportional to the cube of one dimension in each case. This restricts the group of triangular and cylindrical prisms (which includes rectangular parallelepipeds) to that for which the surface contact area \( A_s \) is proportional to the square of the height \( h \). In effect this implies that, for example, in the case of triangular prisms, we can let the sizes change but the shapes must be similar to the reference shape.

Since the yield is directly proportional to the volume, it can also be said that for this class of shapes the distance to the center of mass is proportional to the cube root of the yield. Thus, if we let

\[
W_L = W \bigg| z_{CG} = L
\]

(63)

where \( W_L \) is the weapon yield for a charge shape in the same class as those in Figure 18 and whose center of mass is at a height \( L \) above the surface, then
Figure 18. A Set of Four Charge Shapes

Aₕ is proportional to h²
\[ C_F = \frac{1}{4} \left[ 2 - \left( \frac{W}{W_L} \right)^{1/3} \right] \]  

(64a)

\[ C_{Fo} = \frac{1}{4} \left[ 2 - \left( \frac{W_0}{W_L} \right)^{1/3} \right] \]  

(64b)

\[ C_0^F = \frac{\left[ 2 - \left( \frac{W}{W_L} \right)^{1/3} \right]}{\left[ 2 - \left( \frac{W_0}{W_L} \right)^{1/3} \right]} \]  

(64c)

In the absence of experimental results that would determine \( W_L \), a value of \( 10^6 \) lbs. of TNT has been chosen for \( W_L \) for each of the charge shapes shown in Figure 18.
3. CRATER AND EJECTA FORMATIONS

a. Basic Shape Parameters

The most significant parameters associated with the description of the crater and ejecta shape are shown in Figure 19. If the origin of a cylindrical coordinate system is placed on the original surface at the center of the crater, then the crater depth is assumed to be adequately described by the parabola

\[ z = a + bR + cR^2 \]  \hspace{1cm} (65)

where \( a, b \) and \( c \) are constants and \( R \) is the distance from the origin. If \( D_a \) denotes the apparent depth of the crater at the origin, \( R_a \) the apparent radius at the original surface and if we assume that

\[ \frac{\partial z}{\partial R} \bigg|_{R=0} = 0 \]  \hspace{1cm} (66)

then the crater depth is described by

\[ x = D_a \left( 1 - \frac{R^2}{R_a^2} \right) \quad 0 \leq R \leq R_a \]  \hspace{1cm} (67)

The maximum slope of the crater, which will be of significance later in connection with energy dissipation, occurs at the intersection of the crater with the original surface and is given by

\[ \frac{\partial z}{\partial R} \bigg|_{R=R_a} = -2 \frac{D_a}{R_a} \]  \hspace{1cm} (68)
An aid in visualizing this condition is to note, as shown in Figure 20, that a cavity with this slope everywhere would be a cone with twice the depth of the actual crater.

After a detonation, particles that were originally within the boundary of the crater are located immediately beyond the top rim of the crater on the surface of the earth and this material that has been thrown out is called the ejecta. The depth of the ejecta as a function of distance from the center of the crater was assumed to be the same as that given in Reference 22 for nuclear detonations. This relation is

\[ H_e = \sigma D_a \left( \frac{R}{R_a} \right)^\beta, \quad R \geq R_a \]  

(69)

where \( \sigma \) and \( \beta \) are parameters that depend on the earth media.

If the earth media is assumed to be incompressible, then the volume of the crater should be the same as the volume of the ejecta. Such a relation can be used to express \( \sigma \) in terms of \( \beta \).

The volume of the crater is

\[
V_c = \int_0^{R_a} \int_0^{2\pi} \int_0 R \, dx \, d\theta \, dR
\]

\[
= 2\pi \int_0^{R_a} D_a R \left( 1 - \frac{R^2}{R_a^2} \right) dR
\]
or

\[ V_c = \frac{\pi}{2} D_a R_a^2 \]  \hspace{1cm} (70)

Similarly, if \( \hat{\beta} > 2 \), the volume of the ejecta \( V_e \) is given by

\[ V_e = \int_{R}^{R_j} \int_{0}^{2\pi} \int_{0}^{H_a} R \, dz \, d\theta \, dR 
\]

\[ = 2\pi \int_{R}^{R_j} \sigma D_a R_a^\hat{\beta} \, dR \]

or

\[ V_e = \frac{2\pi}{\hat{\beta} - 2} \sigma D_a R_a^2 \]  \hspace{1cm} (71)

Equating the two volumes yields the relation

\[ \sigma = \frac{1}{4} (\hat{\beta} - 2) \]  \hspace{1cm} (72)

so that, from Equation (69)

\[ H_e = \frac{D_a}{4} (\hat{\beta} - 2) \left( \frac{R_a}{R} \right)^\hat{\beta} \]  \hspace{1cm} (73)

Reference 22 suggests the values \( \sigma = 0.5 \) and \( \hat{\beta} = 3.9 \) for soil, and \( \sigma = 0.3 \) and \( \hat{\beta} = 3.1 \) for rock. However,
Equation (72) yields the value \( \hat{\beta} = 4.0 \) when \( \sigma = 0.5 \) and \( \hat{\beta} = 3.2 \) when \( \sigma = 0.3 \). Such a variation is negligible in view of the disparity in test results.

Of more significance are experimental values for the height of the crater lip. From Equation (73) the analytical expression is

\[
H_0 \bigg|_{R=R_a} = \frac{D_R}{4} (\hat{\beta} - 2) \tag{74}
\]

According to results tabulated by Vortman (Reference 16), the 100-ton Suffield Experimental Station hemispherical shot in clay yielded a crater lip height which was 27 per cent of the crater depth, which produces a value of 3.1 for \( \hat{\beta} \). On the other hand, for the 500-ton Sailor Hat shot on basalt rock, the height of the crater lip was 36 per cent of the crater depth, which yields a value of 3.4 for \( \hat{\beta} \).

These results imply that the values of \( \hat{\beta} \) do not assume the same range of values for conventional high explosives as for nuclear explosives. Furthermore, for conventional explosives the variation in \( \hat{\beta} \) may be quite small for changes in earth media.

For this project, a reference value of 3.1 was chosen for \( \hat{\beta} \) for soil.

It seems plausible to assume that most of the material will move radially outward. For the next section it is necessary to know the positions of the centroids of crater
and ejecta elements that subtend a small angle $\Delta \theta$ (See Figure 21). The crater and ejecta volume elements are

$$
\Delta V_c = \Delta \theta \int_0^R \int_0^R \pi R \, dx \, dR
$$

$$
= \Delta \theta \frac{D_a R^2}{4}
$$

$$
= \Delta V_e
$$

(75)

The coordinates to the centroids of these elements are defined as follows:

$$
\Delta V_c \ R_c = \Delta \theta \int_a^0 \int_0^R \pi R^2 \, dx \, dR
$$

(76a)

$$
\Delta V_c \ x_c = \Delta \theta \int_a^0 \int_0^R \pi xR \, dx \, dR
$$

(76b)

$$
\Delta V_e \ R_e = \Delta \theta \int_0^H \int_a^R \pi R^2 \, dz \, dR
$$

(76c)

$$
\Delta V_e \ z_e = \Delta \theta \int_0^H \int_a^R \pi R \, dz \, dR
$$

(76d)

The results for $\beta > 3.0$ are:

$$
R_c = \frac{8}{15} \ R_a
$$

(77a)

$$
x_c = \frac{D_a}{3}
$$

(77b)
Figure 21. Centroids of Crater and Ejecta Elements
As an example, the centroid for the ejecta for $\beta = 3.2$ is given by

$$R_e = \frac{\hat{\beta} - 2}{\hat{\beta} - 3} R_a \quad (77c)$$

$$z_e = \frac{(\hat{\beta} - 2)^2 D_a}{(\hat{\beta} - 1) 16} \quad (77d)$$

b. Energy Considerations

Suppose an element with initial velocity $v_o$ moves a horizontal distance $X$ and a vertical distance $H$ as shown in Figure 22. If just the effect of gravity is considered in the equations of motion, then from the equation of the trajectory it can be shown that

$$H = -\frac{g}{2} \frac{X^2}{v_o^2 \cos^2 \beta} + X \tan \beta \quad (79)$$

For a conservative estimate on the energy requirement, choose $\beta$ with $H$ and $X$ considered fixed such that $v_o$ is a minimum, that is, set

$$\frac{dv_o}{d\beta} = 0 \quad (80)$$
Figure 22. Trajectory of an Element
This yields

$$\tan \beta = \frac{v_o^2}{gX}$$

which can be written in the alternate form

$$\frac{1}{\cos^2 \beta} = \frac{g^2x^2 + v_o^4}{g^2x^2}$$

By substituting Equations (81) and (82) into (79) we get

$$v_o^2 = gH \left[ 1 + \sqrt{1 + \frac{x^2}{H^2}} \right]$$

(83)

Only the positive sign is appropriate. If $X/H < < 1$, we have the classical vertical motion relation

$$v_o^2 = 2gH, \quad X/H < < 1$$

(84)

whereas, if $X/H > > 1$, we get

$$v_o^2 = gX, \quad X/H > > 1$$

(85)

Suppose that on the average, an element moves from the centroid of a crater element to the centroid of an ejecta element. Then

$$X = R_e - R_c$$

$$= R_a \left( \frac{\beta - 2}{\beta - 3} - \frac{8}{15} \right)$$

(86a)
\[ H = x_o + x_c \]
\[ = D_a \left( \frac{1}{3} + \frac{1}{16} \left( \frac{\omega - 2}{\omega - 1} \right)^2 \right) \]  
\( (86b) \)

For the range \( 3.1 \leq \omega \leq 3.6 \), the smallest value of \( X/H \)
occurs at \( \omega = 3.6 \). Hence
\[ \frac{X}{H} \geq 5.5 \frac{R_a}{D_a}, \quad 3.1 \leq \omega \leq 3.6 \]  
\( (87) \)

For actual shots, it is generally true that the apparent radius is
at least twice the apparent depth so that
\[ \frac{X}{H} \geq 11 \]  
\( (88) \)

Because of the diversity of experimental data, the inequality
associated with Equation (85) can be considered satisfied
and hence, with the use of Equation (86a)
\[ v_o^2 = g R_a \left( \frac{\omega - 2}{\omega - 3} \right) \]  
\( (89) \)

In order that this expression always be positive, we must
have \( \omega > 3 \) which is the same restriction imposed previously
in connection with centroids.

If the mass density of the earth media is denoted by
\( \rho \), the total initial kinetic energy of the earth elements
is approximated by
\[ E_G = \frac{1}{2} \rho v_o v_o^2 \]
\[ = \frac{1}{2} \rho g D_a R_a \left( \frac{\omega - 2}{\omega - 3} \right) \]  
\( (90) \)
It should be emphasized that $E_G$ is not the same as the energy input $E_s$ since a portion of the latter will be dissipated into the ground in the form of heat.

c. Dimensional Considerations

To describe the shape of the crater it is necessary to know the ratio $D_a/R_a$. Postulate that this ratio primarily depends (Reference 23) on the following parameters: (1) an earth media viscosity $\nu'$, (2) mass density of the earth media $\rho$, (3) the kinetic energy input $E_s$, and (4) the apparent crater radius $R_a$. Such a dependence can be expressed analytically by

$$D_a/R_a = f'(\rho, E_s, \nu', R_a)$$

where $f'$ is the unknown function. If $[M]$, $[L]$ and $[T]$ denote the fundamental dimensions of mass, length and time respectively, then the dimensions of the parameters in Equation (91) are

$$[D_a/R_a] = 1$$
$$[\rho] = [M]/[L]^3$$
$$[E_s] = [M] [L]^2/[T]^2$$
$$[R_a] = [L]$$
$$[\nu'] = [M]/[T] [L]$$
According to the Buckingham $\pi$-Theorem, the latter four variables can be combined into one non-dimensional variable which is chosen to be

$$\phi = \frac{2R_a}{E_s}$$

(93)

where

$$v = \frac{v'}{\sqrt{\rho}}$$

(94)

can be considered a generalized viscosity. Now Equation (91) can be given as

$$\frac{D_a}{R_a} = f(\phi)$$

(95)

where $f$ is a non-dimensional function of the parameter $\phi$ and is unknown. Since no analysis in this connection appears to be available as a guide in choosing a suitable form for $f$, assume a simple exponential relation of the following type:

$$\frac{D_a}{R_a} = k \phi^\zeta = k \left( \frac{2R_a}{E_s} \right)^\zeta$$

(96)

where $k$ and $\zeta$ are constants. Note that this relation will yield the maximum slope of the crater wall with the use of Equation (68).
Suppose that for one earth media, values of parameters associated with a reference charge are denoted by a superscript zero. Then, according to Equations (90) and (96)

\[
E_G^0 = \frac{\pi \sigma}{4 \pi \rho} D_a^0 (R_a^0)^3 \left( \frac{\beta - 2 - \frac{8}{\beta}}{\beta - 3} \right) \tag{97a}
\]

\[
\frac{D_a^0}{R_a^0} = k \left( \frac{\nu R_a^0}{E_s^0} \right) \tag{97b}
\]

The parameters \( \rho, \beta \) and \( \nu \) depend only on the type of earth media and not on the size of charge. Hence, these variables do not have the superscript zero. On the other hand, it is assumed that \( k \) and \( \zeta \) are independent of both earth media and charge size.

By taking appropriate ratios of the terms in Equations (90), (96) and (97) the following relations are obtained:

\[
\frac{E_G}{E_G^0} = \frac{D_a}{D_a^0} \left( \frac{R_a}{R_a^0} \right)^3 \tag{98a}
\]

\[
\frac{D_a}{D_a^0} = \left( \frac{R_a}{R_a^0} \right) \left( \frac{E_s}{E_s^0} \right)^{1+\zeta} \tag{98b}
\]

These equations do not contain the terms that depend on the earth media; hence, they can be used for predicting
results from the knowledge of one surface detonation on a given soil or rock.

The following analysis is developed to relate the actual kinetic energy of the earth particles $E_G$ to the kinetic energy delivered to the surface $E_s$.

**d. Energy Dissipation**

The initial kinetic energy $E_G$ of the earth particles will differ from the kinetic energy delivered to the surface $E_s$ by the amount of energy $E_D$ dissipated in the form of heat:

$$E_G = E_s - E_D$$  
(99)

From the expression in the incremental theory of plasticity (Reference 24) for energy dissipation where $\tau$ denotes stress and $\dot{\varepsilon}$ strain rate

$$\tau \dot{\varepsilon} = \nu' \dot{\varepsilon}^2$$  
(100)

it seems appropriate to assume that $E_D$ is linearly proportional to $\nu'$ and also a function of $E_s$, $\rho$ and $R_a$, that is

$$E_D = \nu' \dot{\varepsilon}^2 (E_s, \rho, R_a)$$  
(101)

Dimensional homogeneity for the equation implies that

$$E_D = b E_s \left( \frac{\nu' R_a}{E_s} \right)^{1/2}$$  
(102)
where \( b \) is taken to be a non-dimensional constant and \( \nu \) is defined by Equation (94). For a reference charge, we get

\[
E_D^0 = b \frac{E^0}{E^0} \left( \frac{\nu^2 R_s^0}{E^0} \right)^{1/2}
\]

so that

\[
\frac{E_D^0}{E_D^0} = \left( \frac{E^0}{R_s^0} \right)^{1/2}
\]

For the case of a reference charge, it is convenient to introduce a dissipation ratio

\[
Z_D^0 = \frac{E_D^0}{E_D^0}
\]

which is simply the ratio of the energy dissipated to the energy available at the surface. Hence \( E_D^0 \) must assume a value between 0 and 1.

From Equation (99)

\[
E_g = E_s \left[ 1 - \frac{E_D^0 E_s}{E_D^0 E_s} \right]
\]

90
Substitute Equations (104), (105) and (61b) into (106) to get

$$E_G = E_s \left[ 1 - \frac{E_s^D}{K} \left( \frac{R_a}{R_a^C} \right)^{1/2} \right]$$

$$= E_s \left[ 1 - E_s^D \left( \frac{R_a}{K R_a^C} \right)^{1/2} \right]$$

(107)

Also

$$E_G^C = E_s^C \left[ 1 - E_s^D \right]$$

(108)

so that

$$\frac{E_G}{E_G^C} = \frac{K \left[ 1 - E_s^D \left( \frac{R_a}{K R_a^C} \right)^{1/2} \right]}{1 - E_s^D}$$

(109)

Hence, with the use of Equation (61b), Equations (98a) and (98b) can be written in the alternate form

$$\left[ \frac{R_a}{R_a^C} \right]^{4+\zeta} = \frac{K^{1+\zeta} \left[ 1 - E_s^D \left( \frac{R_a}{K R_a^C} \right)^{1/2} \right]}{1 - E_s^D}$$

(110a)

91
With $R^o_a$, $D^o_a$, $\zeta$ and $E^D_s$ presumed known, these two equations give the apparent radius and depth as a function of $K$ and hence as a function of the yield of the explosive. Then, if $\hat{\beta}$ is known, Equation (73) can be used to predict the ejecta depth.

For a given earth media (alluvium for example), $\rho$ and $\hat{\beta}$ are assumed known. For some reference energy $E^o_s$, the apparent radius and depth, $R^o_a$ and $D^o_a$ respectively can be measured, and values for $\zeta$ and $E^D_s$ determined experimentally. A different earth media will, in general, yield different values for these parameters which will be designated by an asterisk. For a new reference energy $E^*o_s$, $R^*a$ and $D^*a$ can be measured as before. The new density $\rho$ can also be determined experimentally and it is assumed that $\zeta$ remains unchanged. The parameters $\hat{\beta}^*$ and $E^*D_s$ can be determined according to the following analysis.

From Equations (103) and (105)

$$D^o_a/D^*a = \left(\frac{R^o_a}{R^*a}\right)^{1+\zeta} \frac{1}{K^\zeta}$$

(110b)
\[ E^D_s = b \left( \frac{R^a_o}{E_s^o} \right)^{1/2} v^* \]  

(111b)

or, after eliminating \( b \)

\[ E^D_s = E^D_s \left( \frac{R^o}{R^a} \cdot \frac{E^o_s}{E_s^o} \right)^{1/2} \frac{v^*}{v} \]  

(112)

In a similar manner, Equation (97b) yields

\[ \frac{D^o_s}{D^a_o} = \left( \frac{R^o}{R^a} \right)^{1+\xi} \left( \frac{E^o_s}{E^o_s} \right)^{\xi} \left( \frac{v^*}{v} \right)^{2\xi} \]  

(113)

By eliminating \( v^*/v \) between Equations (112) and (113), we get

\[ E^D_s = E^D_s \left( \frac{D^o_s}{D^a_o} \cdot \frac{R^o}{R^a} \right)^{1/2\xi} \]  

(114)

To obtain a value for \( \beta^* \), Equations (97a) and (108) for the two media can be combined to get
Equation (59) can be used to express $E_s^O/\bar{E}_s^O$ in terms of reference charge yields and shapes:

$$\frac{E_s^O}{\bar{E}_s^O} = \frac{C_F^* W_o^*}{C_F W_o}$$

(116)
4. SUMMARY

For easy reference in connection with the computer program, the pertinent equations will be summarized.

For one particular earth media, $W_0$ denotes a reference charge for which the apparent radius $R_a^0$ and apparent depth $h_a^0$ are known. Any other yield is expressed in terms of the reference charge by means of the non-dimensional parameter

$$ T = \frac{W}{W_0} \quad (117) $$

The energy $E_s$ available at the surface is also expressed non-dimensionally by means of the factor

$$ K = \frac{E_s}{E_s} \quad (118) $$

where

$$ K = C_o^F T \quad (119) $$

and

$$ C_o^F = \frac{\left[ 2 - \left( \frac{W}{W_L} \right)^{1/3} \right]}{\left[ 2 - \left( \frac{W_0}{W_L} \right)^{1/3} \right]} \quad (120) $$
For lack of a precise value, $W_L$ is taken to be $10^6$ lbs. or 500 tons of TNT.

With the dissipation ratio $R_0^D$ for the reference charge $W_0$ and the particular earth media assumed known from experimental sources, the apparent radius $R_a$ and depth $D_a$ for charges of various values are determined from

$$\left(\frac{R_a}{R_0^a}\right)^{4+\zeta} = K^{1+\zeta} \left[\frac{1 - R_0^D}{1 - R_0^D} \left(\frac{R_a}{KR_0^a}\right)^{1/2}\right]$$  \hspace{1cm} (121a)$$

$$\frac{D_a}{D_0^a} = \left(\frac{R_a}{R_0^a}\right)^{1+\zeta} \left(\frac{1}{K^\zeta}\right)$$  \hspace{1cm} (121b)$$

The parameter $\zeta$ is assumed to be the same for all earth media and is chosen so that the theoretical results fit the experimental data as closely as possible.

With $\beta$ known, the depth of ejecta is given by

$$H_a = \frac{D_a}{4} (\beta - 2) \left(\frac{R_a}{R}\right)^{\beta}, \quad R > R_a$$  \hspace{1cm} (122)$$

One set of basic reference parameters are those associated with the 100 ton shot at the Suffield Experimental Station.
According to Reference 16, the soil, a silty clay, had a weight density of 94 lb/ft$^3$ and the apparent depth and radius were 21 and 70 feet respectively. As mentioned previously, an appropriate value for $\hat{\beta}$ for soil is 3.1. A value of 0.3 for both $\zeta$ and $E_s^D$ for this reference charge and earth media appears to give reasonable results.

The above equations are also used for a different earth media. However, the new apparent depth $D_a^{*O}$ and apparent radius $R_a^{*O}$ must be determined experimentally for the new reference charge $W_o$. The new dissipation ratio is given by

$$E_s^{*D} = E_s^D \left( \frac{D_a^{*O}}{D_a} \frac{R_a^{*O}}{R_a} \right)^{\frac{1}{2\zeta}}$$  \hspace{1cm} (123)

and the new ejecta parameter $\hat{\beta}^*$ can be found from

$$\left( \frac{\hat{\beta}^* - 2 - \beta}{\hat{\beta}^* - 3 - \frac{15}{15}} \right) = C_{Fo}^* \frac{W_o}{W_o} \left( \frac{1 - E_s^{*D}}{1 - E_s^D} \right) \frac{\rho}{\rho_a} D_a^{*O} \left( \frac{R_a^{*O}}{R_a} \right)^3 \left( \frac{\hat{\beta} - 2 - \hat{\beta}}{\hat{\beta} - 3 - \frac{15}{15}} \right)$$  \hspace{1cm} (124)

where

$$C_{Fo} = \frac{1}{4} \left[ 2 - \left( \frac{W_o}{W_L} \right)^{1/3} \right]$$  \hspace{1cm} (125a)

$$C_{Fo}^* = \frac{1}{4} \left[ 2 - \left( \frac{W_o^*}{W_L} \right)^{1/3} \right]$$  \hspace{1cm} (125b)

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For a discontinuous basalt rock of weight density 190 lb/ft$^3$, Reference 16 states that a charge $W_o = 500$ tons of TNT yields an apparent radius $R_a = 79$ ft. and an apparent depth $D_a = 38$ ft. These values can be used to obtain $E_a$ and $D_a$ for this type of rock. Then equations (121a) and (121b) with the new parameters can be used to find the dimensions of a crater for any other charge below 500 tons of TNT.

The above outline briefly describes a theory that should adequately predict the crater and ejecta shapes for a wide range of yield for conventional explosives. The effect of charge shape is included in the analysis.

For bomb stacks, the theory of this section appears to be satisfactory if only the weight of the high explosive is used. For stacks that are of the same order of magnitude as the barricade, the effect of the barricade, as far as crater and ejecta shapes are concerned, is assumed to be negligible. For cases where the bomb stack is relatively small, the situation is quite different and for most practical purposes, the crater and ejecta shapes are not too significant.

The computer program associated with the theory of this section is described in Appendix III.
SECTION V

ILLUSTRATIVE EXAMPLES

1. INTRODUCTION

In this section, a representative set of curves is presented that is based on the theory of the previous sections and the associated computer programs. Because of the large number of parameters that are present, only typical values were chosen for a graphical representation of the computer output. These curves are intended just to illustrate the type of information that can be obtained. In many instances the computer output is more detailed and can handle several possible situations which are not appropriate for a graphical display.

Some of the results of available experimental data are also plotted to indicate the degree of correlation between predicted and actual values. As stated previously, a certain amount of judgement is necessary when using these programs.
2. RESULTS FROM BLAST PRESSURE PROGRAM

As a typical example, parameters associated with Phases I and II of the "BIG PAPA" (Reference 1) tests were used as input data for the program. The bomb stack dimensions were 30 ft. wide by 50 ft. deep by 8.83 ft. high and the corresponding barricade dimensions were 100 ft. by 70 ft. by 11 ft., respectively.

Associated with a bomb stack are several conversion factors which are listed in Reference 3. The first replaces the weight of the explosive in a bomb by an equivalent weight of TNT. According to Reference 1, which used a factor of 1.23 in converting tritonal to TNT, the bomb stacks contained an equivalent weight of 307,500 lbs. of TNT. From Reference 3, a factor of 0.6 was considered most appropriate for replacing the bomb stack by a bare charge (184,000 lbs.) that would yield the same blast pressure characteristics. A different factor must be used for impulse but since the procedure is quite analogous, impulse distributions are not given.

Pressure versus distance is plotted in Figure 23 for the following cases:

a. Bare hemispherical unbarricaded charge,
b. Bare hemispherical barricaded charge,
c. Rectangular unbarricaded charge, and
d. Rectangular barricaded charge.

Figure 23a shows rather predictable results for the effect of the barricade on the blast pressure from a hemispherical charge. For a given distance from the center of the charge, the pressure out the front or open end of the barricade is
(a) Hemispherical Barricaded and Unbarricaded (Bare) Charges

Figure 23. Pressure versus Range for Various Charge and Barricade Combinations
Figure 23.  (Continued)
Figure 23. (Continued)

(c) Rectangular Barricaded and Hemispherical Unbarricaded (Bare) Charges

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higher than that for the corresponding unbarricaded charge while the pressures out the side and the back are lower. For large ranges, the pressures approach those of the unbarricaded charge.

The pressure-distance relations for a bare rectangular charge with the same weight are shown in Figure 23b. When compared with the corresponding result for a hemispherical charge, there is a region where the pressures out the front and side of the charge decrease quite rapidly. An explanation for this is that the model initially assumes that the pressure waves propagate in directions perpendicular to each of the charge faces. Thus, rarefaction waves that originate at the corners of the charge will travel parallel to the faces as the main pressure wave travels out. When the rarefaction wave reaches the point directly out from the center of a charge face, a further decrease in pressure could be expected. However, this phenomenon needs more study and as more data become available, the appropriate coefficients in the computer program should be changed.

The combined charge geometry and barricade effects are shown in Figure 23c together with the experimental results from "BIG PAPA" as compiled in Figure 27 of Reference 1. The correlation between the "BIG PAPA" tests and the predicted pressure distribution out the back of the barricade ($\theta = 180^\circ$) is not very satisfactory. However, until test results for the effects of geometry on the pressure from large scale charges become available, the program is forced to use the data from the limited range of charge sizes used in Reference 4.
Pressure isobars for a bare hemispherical barricaded charge are shown in Figure 24a. The isobars for the unbarricaded charge would just be circles and, hence, are not included.

The effect of charge shape geometry is dramatically illustrated in Figure 24b which gives the pressure isobars for an unbarricaded rectangular charge for the same case illustrated in Figure 23b. Similar curves for the rectangular barricaded charge are shown in Figure 24c.
Figure 24. Pressure Isobars for Various Charge and Barricade Combinations

(a) Hemispherical Barricaded Charge
(b) Rectangular Unbarricaded Charge

Figure 24. (Continued)

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Figure 24. (Continued)
3. FRAGMENT DISTRIBUTIONS

To illustrate the type of data that can be obtained from this portion of the program, the bomb parameters given in Figure 9 were used in conjunction with the stack of bombs considered in Part 2 of this Section. In addition, the following information was assumed:

a. The front of the bomb was oriented at an angle of 270° counterclockwise from the front of the barricade ($\theta_B = 270°$)

b. Each bomb had a gross weight of 1500 lbs.

c. Each bomb contained 750 lbs. of TNT

d. There were 333 bombs in the stack, and

e. The number of effective bombs was 266.

It should be emphasized that the bomb characteristics outlined above are purely fictional because of security reasons so that it will not be possible to compare results with experimental data.

Typical fragment trajectories associated with these bomb characteristics are shown in Figure 25. This particular set of curves was computed using a 10 degree increment for beta. These trajectories indicate that fragments ejected by the bomb for approximately $5° < \beta < 50°$ will impact at ranges furthest from the bomb; thus, a high density of fragments is to be expected at these impact points. However, because of air
Figure 25. Typical Fragment Trajectories for a Fixed Value of Azimuth Angle and Incremental Departure Angles
friction, the impact velocity is relatively low.

Impact conditions versus range at selected azimuth angles are shown in Figure 26. These curves appear as piece-wise lines of constant value because of the averaging techniques used in the program. By decreasing the increment in $\beta$, the changes would not be nearly as abrupt and hence, would be more realistic. All diagrams indicate a high fragment density at large ranges.

In Figure 26a, the presence of the large impact velocity is due to the absence of a barricade wall at that azimuth angle. Fragments ejected approximately parallel to the ground strike the ground much sooner than do those with a larger departure angle $\beta$ and hence, these large impact velocities are to be expected.

Figures 26b, 26c, and 26d show the variation in impact conditions around the stack for representative values of the azimuth angle. For similar directions of propagation from the barricade, the impact conditions are different in Figures 26e and 26f because of the different fragmentation properties of the bomb in these directions.
Figure 26. Impact Conditions versus Range at Selected Azimuth Angles for Sample Problem
Figure 26. (Continued)
Figure 26. (Continued)
4. APPARENT CRATER AND EJECTA DIMENSIONS

The apparent radius and depth of craters in soil according to the theory of Section IV and the computer program described in Appendix III is shown in Figure 27 for a range of 10 to 500 tons of TNT. It is evident from the figure that the apparent crater radius and depth (70 ft. and 21 ft., respectively) associated with a 100 ton TNT hemispherical shot at the Suffield Experimental Station have been used as the reference parameters for this program. In addition, the following values have been assumed:

a. The dissipation ratio $E^D_s = 0.3$,

b. The ejecta parameter $\beta = 3.1$, and

c. For the range of charge sizes 10 to 500 tons of TNT,
   $\zeta = 0.3$ and $W_L = 500$ tons.

These resultant curves of Figure 27 show significant variations from scaling laws which would be represented by straight-line relationships on this plot for both apparent radius and apparent depth. Because of the attempt to include fundamental quantities in the theory, these curves should predict apparent crater dimensions more accurately than the curves associated with scaling laws. Of more importance, the parameters $E^D_s$ and $\zeta$ can be changed if more data warrant such an adjustment. Furthermore, the effect of charge size is included in the theory and changes in shape can be accounted for by adjusting $W_L$.

Strictly speaking, the predicted results are applicable only for the earth media associated with the reference shot where
Figure 27. Apparent Crater Dimensions in Soil versus Charge Weight
the soil, a silty clay, had a weight density of 94 lb./ft. However, for easy reference, results from shots that may have been in a slightly different soil are also included in the figure. It is assumed that bomb stacks can be replaced by a bare charge with the equivalent amount of TNT as far as crater dimensions are concerned. Thus, some of the "BIG PAPA" test results are also included in Figure 27.

The depth of ejecta can be obtained from Figure 28 where the ejecta depth to apparent crater depth ratio is plotted as a function of the ratio of distance from the crater center (at the surface) to the apparent radius for various values of the ejecta parameter $\hat{\beta}$. Hence, to obtain the depth for a particular location, the apparent radius and depth and $\hat{\beta}$ must be known. When the earth media is soil, a value of 3.1 is used for $\hat{\beta}$.

For the type of rock encountered in the Sailor Hat test, the weight density was 190 lb./ft. A hemispherical charge of 500 tons of TNT produced a crater with an apparent radius of 79 ft. and an apparent depth of 38 ft. Results for hemispherical charges of other sizes are shown in Figure 29 together with the predicted values of $\hat{\beta}$ and the dissipation ratio.
Figure 28. Non-dimensional Ejecta Shapes as a Function of Earth Media Parameter β.
5. SUMMARY

Representative sets of curves have been given based on the computer programs and the theory of the previous sections. For given charge size and shape and barricade dimensions, the programs yield the following information:

a. Pressure versus range and impulse versus range for various azimuth angles,

b. Pressure isobars,

c. Impact velocity, number of fragments/ft.², average fragment mass as a function of range and azimuth angle,

d. Apparent crater radius and depth as a function of charge yield and shape, and earth media, and

e. Ejecta depth as a function of apparent radius and depth, and earth media.

Normally, using the computer programs for a given set of input data will be the most convenient method for design purposes. However, if a given situation occurs repeatedly, then it would be more convenient to construct a set of curves similar to those illustrated in this Section.
SECTION VI

RECOMMENDED INVESTIGATIONS

1. INTRODUCTION

During the course of this project it became apparent that a large amount of important information was not available. On the other hand, there were certain areas such as cratering in soil for which a great deal of data had been gathered. This section outlines the experimental data that would be necessary to corroborate a complete theoretical model that could be used with some degree of confidence. The requirements for data have been listed in the same order as the topics were covered in this report. It is rather obvious, however, that more than one type of data could be gathered from one test.

In addition to experimental data, the overall problem of safely storing bombs suggests a corresponding analytical study in linear programming where such factors as cost, time and safety are the limiting parameters. It is believed that such a study would be extremely useful to the Air Force and accordingly, a brief outline of the approach is given.
2. PRESSURE AND IMPULSE DATA

a. Single Bombs

Because the shape of a bomb is significantly different from that of a spherical or hemispherical charge, peak overpressure and impulse data should be obtained at various angles of azimuth and distance for bombs resting on the surface of the earth. Furthermore, the confining effect of the bomb casing should be investigated by obtaining data for bombs with the same amount of charge but with different case thicknesses. Intuitively, one might expect the initial value and the rate of decay with distance of the peak overpressure to increase as the casing thickness is increased. However, whether or not this is true, the extent of the variation should be investigated both analytically and experimentally.

b. Bomb Stacks

Similar pressure and impulse measurements should be made for bomb stacks. Tests should be conducted with the following sequences: (1) Stacks with similar shapes but with different sizes, and (2) Stacks with the same number of bombs but with different shapes.

Such a program would determine whether the confining effect of several bombs tends to increase the initial values of the peak overpressure above that expected for the amount
of explosive present or whether a slight time difference in detonation of the individual bombs results in a lowering of the expected value. Obtaining values for the unit impulse is also extremely important.

A side benefit of these results might be the preference for a particular stack shape and size based on pressure and impulse limitations rather than stacking convenience.

c. Barricades

Very little pressure and impulse data appear to be available for the region immediately outside the barricade. For a given stack size and geometry, a series of tests should be conducted for barricades with various dimensions. Significant differences could be expected close to the barricade but for regions farther away, the results should approach those of the unbarricaded stack.
3. FRAGMENT DATA

There appears to be sufficient data on the fragment sizes, number of fragments and initial velocities of fragments for individual bombs. One aspect that could be handled simultaneously with the pressure data of the previous section is the acquisition of information concerning the distribution and impact velocities of fragments from bomb stacks of various sizes and shapes. These data would yield essential information concerning interaction effects and hence, whether or not the simplified theory of Section III is adequate. If the theory associated with the fragment trajectories is fairly accurate, then the effect of barricades can be predicted quite confidently and hence a special experimental program considering barricades is not warranted in this connection.
4. CRATER DATA

A vast number of cratering programs have been conducted for bare hemispherical and spherical charges but predicting crater dimensions with the use of scaling laws is not completely satisfactory. Examples of unexpected crater sizes include 500 ton shots of the Suffield Experimental Station and of "Operation Sailor Hat". It is believed that the level of the underground water table may have affected the results of the first shot mentioned above. The variation from the normal crater shape of the latter shot may be due to the type of rock at that particular location.

In light of the large amount of crater data available it does not seem advisable at this point to conduct more tests of the same type until there exists a better understanding of the effects of the various parameters that describe the earth media. However, in connection with this program, a number of tests do seem advisable.

One of these is concerned with the effect of charge shape on the crater dimensions. For example, for the same earth media and the same charge weight, a series of shots should be conducted in which the charge shape is varied. Typical examples would be rectangular, cubical, and triangular shapes.

Another series could involve the use of stacked bombs, again for one earth media. Such tests would illustrate the interaction effects of bombs and the effect of stack size and
shape. Furthermore, tests of this kind could lead to comparisons with the results of bare charges of the type mentioned above. According to the theory developed in Section IV the shape with the lowest center of mass will produce the largest crater and the basic hypothesis behind this theory should be checked.

Also of considerable interest is the effect of barricade size on crater dimensions. Experimental data in this area would be very useful for both theoretical and immediate practical use.
5. OPTIMIZATION OF STORAGE AREAS

In developing a munitions storage area, several factors must be taken into consideration. These include the cost and availability of land, possible methods of stacking bombs and building barricades, degree of safety in connection with fragments, cratering, peak overpressure and impulse, the time available to stack the bombs, and so on. With the experimental and theoretical methods available it appears that it might be possible to develop a computer program that would optimize a given parameter under a given set of circumstances.

One example could be the following: Suppose that a particular amount of munitions had to be stored on a given area and the safety requirement was primarily one of ensuring that no fragments landed outside this area. The problem would then entail finding the appropriate combination of munition stack shapes, dimensions and distributions of the stacks together with barricade shapes and dimensions that would satisfy this requirement. If more than one combination was adequate, then additional factors such as cost and time could be included in the program.

Another possibility would be to determine the "safest" possible arrangement that could be developed in a given amount of time. To determine the safety aspect, degrees of importance would have to be attached to each of the hazardous factors associated with a munitions dump. Likewise, the parameters
describing the time to stack the bombs would be included and by using the principles of linear programming, the optimum configuration would be predicted.

Since there are a large number of possibilities that could be of interest to the Air Force, it would seem that the possibility of developing a program that could predict optimal arrangements should be considered. The results could be significant improvements in safety, time and cost.
SECTION VII
CONCLUSIONS

Analytical models and subsequent computer codes have been developed for typical large quantity high-explosive detonations of those types of conventional munitions stored by the Air Force in aboveground barricaded modules. The parameters that are predicted from these codes include peak overpressure, unit impulse, distributions of fragment impact coordinates and velocities, crater dimensions and depth of ejecta. The geometries of the bomb stack and the barricade are taken into account as well as the type of earth media. Results of large-scale tests had indicated that the burning time of detonation and the point of initiation of a bomb stack were not too significant and, hence, these parameters are not considered.

Because of the lack of wide-scale, definitive experimental data, it was considered more appropriate to use a combination of analysis and empirical curve fitting in connection with the models. Accordingly, some engineering judgement must be used with the computer codes since there may be some disparity in the values of parameters for an actual problem and the values that are used in the model.

Every effort was made to use the latest experimental and theoretical results. However, there are several areas in which
vital gaps in fundamental knowledge exist. A limited program of testing is necessary to obtain this information and the types of tests that should be run are listed in this report.

Of more immediate benefit to the Air Force is the development of computer codes which would optimize a base layout under a given set of conditions. Such codes could produce the safest possible combination of munition modules for a given area or, alternatively, the cost and amount of time required to construct a safe munitions storage area could be minimized.

The codes that have been developed should be extremely helpful in predicting the danger zone for a munitions storage area. In selecting models that yield governing parameters with respect to the safety of a base, a conservative approach has been adopted. Thus, as better technical information becomes available, these codes can be adjusted and better use of available ground space for storing munitions can be made.
APPENDIX I

BLAST EFFECT PROGRAM

1. FORTRAN PROGRAM DESCRIPTION

The computer code described in this Appendix follows the development of Section II on Blast Effects. The computations are performed in the same order as outlined in the development of the analytical model whenever possible. A flow chart for the computer code is included in Appendix I-2. A printout of the computer code is included in Appendix I-4.

The first section of the computer code establishes (a) the coefficients for the various polynomials needed during the computations, (b) overpressures to be solved in isobar option, and (c) degrees of different polynomials required in computations, and (d) lists format statements.

Each problem to be run requires a control card to be read. If more data are to be read, the control card indicates the amount to be read and the variables that are to be reassigned. The control card also sets the parameters describing bomb stack and barricade and indicates azimuth angles for which the pressure and impulse are desired. After the control card is read, the heading on the output is printed to record the parameters of the problem for future reference.

The solution is obtained by computing the pressure and positive impulse for a bare hemispherical charge of TNT at the
scaled distances $Z = 4.0, 4.1, 4.2, ..., 480, 490, 500$. The incremental steps of $Z$ are as follows:

\[
\begin{align*}
\Delta Z &= 0.10 \text{ for } 4.0 < Z < 5.0 \\
\Delta Z &= 0.20 \text{ for } 5.0 < Z < 10.0 \\
\Delta Z &= 1.0 \text{ for } 10.0 < Z < 50.0 \\
\Delta Z &= 2.0 \text{ for } 50.0 < Z < 100.0 \\
\Delta Z &= 10.0 \text{ for } 100.0 < Z < 500.0
\end{align*}
\]

Pressure and impulse are evaluated from the polynomials previously fitted to the $\ln P - \ln Z$ and $\ln I - \ln Z$ representations of Figure 8. If a scaled distance $Z$ falls within the confines of the barricade the pressure and impulse are not computed. This evaluation of pressure and impulse for a bare hemispherical charge is completed previous to statement number 335 in the code.

If the charge of TNT is rectangular rather than hemispherical, the effects of the change in geometry are evaluated according to the theory of Section II-4. The evaluation of effect of charge geometry on pressure and impulse distributions is performed between statements 335 and 460 in the computer code. The procedure used is to evaluate the pressure ratio and positive impulse ratio perpendicular to the faces of the rectangle and along a line through the center of mass of the charge and the corner where the faces of the rectangle meet. The values of pressure ratio and positive impulse ratio for angles other than those perpendicular to the faces and through the corners are obtained by linear interpolation between the
two known values that span the angle. Later in the program the pressure ratio and positive impulse ratio will be used to multiply the corresponding values of pressure and positive impulse at a distance \( z \) for a bare hemispherical charge to obtain pressure and positive impulse for the rectangular charge being modeled.

If a barricade is present around a stack of TNT, its shape is assumed to be rectangular with the center of mass of the stack of TNT very nearly corresponding to the geometric center of the barricade in the plan view. The walls of the barricade are assumed to be parallel to the sides of the stack of TNT.

The effect of the presence of a barricade is evaluated according to the theory of Section II-5 between statement numbers 465 and 555 in the computer code. The pressure and positive impulse ratios (BP and BI), that will be multiplied by the pressure and positive impulse for a bare hemispherical charge at the corresponding distances, can be evaluated directly for directions perpendicular to the walls of the barricade and out the rear corner of the barricade by interpolation from the input data. The ratios for angles not equal to those just mentioned are obtained by a linear interpolation scheme from the values obtained for direction perpendicular to the walls and out the rear corner of the barricade. It is only necessary to determine which two known directions the angle theta lies between to choose the proper data for interpolation.

This concludes the evaluation of the pressure and positive impulse ratios that are needed to estimate the effective change.
in pressure and impulse distribution produced by the change in charge geometry from a hemispherical to a rectangular shape and the presence of a barricade around the charge.

To obtain the estimated pressure and positive impulse distributions, it is only necessary to multiply the pressure and positive impulse distributions for the bare hemispherical charge by the appropriate pressure and impulse ratios as derived above. These computations are performed and printed out in the computer code between statements 560 and 565.

If isobar plots are desired to indicate distance to lines of constant pressure the statements 630 through 680 are executed by setting IBO = 0, otherwise IBO = 1. The distances to points of equal pressure along lines separated by 5° increments are evaluated by starting at the extreme distance (Z = 500) and comparing expected pressure to isobar pressure for decreasing values of Z until expected pressure is greater than the isobar pressure. When the points on either side of the distance where isobar pressure equals expected pressure are found, the distance to the isobar pressure is found by linear interpolation. If the expected pressure along a direction of propagation does not attain the isobar pressure, the symbol PMR is printed instead of the distance. This indicates that the isobar pressure is not reached along that direction. This method of evaluation continues until all the distances to the isobar pressures have been evaluated along the directions indicated.
2. **BLAST PROGRAM FLOW DIAGRAM**

SET VALUES OF ALL POLYNOMIAL COEFFICIENTS

READ SL, SD, SH, BL, BD, QUAN, NTHETA, NGPD, NGID, NEPD, NBID, NO, NB, IBO, NEFPRD, NEFIRD

PRINT RUN HEADINGS

IF NGPD ≠ 1

READ NEW GEOMETRY PRESSURE EFFECT POLYNOMIAL COEFFICIENTS FOR STACK FACE

IF NGID ≠ 1

READ NEW GEOMETRY IMPULSE EFFECT POLYNOMIAL COEFFICIENTS FOR STACK FACE

IF NEFPRD ≠ 1
READ NEW GEOMETRY
EFFECT EDGE TO FACE PRESSURE
RATIO POLYNOMIAL COEFFICIENTS

IF
NEFIRD -1

READ NEW GEOMETRY
EFFECT EDGE TO FACE IMPULSE
RATIO POLYNOMIAL COEFFICIENTS

IF
NBPD -1

READ NEW BARRICADE PRESSURE
EFFECT POLYNOMIAL COEFFICIENTS

IF
NBID -1

READ NEW BARRICADE IMPULSE
EFFECT POLYNOMIAL COEFFICIENTS

IF
NTHETA

SOLUTION OBTAINED
ONLY FOR 0 = NTHETA

SOLUTION OBTAINED
FOR 0° ≤ θ ≤ 180°
IN STEPS OF 5°
INDEX PER VALUE OF NTHETA

PRINT VALUE OF NTHETA AND COLUMN HEADINGS

INDEX Z FROM
Z = 4.0 THRU Z = 500.0

ARE POINT COORDINATES (θ, Z) WITHIN BARRICADE

NO

YES

COMPUTE BARE PEAK OVERPRESSURE AND POSITIVE IMPULSE

IF

NGO - 1

COMPUTE GEOMETRY EFFECT FACTORS

GEOMETRY EFFECT FACTORS ARE SET TO 1.0

IF

NBO - 1

COMPUTE BARRICADE EFFECT FACTORS
BARRICADE EFFECT FACTORS ARE SET TO 1.0

MULTIPLY BARE OVER-PRESSURE AND IMPULSE VALUES BY APPROPRIATE FACTORS

CHANGE INDEX OF Z DEPENDING ON VALUE OF Z AND RETURN

CONTINUE

IF IBO = 1

COMPUTE ISOBAR COORDINATES

STOP
3. LIST OF VARIABLES TO COMPUTER PROGRAM FOR ANALYTICAL BLAST EFFECT MODEL

A(I,J)  Polynomial Coefficients to determine rectangular charge face pressure to spherical charge pressure ratio.

APPR  Average pressure at a distance Z perpendicular to faces of charge.

AFSIR  Average impulse at a distance Z perpendicular to faces of charge.

ARD  Face/Area ratio from front of bomb stack.

ARL  Face/Area ratio from side of bomb stack.

Al, A2, A3  Polynomial to evaluate pressure out from faces of stack at a distance Z from the blast.

B(I,J)  Polynomial Coefficients to determine rectangular charge face impulse to spherical charge pressure.

BD  Barricade depth, ft.

BI  Factor to multiply by bare hemispherical charge impulse to include effect of barricade.

BIE(I,J)  Polynomial coefficients to determine effect of a barricade on blast impulse distribution.

BL  Barricade length, ft.

BOP(I)  Overpressure from a bare hemispherical unbarricaded charge.

BF  Factor to multiply by bare hemispherical charge pressure to include effect of barricade.

BPE(I,J)  Polynomial coefficients to determine effect of a barricade on blast pressure distribution.
BPHI1: Angle whose tangent is (BL/BD).
BPHI2: Angle whose tangent is (BL/-BD).
BSOPI(I): Impulse from a bare hemispherical unbarricaded charge.
BTHETA: Angle through corner of barricade.
B1, B2, B3: Polynomial to evaluate impulse out from faces of stack at a distance Z from the blast.
C: Polynomial for pressure from a bare hemispherical charge evaluated at a distance Z.
CRQ: Cube root of charge yield, lbs.\(^{1/3}\).
D: Polynomial for impulse from a bare hemispherical charge evaluated at a distance Z.
EFIR(I): Polynomial coefficients to determine edge to average face impulse ratio versus Z.
EFPR(I): Polynomial coefficients to determine edge to average face pressure ratio versus Z.
FG: Factor to multiply by bare hemispherical charge pressure to include effect of rectangular charge.
FOP(I,J): Pressure expected due to changes in geometry and (OR) barricade.
FSOPI(I,J): Impulse expected due to changes in geometry and (OR) barricade.
GI: Factor to multiply by bare hemispherical charge impulse to include effect of rectangular charge.
GTHETA: Complementary angle of NTHETA.
IBO: Isobar Option, IBO = 0 solves for isobars, IBO = 1 no isobars computed.
M: Number of increments of Z within a certain range of Z values.
Number of cards to be read containing new barricade impulse data.

Barricade option, \( NBO = 0 \) rectangular barricade is included, \( NBO = 1 \) solves for no barricade.

Number of cards to be read containing new barricade pressure data.

Degree of polynomial for estimating barricade impulse effect.

Degree of polynomial for estimating barricade pressure effect.

Degree of polynomial for estimating edge/face impulse ratio.

Degree of polynomial for estimating edge/face pressure ratio.

Integer number of 5-degree increments in \( N\)THETA.

Degree of polynomial for rectangular charge face impulse to spherical charge impulse.

Degree of polynomial for rectangular charge face pressure ratio to spherical charge pressure.

Degree of polynomial for pressure versus \( Z \) for a spherical charge.

Degree of polynomial for impulse versus \( Z \) for a spherical charge.

Number of cards to be read containing new edge/face impulse ratio data.

Number of cards to be read containing new edge/face pressure ratio data.

Number of cards to be read containing new geometry impulse data.

Geometry option, \( NGO = 1 \) solves for hemispherical charge, \( NGO = 0 \) solves for rectangular charge.
<table>
<thead>
<tr>
<th>Identifier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGPD</td>
<td>Number of cards to be read containing new geometry pressure data.</td>
</tr>
<tr>
<td>NTHETA</td>
<td>Angle at which pressure and impulse desired, degrees.</td>
</tr>
<tr>
<td>NUM</td>
<td>Indexing variable.</td>
</tr>
<tr>
<td>OP(I)</td>
<td>Polynomial coefficients to determine pressure versus Z for a hemispherical charge.</td>
</tr>
<tr>
<td>P(I)</td>
<td>Isobar pressures to be solved, psi.</td>
</tr>
<tr>
<td>PP</td>
<td>Isobar pressure to be solved, psi.</td>
</tr>
<tr>
<td>PRE</td>
<td>Polynomial to evaluate pressure out from corner of stack at a distance Z from the blast.</td>
</tr>
<tr>
<td>P2, P1</td>
<td>Known pressures at distances Z2, Z1, psi.</td>
</tr>
<tr>
<td>QUAN</td>
<td>Equivalent amount of TNT in stack, lbs.</td>
</tr>
<tr>
<td>RAD</td>
<td>Number degrees per radian.</td>
</tr>
<tr>
<td>RD(I,J)</td>
<td>Distance from blast, ft.</td>
</tr>
<tr>
<td>RR</td>
<td>Converts fixed point variable to floating point.</td>
</tr>
<tr>
<td>S</td>
<td>Size of increments of I within a certain range of Z' values, ft/(lbs.(^{1/3})).</td>
</tr>
<tr>
<td>SD</td>
<td>Stack depth, ft.</td>
</tr>
<tr>
<td>SH</td>
<td>Stack height, ft.</td>
</tr>
<tr>
<td>SIRE</td>
<td>Polynomial to evaluate impulse out from corner of stack at a distance Z from the blast.</td>
</tr>
<tr>
<td>SL</td>
<td>Stack length, ft.</td>
</tr>
<tr>
<td>SOPI(I)</td>
<td>Polynomial coefficients to determine impulse versus Z for a hemispherical charge.</td>
</tr>
<tr>
<td>TB</td>
<td>Same angle as NTHETA.</td>
</tr>
<tr>
<td>TBI</td>
<td>Temporary barricade impulse ratio.</td>
</tr>
</tbody>
</table>
THETA  Temporary barricade pressure ratio.
THETA  Degrees, Angle Θ in degrees.
THETA  Angle measured from front of bomb stack to
corner of bomb stack.
TN  Θ - 90°.
TR  Θ /90.
X  Log z.
Z  Scaled distance from blast, ft/(lbs.$^{1/3}$).
ZC  Absolute value of z cos(Θ), ft/(lbs.$^{1/3}$).
ZI(J,N)  Scaled distance to isobar pressure PP, ft/(lbs.$^{1/3}$).
ZQ  Value of z sin (Θ), ft/(lbs.$^{1/3}$).
ZR(I,J)  Scaled distance at a particular angle and range.
Z2, Z1  Known distances that span distance to isobar
pressure, ft/(lbs.$^{1/3}$).
4. PRINTOUT OF PROGRAM FOR ANALYTICAL BLAST EFFECT MODEL
READ CONTROL CARD

NL = FT. = STACK LENGTH
SD = FT. = STACK DEPTH
SH = FT. = STACK HEIGHT
BL = FT. = BARRICADE LENGTH
BD = FT. = BARRICADE DEPTH
WUN = LBS. = EQUIVALENT AMOUNT OF TNT
NTHETA = DEGREES = ANGLE AT WHICH PRESSURES AND IMPULSE ARE DESIRED.

NTHETA = -1 WILL SOLVE FOR ANGLES FROM 0 TO 360 DEGREES IN STEPS OF 5 DEGREES

NWD = NUMBER OF CARDS TO BE READ WITH NEW GEOMETRY PRESSURE DATA
NGD = NUMBER OF CARDS TO BE READ WITH NEW GEOMETRY IMPULSE DATA
NBD = NUMBER OF CARDS TO BE READ WITH NEW BARRICADE IMPULSE DATA
NG0 = GEOEMETRY OPTION, IF NG0 = 1 THE OPTION IS NOT USED

HBO = BARRICADE OPTION, IF HBO = 0 BARRICADE EFFECT IS INCLUDED

IF HBO = ONE(1) THE PROBLEM IS SOLVED EXCLUDING BARRICADE EFFECT

THO = INITIAL COORDINATE OPTION, IF THO IS ONE(1) THE OPTION IS NOT USED. IF THO IS ZERO THE OPTION SOLVES FOR THE RADIUS TO POINTS OF EQUAL PRESSURE IN 5 DEGREE INCREMENTS.

NEPFD = NUMBER OF CARDS TO BE READ IN CONTAINING NEW EDGE.FACE
C----- PRESSURE RATIO DATA
C
C   NEFPRO = NUMBER OF CARDS TO BE READ IN CONTAINING NEW EDGE/FACE
C
C   IMPULSE RATIO DATA
C
C
000044 199 READ 10 , SL, 50, 5H, BL, 5D, QUAN, NT квар, NGID, NBPO, NGID, NGD, MNO, MNO,
C   1 50, NEFPRO, NEFPRO
C
C   PRINT HEADING ON OUTPUT
C
C
000187 IF (MNO = 1 ) 200, 203, 203
000192 200 PRINT 134
000195 PRINT 134, SL, 50
000202 GO TO 200
000199 203 PRINT 134
000206 IF (MNO = 1 ) 209, 212, 212
000209 209 PRINT 137
000210 PRINT 137, SL, 80
000216 GO TO 219
000215 212 PRINT 134
000219 215 PRINT 4, QUAN
000224 CRO = QUAN ** 0.333333
C----- THEETA IS THE ANGLE MEASURED FROM FRONT OF BOMB STACK TO CORNER OF
C----- BOMB STACK.  THEETA = ATAN2(SL, 50) * RAO
C
C
000361 THEETA = ATAN2(SL, 50) * RAO
C
C   NEW GEOMETRY PRESSURE DATA OPTION, NGPD IS THE NUMBER OF CARDS TO
C   BE READ CONTAINING NEW DATA
C
C
000464 IF (NGPD = 11 ) 216, 216, 216
000471 216 NGPD = NGPD + 1
000477 READ 13 , (A(1,1), A(2,1), A(3,1), I = 1, NGPD)
000482 NGPD = NGPD
C
C   NEW GEOMETRY IMPULSE DATA OPTION, NGID IS THE NUMBER OF CARDS TO BE
C   READ CONTAINING NEW DATA
C
C
000521 IF (NGID = 11 ) 221, 224, 224
000528 221 NGID = NGID + 1
000534 READ 13 , (A(1,1), A(2,1), A(3,1), I = 1, NGID)
000542 NGID = NGID
C
C   NEW EDGE/FACE PRESSURE RATIO DATA OPTION, NEFPRO IS THE NUMBER OF
C   CARDS TO BE READ CONTAINING NEW DATA
C
C
000584 227 IF (NEFPRO = 11 ) 233, 230, 230
000590 230 NEFPRO = NEFPRO + 1
000596 READ 31 , (EFIR(I), I = 1, NEFPRO)
000606 NEFPRO = NEFPRO
C
C   NEW EDGE/FACE IMPULSE RATIO DATA OPTION, NEFREL IS THE NUMBER OF
C   CARDS TO BE READ CONTAINING NEW DATA
C
C
000645 233 IF (NEFREL = 11 ) 239, 239, 239
000652 239 NEFREL = NEFREL + 1
000658 READ 31 , (EFER(I), I = 1, NEFREL)
000668 NEFREL = NEFREL
C
C   NEW BARRICADE PRESSURE DATA OPTION, NBPO IS THE NUMBER OF CARDS TO
C   BE READ CONTAINING NEW DATA
C
C
000706 243 IF (NBPO = 11 ) 249, 242, 242
079311 243 NBPO = NBPO + 1
READ 10 (OPE(1,2),OPE(2,1),OPE(3,1),OPE(4,1),I=1,NK,-
HIDPE = HIDPO
295 DO 299 J=1,NK
299 DO 299 T=1,6
295 HIDPE
C NEW BARRYCASE IMPULSE DATA OPTION. NBIID IS THE NUMBER OF CARDS TO BE READ CONTAINING NEW DATA
C
IF (HIDIO - 1) 249,259,259
295 NBIOD = NBIOD + 1
295 NBIOD
RTOTE = RTOTI
295 IF (RTOTI) 249,279,279
295 NMM = 181
295 JN = 1
295 GO TO 279
295 NMM = NTHETA + 2
295 JN = NTHETA + 1
C MAJOR LOOP - INDEXES THETA FROM 0-180. IF NTHETA READ IN IS -1
C WHEN NTHETA IS POS. PROGRAM SOLVES ONLY FOR ANGLE NTHETA
C THETA IS TO BE READ INTO PROGRAM IN DEGREES BETWEEN 0 AND 180
C TO REDUCE THE AMOUNT OF PRINTOUT WHEN SOLVING FOR PRESSURE ISODIARS
C SUPPRESS PRINT OF PRESSURES AND IMPULSES VS. DIST. FOR ANGLES
C COMPUTED BY MAKING STIFS 280,281,282,283, AND 621 INTO
C HOMEEXECUTABLE COMMENTS AND ADD A CARD 621 CONTINUE
C
275 DO 625 NN = JN,NMM,J
275 NTHETA = NN - 1
C SET FIRST INCREMENT OF DISTANCE
C
Z = 3,9
289 PRINT 180, NTHETA
C PRINT OUTPUT COLUMN HEADINGS
C
285 PRINT 192
290 PRINT 183
C --- ESTABLISH CONSTANTS FOR PROBLEM PARAMETERS
C
N = 11
C
S = 0,12
C
BPMM1 = ATAN2(ML,SL)*RAD
C
BPMM2 = ATAN2(ML,SL)*RAD
C
NMM = 6
C
RR = NTHETA
C
THETA = RR / RAD
C
NDEG = NTHETA / 5 + 1
C
SECOND MAJOR LOOP - INDEXES Z FROM 0 - 800
C
300 DO 565 K=1,N
C
NUM = NUM + 1
C
RM = 0,0
C
FG = 0,0
C
GI = 0,0
C
A1 = 0,0
C
HP(NUM) = 7,0
C
RSPI(NUM) = 0,0

148
008574  POP(NIND,NUM) = 0.0
008477  P30P(NIND,NUM) = 0.0
008677  2 = 2 + 5
008981  2N(NIND,NUM) = 2
008684  20 = 2 * COS(THETA)
009988  20 = RINT20
009514  20 = 2 * SIN(THETA)
008813  IF (UPH1 - U1HYAT) > 309,315,315
008817  353 IF (UPH12 - U1HYAT) > 315,315,315
008922  318 IF (R2 - ((18.72,0)/CR0)) > 369,328,328
009527  318 IF (R2 - ((1807,0)/CRO)) > 369,328,328
009533  353 X = AL0G2(2)
009539  C= 0.0
Cc
              C BARE PRESSURE VS Z
008937  DO 339 J = 1,NDOP
008943  N = J - 1
008946  329 C = C + 0P(J) + 1X * N
008953  90P(NUM) = EXP(C)
009556  0 = 0.0
Cc
              C BARE IMPULSE VS Z
009557  DO 339 J = 1,NDOP2
009565  N = J - 1
009568  338 O = O + SOP(J) * (X ** N)
009573  950P(NUM) = EXP(O) * CRO
Cc
              BEGINNING OF GEOMETRY OPTION - IF DESIRED, THIS SECTION SOLVES FOR
              TWO FACTORS PG AND GI WHICH ARE TO BE MULTIPLIED BY BARE PRESSURE
              AND BARE IMPULSE TO INCLUDE RECTANGULAR CHARGE GEOMETRY EFFECT
008877  IF (WGO = 1) 339,339,339
009692  339 IF (Z - 56.0) 343,343,343
009607  360 AR1 = 1.0/(30/SH) + 2.0 + 2.0/(30/SL1)
009614  400 AR2 = 1.0/(35/SH) + 2.0 + 2.0/(35/SL2)
009621  A1 = 5.0
009622  A2 = 7.0
009627  43 = 0.0
009624  91 = 0.0
009625  92 = 0.0
009629  93 = 0.0
009626  PRE = 0.0
009626  S1PR = 0.0
Cc
              ------ EVALUATE POLYNOMIALS AT, AT, AT, AT Z
009627  DO 400 L = 1,MDGPO
009643  J = L - 1
009641  A1 = A(1,L) *(Z ** J) + A1
009646  A2 = A(2,L) *(Z ** J) + A2
009651  400 AT = A(3,L) *(Z ** J) + AT
009662  IF(Z.LE.26.0) GO TO 405
DO 410 L = 1, NOSID
J = L - 1

DO 419 B1 = B1(L, L) + (2 ** J) + 61

DO 418 B3 = B3(L, L) + (2 ** J) + 63

IF (Z, L.F., 23, 61) GO TO 410

415 STR1 = B1 + B2 + AND + B3 *(AND + 2)
STR0 = B1 + B2 + AND + B3 *(AND + 2)

414 AVER = (PRL + PRO) / 2.0

425 PRE = PRE + EFPR*(L) * (2 ** J)

IF (PRL, LT, 0.0) PRE = 0.0
IF (Z, GT, 20.0) PRE = 1.0

PRES = PRE * AVER

IF (SIRF, LT, 0.0) SIRE = 0.0
IF (Z, GT, 37.0) SIRE = 1.0

C ---- EVALUATE POLYNOMIAL COEFFICIENTS B1, B2, AND B3 AT Z
C ---- EVALUATE IMPULSE RATIO AT DIST. Z PERPENDICULAR TO DEPTH AND
C ---- LENGTH OF STACK
C ---- AVERAGE PRESSURE RATIO
C ---- AVERAGE IMPULSE RATIO
C ---- SOLVE FOR PRESSURE AND IMPULSE RATIO OUT CORNER OF STACK
C ---- PRESSURE OUT CORNER AT DIST. Z = PRESSURE RATIO * AVG PRESSURE
FROM PAGES
C ---- IMPULSE OUT CORNER AT DIST. Z = IMPULSE RATIO * AVG IMPULSE
FROM PAGES
**SECTION 1**

**INPUT**

- `T` = TRUE
- `F` = FALSE

**OUTPUT**

- `P` = PRESSURE
- `I` = IMPULSE
- `W` = WEIGHT
- `Q` = QUANTITY

**FORMULAS**

- `P = F * (T * W)`
- `I = F * (T * W)`
- `Q = F * (T * W)`

**PROCEDURE**

1. **IF** `T` = TRUE, **THEN** `P = F * W`**.**
2. **ELSE IF** `F` = TRUE, **THEN** `I = F * W`**.**
3. **ELSE IF** `Q` = TRUE, **THEN** `Q = F * W`**.**

**EXAMPLES**

- **IF** `T` = TRUE, **AND** `F` = TRUE, **AND** `W` = 1.0, **THEN** `P = 1.0`**.**
- **IF** `T` = FALSE, **AND** `F` = TRUE, **AND** `W` = 1.0, **THEN** `I = 1.0`**.**
- **IF** `T` = FALSE, **AND** `F` = FALSE, **AND** `W` = 1.0, **THEN** `Q = 1.0`**.**

**NOTES**

- **IF** `T` = TRUE, **AND** `F` = FALSE, **AND** `W` = 1.0, **THEN** `P = 1.0`**.**
- **IF** `T` = FALSE, **AND** `F` = TRUE, **AND** `W` = 1.0, **THEN** `I = 1.0`**.**
- **IF** `T` = FALSE, **AND** `F` = FALSE, **AND** `W` = 1.0, **THEN** `Q = 1.0`**.**
C GO TO 960
C------ FOLLOWING STATEMENTS TO 555 APPLY FOR THETA GREATER THAN PI/2
C
C 525  OTHETA = ATAN(BD/BL) * RAD * 90,
C 524  YD = OTHETA
C
C------ CHECK LOCATION OF THETA WITH RESPECT TO ANGLE THROUGH CORNER
C OF BARRICADE TO DETERMINE APPROPRIATE SET OF EQUATIONS
C TO INTERPOLATE FOR EFFECT OF BARRICADE ON PRESS. AND
C IMPULSE RATIOS ( BP AND BI )
C
C IF (TH - OTHETA) > 525, 525, 940
C 925 DO 530 J = 1, NOPE
C 526 L = J - 1
C 527 PE = ( (TH - OTHETA - 90.) ) * (BPE(J,J) - BPE(2,J) + BPE(2,J))
C 528 930 BP = BP + PE * (2 * 9 ° L)
C
C 530 DO 350 J = 1, NOPE
C 531 L = J - 1
C 532 EI = ( (TH - OTHETA - 90.) ) * (BIE(J,J) - BIE(2,J) + BIE(2,J))
C 533 934 BI = BI + EI * (2 * 9 ° L)
C
C IF(BI.GE.1.0) GI = 1.0
C 536 IF(BP.GE.1.0) GP = 1.0
C 537 GO TO 960
C
C 540 DO 949 J = 1, NOPE
C 541 L = J - 1
C 542 PE = ( (TH - OTHETA - 180. - OTHETA) ) * (BPE(J,J) - BPE(3,J) + BPE(3,J))
C 543 945 BP = BP + PE * (2 * 9 ° L)
C
C 949 DO 999 J = 1, NOPE
C 950 L = J - 1
C 951 EI = ( (TH - OTHETA - 180. - OTHETA) ) * (BIE(J,J) - BIE(3,J) + BIE(3,J))
C 952 955 BI = BI + EI * (2 * 9 ° L)
C
C IF(BI.GE.1.0) GI = 1.0
C 956 IF(BP.GE.1.0) GP = 1.0.
C 957 GO TO 960
C
C 960 BP = 1.0
C 961 GP = 1.0.
C------ MULTIPLY OVER PRESSURE FOR A BARE HEMISPHERICAL CHARGE BY EFFECTS
C OF GEOMETRY (FG) AND BARRICADE (BP) TO OBTAIN THE
C PREDICTED VALUE FOR PRESSURE AT DISTANCE Z AND ANGLE
C THETA
C
C 960 FOP(HOEG,NUM) = GOP(NUM) * RP * FG
C
C------ MULTIPLY IMPULSE FOR A BARE HEMISPHERICAL CHARGE BY EFFECTS
C OF GEOMETRY (GI) AND BARRICADE (BI) TO OBTAIN THE
C PREDICTED VALUE FOR IMPULSE AT DISTANCE Z AND ANGLE
C THETA
C
C 960 FSOPI(HOEG,NUM) = GSOPI(NUM) * BI * GI
C
C------ CONVERT Z TO FEET
C
152
RO(INDEG,NUM) = IR(INDEG,NUM) * CPR

663 PRINT 181, IR(INDEG,NUM), ROP(INDEG,NUM), FOP(INDEG,NUM), BSOPI(NUM), FSOPI(ND)

001473 CONTINUE

001476 IF (Z - 4.9) 475, 575, 575

001480 IF (Z - 9.9) 405, 505, 505

001486 M = 25

001487 S = 0.70

001488 GO TO 300

001491 IF (Z - 44.91) 591, 611, 610

001494 M = 40

001495 S = 1.8

001496 GO TO 300

001499 IF (Z - 99.9) 605, 610, 610

001500 M = 25

001501 S = 2.1

001502 GO TO 300

001505 IF (Z - 499.41) 615, 620, 620

001508 M = 40

001510 S = 18.0

001511 GO TO 300

155 PRINT 125

001535 625 CONTINUE

C

C ISOBAR COORDINATE OPTION - THIS SECTION SOLVES FOR THE Z AT THE
C ANGLES 8 - 180 FOR THE PRESSURES INPUT AS P(IN) IN THE DATA
C

001541 IF (IN = 11) 830, 605, 645

C

001544 DO 660 M = 1, 22

001545 PP = P(N)

001546 PRINT 195, PP

001547 PRINT 154

001548 PRINT 196

C

001553 DO 680 J = 1, 77

001554 M = (J - 11) * 9

001556 LL = 140

001557 DO 670 L = 1, 141

001558 LL = LL - 1

001559 IF (FOPI(J,LL) = PP) 670, 661, 645

001560 LLL = LL + 1

001561 Z2 = 2R(J,LLL)

001562 Z1 = 2R(J,LL)

001563 P2 = FOPI(J,LLL)

001564 PI = FOPI(J,LL)

001565 Z(J,M) = ((Z2-Z1) * (PI-PP)) / (PI-P2) + Z1

001566 GO TO 675

001567 Z(J,M) = 2R(J,L)

0..636 GO TO 675

001572 670 CONTINUE

C

001587 PRINT 148, M

001588 GO TO 680

001589 PRINT 197, M, Z(J,M)

001590 CONTINUE

C

TO RUN A SINGLE PROBLEM THE FOLLOWING TWO CARDS SHOULD BE
C
C 645 CALL EXIT

END

C

TO RUN A SERIES OF PROBLEMS THE FOLLOWING THREE CARDS SHOULD BE
C
C 645 GO TO 199

153
CALL EXIT
END
GO TO 199
CALL EXIT
END
5. INPUT FORMAT

The input to the Blast Program normally is one card (See Figure 30) consisting of the following parameters and control options in their respective order on the input card:

a. SL - F6.2 Format—stack length in feet, measured parallel to the open end of the barricade, or perpendicular to the line for theta (θ) equal to zero degrees (See Figure 31).

b. SD - F6.2 Format—stack depth in feet, measured perpendicular to the open end of the barricade or parallel to the line for theta (θ) equal to zero degrees (See Figure 31).

c. SH - F6.2 Format—stack height in feet.

d. BL - F6.2 Format—barricade length in feet, measured parallel to the open end of the barricade (See Figure 31).

e. BD - F6.2 Format—barricade depth in feet, measured perpendicular to the barricade open end (See Figure 31).

f. QUAN - F8.0 Format—quantity of explosives in explosive stack in equivalent pounds of TNT. The value of QUAN is to be determined by converting the weight of explosives in the stack to its equivalent weight of TNT and multiplying by the appropriate bomb factor.

g. NTHETA - I4 Format—for 0 ≤ NTHETA ≤ 180 the computer code will solve for peak overpressures and positive impulses at selected values of scaled distance Z (4.0 ≤ Z ≤ 500.0) only along the angle specified (See Figure 31). For NTHETA = -1 the computer code will solve for peak overpressure and positive impulse
**Figure 30. Typical Input Data Card for Program BLAST**

<table>
<thead>
<tr>
<th>COLUMN NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
</tr>
<tr>
<td>30.00</td>
</tr>
</tbody>
</table>


Figure 31. Stack and Barricade Geometry Parameters
at selected values of scaled distance $s$ ($4.0 \leq s \leq 500.0$) along lines from theta $\theta$ equal to zero degrees through theta $\theta$ equal to 180 degrees in increments of 5 degrees.

d. NGPD = I4 Format—new geometry pressure data option.

For NGPD = 0 the computer code uses internal polynomial coefficients to account for stack geometry effects on peak over-pressure along lines perpendicular to the vertical stack faces and through the stack center. For NGPD > 0 the computer code will read new polynomial coefficients to account for geometric effects. NGPD must be set to a value equal to the highest degree of the new polynomials whose coefficients are to be reassigned. These coefficients will be for polynomials corresponding to B, C, and D in Equation (7) or A1, A2, and A3 in the computer code. The method for obtaining the appropriate values for these coefficients is described in Section II.

To input new pressure data for the appropriate polynomial coefficients a total of NGPD + 1 data cards are required for polynomials of maximum order equal to NGPD. Each data card will contain one coefficient for each polynomial B, C, and D in a 3E14.7 Format. The first card will contain the zeroth order coefficients for B, C, and D respectively. The second card will contain the first order coefficients for B, C, and D respectively, etc. The final card in this data set will contain the NGPD$^\text{th}$ order coefficients for B, C, and D respectively.
i. NGID = 14 Format—new geometry impulse data option.

For NGID = 0 the computer code uses internal polynomial coefficients to account for stack geometry effect on impulse along a line perpendicular to the vertical stack faces and through the stack center. For NGID > 0 the computer code will read new polynomial coefficients to account for geometric effects. The number of coefficients, number of data cards, and the values for the coefficients can be determined as in h above. The variations from part h is that the coefficients will be for polynomials F, G, and H in Equation (7) or B1, B2, B3 in the computer code.

j. NBPD = 14 Format—new barricade pressure data option.

For NBPD = 0 the computer code uses internal polynomial coefficients to account for barricade geometry effects on peak overpressure along lines perpendicular to the barricade walls and through the barricade center, and along lines through the corner where the barricade walls meet and the barricade center. For NBPD > 0 the computer code will read new polynomial coefficients as in h above. These new coefficients will be for polynomials to define pressure ratios in directions A, B, C, and D in Figure 8. The number of coefficients, number of data cards, and values of coefficients can be determined in a manner similar to part h above. Each data card will contain one coefficient for each polynomial. The data card format will be 4E14.7.

k. NBID = 14 Format—New barricade impulse data option.

For NBID = 0 the computer code uses internal polynomial coefficients to account for barricade geometry effects on impulse
ratios in directions A, B, C, and D in Figure 8. The number of coefficients, number of data cards, and values of coefficients can be determined in a manner similar to part h above. Each data card will contain one coefficient for each polynomial. The data card format will be 4E14.7.

1. NGO - I4 Format—no geometry option. For NGO = 0, the program solves the problem according to the model development and includes explosive stack geometry effects. For NGO = 1, the program solution excludes explosive stack geometry effects.

m. NBO - I4 Format—no barricade option. For NBO = 0, the program solves the problem according to the model development and includes barricade effects. For NBO = 1, the program solution excludes barricade effects.

n. IBO - I4 Format—isobar option. For IBO = 1, the program computations exclude the isobar option. For IBO = 0, the computations include the isobar option which also requires that NTHETA = -1 (See part g above).

o. NEFPRD - I4 Format—new edge to face pressure ratio data option. For NEFPRD = 0, the computer code uses internal polynomial coefficients to account for stack geometry effect on the ratio of pressure along a line through the corner where the vertical faces of the bomb stack meet and the center of the bomb stack to pressure along a line perpendicular to the vertical faces and through the stack center. For NEFPRD > 0, the computer code will read new polynomial coefficients as in h above. The number of coefficients, number of data cards, and values of
coefficients can be determined in a manner similar to part h above. Each data card will contain one coefficient in an E14.7 Format.

p. NEFIRD - E4 Format—new edge to face impulse ratio data option. For NEFIRD = 0, the computer code uses internal polynomial coefficients to account for stack geometry effect on the ratio of impulse along a line through the corner where the vertical faces of the bomb stack meet and the center of the bomb stack to impulse along a line perpendicular to the vertical faces and through the stack center. For NEFIRD > 0, the computer code will read new polynomial coefficients as in h above. The number of coefficients, number of data cards, and values of coefficients can be determined in a manner similar to part h above. Each data card will contain one coefficient in an E14.7 Format.
6. OUTPUT FORMAT

The output from the Blast Program depends on the options that are chosen on the input control card. The output will be as follows:

a. Geometry effect

(1) If the geometric effects of the stack SL X SD are to be considered, the program will print out

GEOMETRY OPTION USED
STACK LENGTH = SL  STACK DEPTH = SD

(2) If the geometric effect of the stack is not considered, the program will solve the remainder of the problem for a bare hemispherical charge and print out

GEOMETRY OPTION NOT USED

b. Barricade effect

(1) If the effect of the presence of a barricade BL X BD around the stack is to be considered, the program will print out

BARRICADE OPTION USED
BARRICADE LENGTH = BL  BARRICADE DEPTH = BD

(2) If the problem is to be solved without a barricade, the program will print out

BARRICADE OPTION NOT USED
c. Charge Weight

The equivalent amount of TNT (i.e., m lbs.) that is represented in the stack of bombs is printed out as

QUANTITY OF EXPLOSIVES IN STACK = m LBS OF TNT

4. Pressure and Impulse Distributions

(1) The azimuth angle $\theta$ is first printed

AT THETA = 0 DEGREES

(2) The following headings are then listed:

<table>
<thead>
<tr>
<th>BARE</th>
<th>MODIFIED</th>
<th>BARE</th>
<th>MODIFIED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z OVERPRESSURE</td>
<td>OVERPRESSURE</td>
<td>IMPULSE</td>
<td>IMPULSE</td>
</tr>
<tr>
<td>RADIUS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(3) Under these titles, the following computed values are printed: (a) scaled distance, (b) pressure from a bare hemispherical charge, (c) estimated pressure from the actual charge (shaped and/or barricaded), (d) positive impulse from a bare hemispherical charge, (e) estimated impulse from the actual charge, and (f) distance in feet.

e. Pressure Isobars

(1) If the isobar option has been used the program computes the scaled distance to the isobar pressures in increments of 5 degrees between the azimuth angles of 0 and 180 degrees. Scaled distance will be solved for isobar pressures of 1000, 800, 600, 400, 200, 100, 80, 60, 40, 20, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.5, and 0.1 psi.
The first line to be printed under this option is

THE ISOBAR COORDINATES FOR AN OVERPRESSURE OF 1000 ARE

(2) The next line

(PNR = PRESSURE NOT REACHED)

defines the symbol which is used instead of the radius when
the pressure given in Part (1) is not attained.

(3) The following headings are then listed:

THETA

(4) Under these titles, computed values of the azimuth
angle and scaled distance for the prescribed pressure are
printed. If the prescribed pressure is higher than any of
the computed values for the particular line of propagation,
then the symbol PNR is printed under I.

The sequence of output given by Parts (1) to (4) is
repeated for each of the pressures listed in Part (1).
APPENDIX II

FRAGMENTATION PROGRAM

1. FORTRAN PROGRAM DESCRIPTION

This computer code corresponds to the analytical model described in Section III.

The first step is to define the problem. A control card is read to instruct the computer to retain previous sets of data for barricade, fragment, or fragment dispersion on multiple runs or to read in new data for barricade, fragment, or fragment dispersion. The control card also instructs the computer to (a) solve the problem with or without a barricade, (b) sets the increments of theta (azimuth angle) and beta (angle of departure), (c) solve for a certain angular orientation of bombs in the barricade, and (d) sets the height of the center of the bomb stack.

When the barricade data are read into the code, the input is converted to radius to barricade, R3(J), and height of barricade, ZW(J), for each angle of $\theta$, $\theta(J)$. $J$ is an integer where $1 \leq J \leq (360/ITH)+1$. ITH is the increment of theta.

Initial conditions for the fragments are read into the program in terms of polar angle measured from the nose of the
bomb. The input increments of polar angle must correspond to the increments of azimuth angle for the barricade (cylindrical) coordinates (i.e., if \( \Delta \theta_{\text{output}} = 20^\circ \), values of fragment mass, initial velocity, and number of fragments must be read for values between 0° and 180° at the angles 0°, 20°, 40° ..., 180°).

To include the effect of a multiple number of bombs existing in the stack, a correction factor is included. This factor has been named "EFNB" for "Effective Number of Single Bombs in Stack." EFNB must be determined experimentally such that the fragment dispersion pattern for the "Effective Number of Bombs" is the same as for the detonated stack.

If the current problem being solved has experimental results to compare with the computer output, a permanent record can be printed with the output by using Table 4—Experimental Fragment Dispersion Data. To use this option, NCD4 is given a number on the Control Card corresponding to the number of data cards that are to be read into Table 4. The input format will be discussed in Appendix II-5. No computations are performed using these data. The information is read in and immediately printed out to establish a permanent record.

So far in this section the emphasis has been to organize the available information in a usable form for the subroutine
The subroutine in this program computes the trajectory for the fragment "launched" at the azimuth angle, $\theta$, and departure angle, $\beta$; considers properties of the fragment and forces acting on it; estimates the range, velocity, number of fragments, and fragment mass at the impact point, Table 5; and estimates the distribution along the directions of propagation, Table 6.

To produce the distribution pattern, the differences in angle for the directions of propagation are established by the value of $ITH$ read from the control card. The program is designed to solve for the distribution $360^\circ$ around the bomb stack in increments of $ITH$. $TTA$ is the name given to the angle measured from the center of the open side of a three-sided barricade to the radial direction of the trajectory. $TTA$ will take on the values $0^\circ < TTA < 360^\circ$ and will increase in increments of $ITH$. NOTE: This convention for $TTA$ is established as a standard. Actually, barricades of any shape that can be approximated by one or more broken lines of finitely many linear segments can be handled by reading in the angles and distances to the ends and the height of the segments. The format for reading in the barricade data will be described in Appendix II-5. In general, the origin for measuring theta can be placed in any
position, but the standard has been chosen to produce computer results that can be easily compared.

The computer code will solve for the increments of TTA just described when the DO statement on the major loop of TRAJ3 is as follows:

DO 1800 J = 1, JTMM1

JTMM1 is the integer value of 360° divided by increment Theta, ITH, where any resulting decimals are dropped.

\[ JTMM1 = \frac{360^\circ}{ITH} \]

Example 1. If the radial directions of the trajectory are described in 20° increments, ITH = 20, the program must go through the DO loop 360/20 or 18 times.

Example 2. For ITH = 14° the program must go through the DO loop 360/14 = 25.7 or 25 times.

If the distribution pattern is desired in a specific direction θ it is necessary to compute the number of increments of ITH in θ, rounding the result to the nearest integer value.
For future discussion, call this integer L. The Do statement in the major loop of TRAJ3 would be

```
DO 1800 J = L, L
```

Example 3. If the radial distribution is desired for the direction

\[
\tilde{\theta} = 120^\circ \text{ and } \text{ITH} = 20^\circ
\]

\[
120^\circ/20^\circ = 6
\]

OR

L = 6

Example 4. If \( \tilde{\theta} = 131^\circ \text{ and } \text{ITH} = 20^\circ \)

\[
131^\circ/20^\circ = 6.55
\]

OR

L = 7

This means that the computer would solve the problem for \( \tilde{\theta} = 140^\circ \) instead of the angle 131° desired. To avoid this difference, it would be necessary to change the increment of theta to a more suitable value to produce an angle exactly equal or very near to the desired angle. Note that when the distribution in a direction \( \tilde{\theta} \) is computed, the area effected by the fragments in that trajectory is between the angles \( \tilde{\theta} - \text{ITH}/2 \) and \( \tilde{\theta} + \text{ITH}/2 \).
For each azimuth angle TTA to be used the program will solve for a series of departure angles from the barricade, BETA. The values of BETA will be between the angles $-89^\circ$ and $+89^\circ$ since $+90^\circ$ and $-90^\circ$ are of no interest and cause problems with some of the trigometric functions. The distinct values of BETA will be determined by the increment of beta, IB, on the control card. A large value for IB will produce coarse approximations, but require fewer computations than a small value for IB.

Example 5. For IB = 20° the program will compute JBMX trajectories for each angle TTA. JBMX is computed in the program as follows:

1) The number of increments of IB in 89° dropping any resulting decimal values is NB.

$$NB = \frac{89^\circ}{20^\circ} = 4$$

2) The maximum number of increments of BETA that will be solved between $-89^\circ$ and $+89^\circ$ is JBMX.

$$JBMX = 2 \times NB + 1 = 9$$

For each value of TTA the trajectory will be computed for BETA = $-80^\circ$, $-60^\circ$, $-40^\circ$, $-20^\circ$, $0^\circ$, $20^\circ$, $40^\circ$, $60^\circ$ and $80^\circ$. 

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Example 6. For IB = 10°

1) \( NB = \frac{89°}{10} = 8 \)

2) \( JBMX = 2 \times 8 + 1 \)

\[ = 17 \]

For each value of TTA the trajectory will be computed for

BETA = \(-85°, -80°, -75°, \ldots, +80°, \) and \(+85°.\)

To change the program to compute trajectories for BETA from 0° to 89° would require the following card changes

**Statement No.**

1640-12 \( JBMX = NB + 1 \)

1640-1 \( BETA = 0. \)

Increments of beta, IB, would remain as previously discussed.

To compute a trajectory the governing parameters for the fragment must be set. Since the fragment parameters are in terms of polar bomb coordinates, the angle between the initial direction of the fragment and the bomb centerline out the nose of the bomb must be computed. This angle has been named GAMMA and will be a function of TTA, BETA, and the angle to the centerline out the nose of the bomb, ANGD. This computation appears in the program as statement 1640 + 17.
\[ 1640 + 17 \ \text{GAMMA} = (\text{ASIN}((\text{SBS} + \text{CBS} \times \text{SNS}) ^{0.5})) \times 57.3 \]

where

- \( \text{SBS} = \text{SIN}^2(\text{BETA}) \)
- \( \text{CBS} = \text{COS}^2(\text{BETA}) \)
- \( \text{SNS} = \text{SIN}^2(\text{THETA-ANGD}) \)

Since GAMMA can take on any value between 0° and 180° and the fragment parameters are read in at discrete angles, the values at the discrete angle nearest to GAMMA are applied as the conditions at GAMMA.

Each trajectory is computed as a broken line of finitely many linear segments as indicated by Equations (26a) to (26c). The initial conditions at the beginning of each linear segment are the initial conditions at the bomb stack or are the end conditions from the previous segment.

The difference in angle \( a \) between adjacent segments is DEL. The value of DEL is computed in the program as a function of position, velocity, and direction of fragment velocity.

The initial value of DEL is computed so that the horizontal distance that the fragment has traveled after the first step is slightly beyond the barricade wall. This appears in the program at Statement No. 1640 + 21 as

\[ 1640 + 21 \ \text{DEL} = G \times 1.01 \times \text{DISTB} / (\text{VZER} \times \text{VZER}) \]

where

- \( G = \text{gravity constant} \)
- \( \text{DISTB} = \text{distance to barricade} \)
- \( \text{VZER} = \text{initial velocity at bomb stack} \)
Succeeding values of DEL are computed in such a way that either
the increase in range or change in height is 50 ft. depending
on whether or not BETA is less than or greater than 45° respec-
tively. In the computer program the statements appear as
follows: To increment the range in 50 feet increments state-
ment 1752 is used

1752 DEL = G * 50./VSQ

Check if absolute value of BETA is greater than 45°, if it is,
DEL is changed by the two statements following 1725:
1725 + 1 VAL1 = ABS(ALPH1)
1725 + 2 (VAL1.GE.0.7853) DEL = ABS(DEL*COSAL1)/SINAL1)

where

ALPH1 = the angle the segment of the trajectory being
considered makes with the horizontal.

COSAL1 = COS(ALPH1)

SINAL1 = SIN(ALPH1)

Two exceptions exist that cause DEL to take on different
values than just described. The first exception occurs when
the value of DEL that is computed as above is used in Statement
No. 1546+4 and the resulting velocity, V2, is negative. V2 is
the predicted velocity at the end of the linear segment being
considered. In this case DEL is repeatedly cut in half and the
velocity recalculated until $V_2$ remains positive. This check and modification is done with Statement Numbers 1649-3 to 1649-1.

1649-3 IF($V_2 .GT. 0.$) GO TO 1649
1649-2 DEL = DEL/2.
1649-1 GO TO 1646

The second exception occurs near the top of the trajectory when the speed of the fragment is less than 100 feet/second. The value of DEL should be much less than one. Since DEL is a function of one divided by speed squared, small speeds can produce values for DEL on the order of one hundred. To avoid this possibility, set DEL equal to 0.1 for speeds less than 100 fps to establish the proper order of magnitude and let the routine in the preceding paragraph make any further modifications that may be required. This adjustment to the program variable DEL is checked and modified with statements 1725-3 to 1725-1 as follows:

1725-3 IF($V_1 .GT. 100.$) GO TO 1725
1725-2 DEL = .1
1725-1 GO TO 1645

The last bit of information required before computing the trajectory is the Ballistic Coefficient $C$ which is a function of the fragment mass and hence it must be calculated for each
trajectory since fragment mass varies with the direction of "launch", C is computed in statement 1645-1.

\[ 1645-1 \quad C = \frac{RHP \cdot CD}{(FM(K)^{0.33333})} \]

where

- \(RHP\) = a combined set of constants for a fragment
- \(CD\) = drag coefficient
- \(FM(K)\) = fragment mass in the direction of launch

To indicate if the top of the barricade has been cleared or not cleared, a dummy variable, NBCL, is used. Initially the value of NBCL is -1 indicating that the barricade has not been cleared. If there is no barricade in the radial direction of the trajectory or if the fragment clears the top of the barricade, NBCL is set equal to +1 and the trajectory of the fragment is computed.

The trajectory of the fragment is approximated by a broken line of finitely many linear segments where the angle between the segment and a horizontal line is continuously decreasing. The initial conditions for each segment are known from the terminal conditions of the previous segment or the initial conditions at the bomb. The initial conditions for a segment include range, \(X_1\), altitude, \(Y_1\), velocity, \(V_1\), and angle between the trajectory segment and a horizontal line, \(\alpha_1\). The terminal conditions include range, \(X_2\), altitude, \(Y_2\), velocity, \(V_2\) and direction of terminal velocity, \(\alpha_2\). The terminal conditions
for each segment are computed as the trajectory is mapped until the fragment strikes the ground inside the barricade, strikes the barricade wall, or clearing the barricade and impacts the ground at some distance. The printed output from the program, discussed in detail in Appendix II-6, will include information to indicate that the fragments do not clear the barricade or will record the impact range and velocity for each combination of launch angles TTA and BETA.

The number of fragments landing at each impact point is assumed to be the same as the number initially launched in the trajectories by a single bomb multiplied by the number of effective bombs, EFNB. The number of fragments, NUM(K), in a trajectory will be dependent on the angles TTA and BETA and the increments of each of these angles ITH and IB. NUM(K) can be approximated using equation III-36. In the program this appears as statement 1645-10.

1645-10 NUM(K) = FPS(IGAMA) * RITH * (SIN(RBTA2)) - SIN(RBTA1) * EFNB

where

K - indicates the angle of departure, BETA
IGAMA - indicates the angle GAMMA
FPS( ) - fragments per steradian
RITH - increment of theta, TTA, in radians
RBTA2 - radians to angle BETA + IB/2
RBTA1 - radians to angle BETA - IB/2
EFNB - effective number of bombs in stack
With the impact conditions known along the radial directions from the barricade, the average distribution/sq. ft. can be estimated by the theory of Section III.4f. The data along a radial direction are ordered according to the increasing magnitude of impact ranges using statements 1740 + 1 through 1790. The assumed impact area, the number of fragments/sq. ft. and weight of fragments/sq. ft are computed and then printed as Table 6.
2.0 FRAGMENTATION PROGRAM FLOW DIAGRAM

START

READ PROGRAM AND PROBLEM IDENTIFICATION

PRINT PROGRAM AND PROBLEM IDENTIFICATION

READ KEEP2, KEEP3, KEEP4, NCD2, NCD3, NCD4, KFLAG, ITH, IB, ANGD, HCB

ALL PROBLEMS COMPLETE

PRINT KEEP2, KEEP3, KEEP4, NCD2, NCD3, NCD4, KFLAG ITH, IB, ANGD, HCB

KEEP2 = 1

Yes

No

STOP

Yea

| 178 |
PRINT HEADING ON TABLE 2, BARRICADE DATA

DO FOR EACH CARD IN TABLE 2

READ BARRICADE DATA TH1, R1, TH2, R2, HB

PRINT BARRICADE DATA TH1, R1, HB, TH2, R2, HB

COMPUTE DISTANCE TO BARRICADE AND HEIGHT OF BARRICADE FOR EACH VALUE OF THETA USED

DUPLICATE VALUES FOR A DIRECTION THETA (J)

Yes

USE VALUE THAT YIELDS SMALLEST R3(J)

CONTINUE
PRINT HEADING ON TABLE 3, FRAGMENT DATA

DO FOR EACH CARD IN TABLE 3

READ FRAGMENT INITIAL CONDITIONS
TH1, AFM1, VOL, FPS1

INDEX FRAGMENT INITIAL CONDITIONS IN TERMS OF OUTPUT ANGLES

PRINT INDEXED FRAGMENT INITIAL CONDITIONS
TH2, AFM(i), VO(i), FPS(i)
Yes

NCD4 = 0

No

PRINT HEADING ON TABLE 4. EXPERIMENTAL FRAGMENT DISPERSION DATA

DO FOR EACH CARD IN TABLE 4

READ EXPERIMENTAL FRAGMENT DISPERSION DATA XC, YC, XH, YV, NF1, W1, UW1, NF2, W2, UW2, NF3, W3, UW3

PRINT EXPERIMENTAL FRAGMENT DISPERSION DATA XC, YC, XH, YV, NF1, W1, UW1, NF2, W2, UW2, NF3, W3, UW3

CALL SUBROUTINE TRAJ3

RETURN TO START
SUBROUTINE TRAJ3

READ CD, NEFB

DO FOR EACH INCREMENT OF AZIMUTH ANGLE, THETA

SET CONDITIONS ON MINOR LOOP

PRINT HEADING ON TABLE 5. RANGE AND VELOCITY DATA

DO FOR EACH INCREMENT OF DEPARTURE ANGLE, BETA

COMPUTE GAMMA

SET INITIAL CONDITION FOR THE DIRECTION (THETA BETA) BASED ON THE ANGLE GAMMA
1. **COMPUTE TRAJECTORY OF FRAGMENTS**

2. **DO FRAGMENTS CLEAR BARRICADE**
   - **Yes**
     - **COMPUTE IMPACT RANGE, VELOCITY, AND NUMBERS - K1, V1, NUM(K)**
   - **No**
     - **PRINT RANGE AND VELOCITY DATA TTA, BETA XI, V1, NUM(K), FM(K)**

3. **PRINT RANGE AND VELOCITY DATA TTA, BETA, FRAGMENT DOES NOT CLEAR BARRICADE**

4. **CONTINUE**

5. **CALL SUBROUTINE ORDER**

6. **CONTINUE**

7. **RETURN**
SUBROUTINE ORDER

PRINT HEADING ON TABLE 6: DISTRIBUTION DATA

ARRANGE IMPACT RANGES IN INCREASING ORDER OF MAGNITUDE

DO FOR EACH INCREMENT OF BETA

CALCULATE REPRESENTATIVE IMPACT AREA, AREA

AREA = 0.0

Yes

No

COMPUTE DENS, WTPA

PRINT DISTRIBUTION DATA RA1, RA2, VV(I), DENS, WTPA

CONTINUE

RETURN
3. LIST OF VARIABLES TO COMPUTER PROGRAM FOR ANALYTICAL FRAGMENTATION MODEL

AFM(J)  Average fragment mass emitted by bomb at an angle GAMMA

ALPH1  Direction of fragment velocity at start of a segment of trajectory.

ALPH2  Direction of fragment velocity at end of a segment of trajectory

ANG  Number of radians in TH1.

ANGD  Equal to θ_B in Section III

AREA  Representative area of impact zone for a trajectory.

BETA  Angle between horizontal and initial velocity of fragment.

BETA1, etc.  Angles defining region containing trajectory, used to calculate number of steradians.

C  Ballistic coefficient

CBETA  Cos(BETA)

CBS  Cos^2(BETA)

CD  Drag coefficient

COSAL1, etc.  COS(ALPH1), etc.

D  Distance along barricade

DB  Increment BETA divided by 2.

DELDG  DEL/G

DELTG  Angle between R3 and barricade wall.

DENS  Number of fragments/sq.ft. in impact zone

DISTB  Distance to barricade from center of bomb stack.
DTH
DTHB2
Dl
EFNB
ETA
FITH
FL1, etc.
FM
FPS(J)
G
GAMMA
HB
HCB
HEITB
IB
IGAMA
ITH
JBMX
JTHMX
KANG
KEEP 2
KEEP 3

Angle between ends of barricade segment.
Increment of THETA divided by 2.
Intermediate value to solve for SII and ALPHA.
Number of single bombs to produce same distribution as bomb stack.
Difference between barricade and bomb coordinates.
Floating point increment of THETA.
Floating-point number of TH1, etc.
Fragment mass.
Average fragment/staradian in direction GAMMA, bomb coordinates.
Gravitational constant.
Angle between VO and bomb centerline.
Height of barricade for segment defined by TH1-TH2.
Height of center of bomb stack about ground.
Height of barricade.
Increment of departure angle BETA.
Integer number of increments of THETA in GAMMA.
Increment of azimuth angle THETA.
Number of increments of BETA (IB) between -89° and 89°.
Number of integer values of ITH in 360°.
Integer value for ANGD.

IF 1, Hold Table 2 Data from previous run.
IF 1, Hold Table 3 Data from previous run.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEEP4</td>
<td>IF 1, hol: Table 4 Data from previous run.</td>
</tr>
<tr>
<td>KFLAG</td>
<td>Indicator to initialize R3 and ZW to zero.</td>
</tr>
<tr>
<td>KNG1</td>
<td>Integer number of increments ITH between barricade and bomb coordinates.</td>
</tr>
<tr>
<td>KTH1</td>
<td>Integer degrees to start of barricade segment.</td>
</tr>
<tr>
<td>KTH2</td>
<td>Integer degrees to end of barricade segment.</td>
</tr>
<tr>
<td>NB</td>
<td>Max. number of increments of BETA in 89°.</td>
</tr>
<tr>
<td>NBCL</td>
<td>Index to indicate when barricade has been cleared.</td>
</tr>
<tr>
<td>NCD2</td>
<td>Number of cards to be read for Table 2.</td>
</tr>
<tr>
<td>NCD3</td>
<td>Number of cards to be read for Table 3.</td>
</tr>
<tr>
<td>NCD4</td>
<td>Number of cards to be read for Table 4.</td>
</tr>
<tr>
<td>NF1, etc.</td>
<td>Number of fragments in impact area 1, etc.</td>
</tr>
<tr>
<td>NTH1</td>
<td>Nearest integer number of increments of ITH in TH1.</td>
</tr>
<tr>
<td>NTH2</td>
<td>Nearest integer number of increments of ITH in TH2.</td>
</tr>
<tr>
<td>NUM(K)</td>
<td>Number of fragments in a given trajectory.</td>
</tr>
<tr>
<td>PHI</td>
<td>Angle between barricade and R2.</td>
</tr>
<tr>
<td>RA1</td>
<td>Radius to inner bound of representative impact area.</td>
</tr>
<tr>
<td>RA2</td>
<td>Radius to outer bound of representative impact area.</td>
</tr>
<tr>
<td>RBETA</td>
<td>Number of radians in BETA.</td>
</tr>
<tr>
<td>RBETA1, etc.</td>
<td>Number of radians in BETA1, etc.</td>
</tr>
<tr>
<td>RETA</td>
<td>Number of radians in ETA.</td>
</tr>
<tr>
<td>RHP</td>
<td>Constants for computing drag force.</td>
</tr>
</tbody>
</table>
RIB  Number of radians in increment BETA.
RITH  Number of radians in ITH.
RKTH1, etc.  Number of radians in TH1, etc.
RTH1  Radians in TH1.
RTH2  Radians in TH2.
R1  Radius to beginning of barricade segment being defined.
R2  Radius to end of barricade segment being defined.
R3(J)  Distance to barricade at angle corresponding to J increments of azimuth angle THETA.
SBETA  Sin(BETA)
SBS  Sin²(BETA)
SINAL  Sin(ALPH1)
SII  Angle between barricade and R1.
SN  Sin(ETA)
TH1  Angle to beginning of barricade segment being defined.
TH2  Angle to end of barricade segment being defined.
TS  Tan(S1)
TTA  Azimuth angle, THETA, using cylindrical barricade coordinates.
TTA1, etc.  Angles defining region containing trajectory, used to calculate number of steradians.
UF1, etc.  Maximum fragment weight, grams, etc.
VAL1  Absolute value of ALPH1.
VO(J)  Average fragment velocity in direction GAMMA.
VSQ  Velocity squared.
VSQD  Velocity squared divided by DEL.
VV(I)  Velocity vector.
VZER  Initial velocity.
V1  Velocity at start of a segment of trajectory.
V2  Velocity at end of a segment of trajectory.
WTPA  Weight per sq. ft. at impact areas.
WL, etc.  Minimum fragment weight, grams, etc.
XC  X coordinates of impact area.
XH  WIDTH of impact area.
XV(I)  Range vector.
X1, X2  Initial and end conditions for a segment of trajectory.
YC  Y coordinates of impact area.
YV  Length of impact area.
Y1, Y2  Initial and end conditions for a segment of trajectory.
ZW(J)  Height of barricade at distance R3(J).
4. PRINTOUT OF FRAGMENTATION PROGRAM
PROGRAM FUNCTION (INPUT, OUTPUT)

1. COMMON  TN(30), XMZ(30), VM(30), FPS(90), PT(35), JMAX,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
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   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
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   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
   1. NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW, NW,
```plaintext
101000
111101

TH1 = ITM
2TH1 = TH1 / 57.30

c---- IF KFLAG = 0 INITIALIZE R1 AND 2W TO zero

200101
700101
700101
700101
700101
700101
700101
700101
700101
700101
700101
700101
700101

IF ( KFLAG = EQ = 0 ) GO TO 992
777177
777177
777177
777177
777177
777177
777177
777177
777177
777177
777177
777177
777177

997 IF ( KFLAG = EQ = 1 ) GO TO 699

c------ INPUT TABLE 2 - BARRICADE DATA

)c------ THETA IS THE ANGLE MEASURED FROM THE CENTERLINE OF THE OPEN SIDE

)c------ OF A THREE SIDED BARRICADE

)c------ ANG1 IS THE ANGLE FROM THETA = ZERO TO THE CENTERLINE OF TH BOMP.

)c------ MESSurement AWAY IN SAME DIRECTION IS PLUS THETA. (E.G., ANGLE. E. +360 )

600171
600171
600171
600171
600171
600171
600171
600171
600171
600171
600171
600171
600171

+THM T 316
+THM T 314
+THM T 314
+THM T 314
+THM T 314
+THM T 314
+THM T 314
+THM T 314
+THM T 314
+THM T 314
+THM T 314
+THM T 314
+THM T 314

DO 621 I = 1, NC02
600204
600204
600204
600204
600204
600204
600204
600204
600204
600204
600204
600204
600204

READ S1A, TH1, R1, R2, H9
PRNT S1A, TH1, R1, R8, R8, H9

)c------ CONVERT INTEGER VALUES IN DEGREES TO NEAREST MULTIPLE OF ITM (IN-

)c------ DEGREES OF POLAR ANGLE )

600261
600261
600261
600261
600261
600261
600261
600261
600261
600261
600261
600261
600261

NTM1 = ( TH1 / THM1 ) + 0.5
NTM2 = ( TH2 / THM1 ) + 0.5
KTH1 = NTM1 " THM1
KTH2 = NTM2 " THM1

)c------ CONVERT INPUT ANGLES TH1 AND TH2 INTO RADIANS

600231
600231
600231
600231
600231
600231
600231
600231
600231
600231
600231
600231
600231

THM1 = TH1 / 57.30
THM2 = TH2 / 57.30

)c------ CONVERT ANGLES KTH1, KTH2, TO RADIANS

600257
600257
600257
600257
600257
600257
600257
600257
600257
600257
600257
600257
600257

FL1 = KTH1
FL2 = KTH2

)c------ CONVERT INTEGER VALUES OF KTH1 AND KTH2 TO INTEGER INCREMENTS FOR

)c------ INDEXING PURPOSES

600264
600264
600264
600264
600264
600264
600264
600264
600264
600264
600264
600264
600264

J1 = KTH1 + 1
J2 = KTH2 + 1

)c------ COMPUTE ANGLES OF TRIANGLE MADE BY R1, R2, AND BARRICADE

600267
600267
600267
600267
600267
600267
600267
600267
600267
600267
600267
600267
600267

DTM = KTH2 - KTH1
D1 = 0.5 * ( 3.14 - DTM )
TS = TAN ( 91 )
D2 = ATAN ( ( ( R1 - R2 ) / ( R2 + R1 ) ) * TS )
DTH1 = SIN D1
DTH2 = R1 * ( SIN(DTH1) / SIN(DTH2) )
ANG = KTH1

)c------ SET HEIGHT OF BARRICADE FOR EACH INCR OF THETA FROM JTH1-JTH2

192
```
DO 615 J = J1, J2

C-----COMPUTE ANGLE MADE TV RT AND MARRIAGE WALL

DO 615 J = J1, J2

DELTA = 5.14 - ( PHI + ( RTH2 - ANG ) )

C-----SET HEIGHT OF MARRIAGE FOR DISTANCE R(J)

RD(J) = ANG * ( SIN(PHI) / SIN(Delta) )

C-----CHECK FOR DUPLICATE VALUES OF J--IF TNPFL ARE TWO VALUES OF J / IF

C TWO VALUES OF Y(J, O) THEN USE VALUE THAT YIELDS SMALLEST R3(J)

IF ( (J-1).LT.0.0, (J-JL)) .LT.0 ) GO TO 615

IF ( RI(J).LT.RD(J)) GO TO 615

R(J) = RD(J)

R(J) = R(J)

C-----INPUT TABLE 3 = FRAGMENT DATA

C-----INPUT TABLE 4 = EXPERIMENTAL FRAGMENT DISPERSION DATA

PRINT 577, GAMMA, A(N2), VO(N2), FPS(N2)

CONTINUE

PRINT 577, GAMMA, A(N2), VO(N2), FPS(N2)

CONTINUE

PRINT 577, GAMMA, A(N2), VO(N2), FPS(N2)

CONTINUE

PRINT 577, GAMMA, A(N2), VO(N2), FPS(N2)

CONTINUE

PRINT 577, GAMMA, A(N2), VO(N2), FPS(N2)

CONTINUE

PRINT 577, GAMMA, A(N2), VO(N2), FPS(N2)

CONTINUE

PRINT 577, GAMMA, A(N2), VO(N2), FPS(N2)

CONTINUE
977525  SN = SIN(PT1)
977527  C = COS(PT1)
977529  RT = .RTA

C---------- MINOR LOOP ---------------------
C-------- INCIDENT DEPARTURE ANGLE, RFTA, FROM 0 TO 90 DEGREES

977535  DO 1740 K = 1, 100
977537  RFTA = RFTA / .943
977539  RFTA = COS(RFTA)
977541  RFTA = SIN(RFTA)
977543  RFTA = RFTA * RFTA

C--------- GAMMA IS THE ANGLE BETWEEN THE INITIAL VELOCITY OF THE
C--------- FRAGMENT AND THE CENTERLINE OF THE RORS

977547  GAMMA = (100 (999 + C09 * GW1 ) **.5 ) / 57.3
977553  C = PRINT 1511, GAMMA
977557  1641 FORMAT ( 169, 19.6 )

C---------- COMPUTE NEAREST NUMBER OF INCREMENTS OF THETA(Ith) IN GAMMA

977567  IS4NA = GAMMA / 41.5
977569  C = PRINT 1669, IS4NA
977573  1659 FORMAT ( 169, 19.6 )
977575  FN4K(I) = FN4K(IS4NA)

C---------- SET INITIAL VELOCITY FOR THE FRAGMENT

977558  V7ER = V0T4K)

C---------- SET DEL

977559  NEL = G * 1.919141710 / (V7ER * V7ER)
977561  69 = ID / 2.
977563  RFTA1 = RFTA + 69
977565  RFTA2 = RFTA + 69
977567  RFTA1 = RFTA1 / 57.3
977569  RFTA2 = RFTA2 / 57.3

C---------- COMPUTE THE NUMBER OF FRAGMENTS EJECTED IN DIRECTION OF TRAJECTORY
C----------- INCLUDE THE EFFECTIVE NUMBER OF RORS

977572  NUN(I) = FN4K(I) * COS ( (SIN(RFTA1) - SIN(RFTA2)) * EFNA
977576  199417  ALPH1 = RFTA
977578  199419  V1 = V7ER
977580  199416  V1 = V1

C----------- INCLUDE THE EFFECTIVE NUMBER OF RORS

977582  N3CL = -1 * FRAGMENT HAS NOT CLEARED RARRICAGE
C----------- INCLUDE THE EFFECTIVE NUMBER OF RORS

977584  NSError = +1 * FRAGMENT HAS CLEARED RARRICAGE

977588  NSError = -1
977591  IF ( NSError LT .9999 ) N3CL = +1
977593  C = COS(LTH01)
977595  V97 = V1 * V1
977597  C = ANP + CO / ( FN(K) **.37333 )
977601  C = PRINT 1551, C
977603  1579 SINA1 = SIN(ALPH1)
977605  1564 DEL0G = DEL / G
977607  1570 V570 = V97 * DEL0G

195
177745  C10° = ALP1 - DEL
177747  COSAL2 = COS(ALPH2)

177757  V2 = ( V1 * COSAL1 - G * V1 * VSO ) / COSAL2
177755  IF ( V2.GT.0.0 ) GO TO 1649
177760  DEL = DEL / 2.
177761  GO TO 1675
177762  1540 X2 = X1 + VSO
177764  Y2 = Y1 + VSO * SINA1 / COSAL1

CHECK TO SEE IF PARTICLE HAS HIT THE GROUND INSIDE BARRICADE OR
HAS STRUCK THE BARRICADE WALL.

177767  IF (N9GCL ) 1650,1700,1700
177771  1650 IF(Y2) 1660,1670,1670
177777  1660 PRINT 1970A, XTA, ETA
177783  VV(K) = X1
177784  VV(K) = V1
177785  GO TO 1700
177787  1670 IF(DISTA - Y2) 1690,1720,1720
178012  1690 IF(WHTA-Y2) 1690,1660,1660
178015  1670 N9GCL = 1
178016  GO TO 1720
178017  1700 IF(Y2) 1710,1720,1720
178021  1710 PRINT 1923, XTA, ETA, X1, VI, NUM(K1), FM(K)
178041  VV(K) = X1
178042  VV(K) = V1
178044  GO TO 1700
178046  1720 ALP1 = ALP1
178048  COSAL1 = COSAL2
178050  V1 = V2
178093  Y1 = Y2
178093  VSO = V1 * V1
178095  IF ( V1.GT.100. ) GO TO 1430
178095  DEL = 0.1
178096  GO TO 1649
178097  1730 DEL = G * 59. / VSO
178094  VAL1 = ABS(ALP1)
178095  IF ( VAL1.GT.1.7893 ) DEL=ABS(DEL*COSAL1/SINA1)
178094  GO TO 1645
178095  1740 CONTINUE
181071  CALL DROP
181073  1800 CONTINUE
181076  RETURN
181078  END
SUBROUTINE DGRED
C------ ARRANGE RANGES IN INCREASING ORDER OF MAGNITUDE
C
11334 COMMON TN(199), ANG(199), VU(199), FPS(360), R3(360), JMAX,
1 JMAX, WCA, ANGO, JTHIX, JBMX, TM, TH, "TH, "TH, "TH, "TH,
2 TH1, TH1, FN(140), XV(140), VV(140), NUM(140), TN(140),
3 TN(141), TX(141), TV(147)
C 11335
C 255 FORMAT(242) TABLE G, DISTRIBUTION DATA, 5X, 5NTETA(1) =,
1 14.7, 245 DEGREES THETA(2) =, F4.3, 45 DEGREES, /
2 5X, TH Range 1, 10H RANGE 2, 50H Thr vel, for num/so ft
3 (GRAVS/90 FT)
11336
11337 2574 FORMAT (2X, 2F10.0, F13.1, 2(F4.3))
11338 DO 2794 NN = 2, JMAX
11339 NN1 = NN - 1
11340 DO 2794 N = 1, NUM1
11341 IF ( XV(N1) = XV( N) ) 2750, 2797, 2799
11342 2750 NN1 = N + 1
11343 DO 2493 NN1 = NN1 + NN
11344 IT11 = IT1 - 1
11345 TV(II) = TV(I111)
11346 Y(II) = Y(I111)
11347 TM(II) = NUM(I111)
11348 2753 FM(II) = FM(I111)
11349 XV(N) = XV(NN)
11350 XV(N) = XV(NNN)
11351 FM(N) = FM(NNN)
11352 FM(N) = FM(NN)
11353 DO 2754 I = NN1, NN
11354 TV(I) = TV(I1)
11355 XV(I) = XV(I1)
11356 NUM(I) = NUM(I1)
11357 TN(I) = TN(I1)
11358 2754 FM(I) = TN(I1)
11359 2490 CONTINUE
11360 2490 PRINT 2575, TT1, TT2
11361 PA1 = 0.0
11362 DO 2794 T = 1, JMAX
11363 IP1 = I + 1
11364 PA2 = ( XV( I) + XV( IP1) ) / 2
11365 IF ( PA1.EQ.PA2 ) GO TO 2795
11366 2795 IF ( I.EQ.JMAX ) GO TO 2797
11367 2794 GO TO 2797
11368 2797 IF ( PA1.EQ.PA2 ) GO TO 2794
11369 2794 IF ( APEA.LT.1.0 ) GO TO 2794
11370 2794 GO TO 2797
11371 APEA = XV( I) * RTH * ( PA2 - PA1 )
11372 IF(I.EQ.JMAX) GO TO 2797
11373 2794 GO TO 2797
11374 2794 IF ( APEAL.T.1.0 ) GO TO 2794
11375 APEAL = XV( I) * RTH * ( PA2 - PA1 )
11376 2794 GO TO 2794
11377 DENS = NUM(I) / AREA
11378 C----- COMPUTE WEIGHTS/FT. ( GRAMS/FT.
11379 C
11380 2575 PRINT 2575, PA1, PA2, XV( I), DENS, WTPA
11381 2795 WTPA = PA1 * FM(I)
11382 2795 CONTINUE
11383 RETURN
11384 C
197
5. INPUT FORMAT

The input cards to a problem will depend on the problem being run and the number of variations to be considered in a run. The input to a single run or the first data set of a multiple run will include a card to describe the problem, a control card to instruct the memory to read data for the problem and set parameters, a series of cards containing data to define the barricade geometry surrounding a charge, a series of cards containing fragment initial condition in terms of polar bomb coordinates, and a card containing the typical drag coefficient for a bomb fragment and the number of effective bombs in the stack.

Subsequent data sets on multiple runs will include a card to describe the problem, a control card to instruct the memory storage to retain information from the previous run or to read new data for some or all of the data. If the barricade geometry is to be changed, a series of cards will be included to define the new geometry; otherwise, these cards are omitted. If the geometry of the bomb stack is to be changed, a series of cards containing the fragment initial conditions in terms of polar bomb coordinates will be included; otherwise, these cards are omitted. A card containing the drag coefficient and the number of effective bombs will be included in all data sets.
a. Description Card

Provisions are included to use the first card of each data set to describe in an alphanumeric format the problem being solved. The field for this format will be 80 spaces on one card.

b. Control Card

The second card in a data set will contain information as follows:

(1) KEEP2, I5 Format

In Columns 1-5 enter a zero (0) in Column 5 if barricade data is to be read during execution of the current problem. Enter a one (1) in Column 5 if barricade data is to be retained from the previous problem or if the problem is to be solved without a barricade.

(2) KEEP3, I5 Format

In Columns 6-10 enter a zero (0) in Column 10 if the fragment initial conditions are to be read from data cards during execution of the current problem. Enter a one (1) in Column 10 if fragment initial conditions are to be retained from the previous problem. A one (1) in Column 10 only applies on multiple runs and a zero (0) will be necessary on the initial problem of multiple runs and all single problem runs.

(3) KEEP4, I5 Format

In Columns 11-15 enter a one (1) in Column 15 if experimental fragment dispersion data is to be retained
from the previous problem. Otherwise, enter a zero (0) in Column 15. A one (1) in Column 15 only applies on multiple runs.

(4) \textit{NCD2, NCD3, NCD4, IS Format}

In Columns 16-20, 21-25, and 26-30, enter the number of data cards that are to be read containing barricade data, fragment initial conditions, and experimental dispersion data, respectively.

(5) \textit{KFLAG, IS Format}

In Column 35 enter a zero (0) when reading new barricade data or to solve the problem without a barricade. If, on a multiple run, barricade data from the previous run is to be retained, enter a one (1) in Column 35.

(6) \textit{ITH, IS Format}

In Column 36-40 enter the increment size for the azimuth angle, TTA. A small value for ITH will require larger numbers of fragment data cards to be read and more computations than large values, which are less accurate but faster. In general, a value of 20° for ITH will produce useful results and require reasonable computer time.

(7) \textit{IB, IS Format}

In Columns 41-45 enter the increment size for the departure angle, BETA. Small values for IB will yield more trajectories and impact points and produce a more accurate distribution, but more computer time will be required.
In general, a value of 10° for IB will produce useful results and require reasonable computer time.

(8) ANGD, F5.0 Format

In Columns 46-50, enter the angle between TTA = zero (0) and the centerline out the nose of the bombs in the bomb stack. ANGD will be measured CCW and lie between 0° and +360°.

c. Barricade Data, 5F10.1 Format

Barricade data cards need to be included on single runs, initial problem of multiple runs, and on occasional problems of multiple runs when it is desired to change the barricade configuration. Each card will contain five (5) values to be read in a 5F5.1 Format. The data on the card will be the information necessary to define the finite number of linear segments representing the barricade. Each segment will require one (1) card. The card for each segment will contain the following information in the order presented.

(1) TH1, F5.1 Format

TH1 is the angle, degrees, to the start of the segment being defined.

(2) R1, F5.1 Format

R1 is the distance, ft., from the center of the bomb stack to the start of the segment being defined.

(3) TH2, F5.1 Format

TH2 is the angle, degrees, to the end of the segment being defined.

(4) R2, F5.1 Format

R2 is the distance, ft., from the center of the bomb
stack to the end of the segment being defined.

(5) \( HB, F5.1 \) Format

\( HB \) is the height, ft., of the segment being defined.

d. Fragment Initial Conditions

The cards described in this section are required only on single runs, initial problems of multiple runs and on intermediate problems of multiple runs when the fragment data is to be altered.

One data card will be required for each polar angle where the fragment initial conditions are to be read in. The input angles will begin with 0° and increase in increments equal to the increment of TTA, ITH, previously chosen. The number of card containing fragment initial conditions is equal to NCD2.

Each card will contain the following information:

1. **GAMMA, F10.0 Format**

   Enter in Columns 1-10 the polar angle, degrees, measured in spherical bomb coordinates from the nose of the bomb.

2. **AFM1, F10.0 Format**

   In Columns 11-20 enter the average value over the region \( \text{GAMMA} + 1/2 \text{ITH} \), for the fragment mass, grams, in the direction GAMMA.

3. **VOL, F10.0 Format**

   In Columns 21-30 enter the average value, over the region \( \text{GAMMA} + 1/2 \text{ITH} \), for the fragment velocity ft./sec., in the direction GAMMA.
(4) FPS1, F10.0 Format

In Columns 31-40 enter the average value, over the region GAMMA + 1/2 ITH, for the number of fragments per steradian ejected by a single bomb in the direction GAMMA.

e. Experimental Fragment Dispersion Data

When experimental results are available for a problem being solved by the program, the experimental measurements may be read into the program to produce a printed record for comparison with the results predicted by the code. There will be one data card for each fragment recovery area. The information on each data card will be as follows:

(1) XC, F6.1 Format

Enter in Columns 1-7 the distance, ft., from the center of the bomb stack to the center of the recovery area measured parallel to the direction TTA = zero.

(2) YC, F6.1 Format

Enter in Columns 7-12 the distance, ft., from the center of the bomb stack to the center of the recovery area measured parallel to the direction of TTA = 45°.

(3) XH, F6.1 Format

Enter in Columns 13-18 the dimension, ft., of the recovery area in the direction of XC.
(4) Yv, F6.1 Format

Enter in Columns 19-24 the dimension, ft., of the recovery area in the direction of YC.

(5) NF1, NF2, NF3, IS Format

Enter in Columns 25-29, 40-44, and 55-59 the number of fragments recovered in the recovery area in the heaviest weight class, second heaviest weight class, and third heaviest weight class, respectively.

(6) W1, W2, W3 F5.1 Format

Enter in Columns 30-34, 45-49, and 60-64 the minimum fragment weight, grams, in heaviest weight class, second heaviest weight class, and third heaviest weight class, respectively.

(7) UW1, UW2, UW3 F5.1 Format

Enter in Columns 35-39, 50-54, and 65-69 the maximum fragment weight, grams, in heaviest weight class, second heaviest weight class, and third heaviest weight class, respectively. More than three weight ranges can be included by changing Formats 530 and 536 and by increasing the number of variables in Statements 650+3 and 650+4.

f. Drag Coefficient and Effective Number of Bombs in Stack (CD and EFNB)

(1) CD, F8.2 Format

In Columns 1-8 enter the value of the drag coefficient to be read in a F8.2 Format. This card is required for each
problem of a multiple run and obviously for a single run. Setting drag coefficient equal to zero will solve for friction free trajectory. In general, CD will have a value between 0.3 and 2.0.

(2) EFNB, F8.2 Format

In Columns 9-16 enter the number of single bombs that must be exploded one at a time to produce the same fragment dispersion pattern as the bomb stack being modeled. In general, EFNB will be less than the actual number of bombs in the stack.

g. Blank Cards

After the last data set, include two blank data cards to terminate the run.

Notes on data sets

Normally a single run or the first problem of a multiple run will require data cards a, b, c, d, and f as a minimum. The inclusion of e is optional on any problem. These data cards will describe the problem and solve the dispersion pattern for a number of bombs in a specific barricade configuration.

If on the second problem of a multiple run the barricade geometry is to be changed and the bomb stack remains the same as the first problem, data cards a, b, c, and f would be included in the data set.
If, instead of changing the barricade on the second problem, the type of bomb is to be changed, data cards a, b, c, and f would be included in the data set.

h. Typical Set of Input Data

The data shown in Figure 32 are for a single run. All data cards discussed in this section are included with the exception of e.
<table>
<thead>
<tr>
<th>COLUMN NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 10 15 20 25 30 35 40 45 50 55</td>
</tr>
<tr>
<td>blank</td>
</tr>
<tr>
<td>blank</td>
</tr>
<tr>
<td>.48 266.0</td>
</tr>
<tr>
<td>180 40 1000 10000</td>
</tr>
<tr>
<td>160 31 2554 7000</td>
</tr>
<tr>
<td>140 23 4108 5000</td>
</tr>
<tr>
<td>120 16 5662 3000</td>
</tr>
<tr>
<td>100 9 7216 11000</td>
</tr>
<tr>
<td>80 6 7552 8000</td>
</tr>
<tr>
<td>60 10 6664 3000</td>
</tr>
<tr>
<td>40 14 5776 3000</td>
</tr>
<tr>
<td>20 17 4888 4000</td>
</tr>
<tr>
<td>0 20 4000 5000</td>
</tr>
<tr>
<td>228.0 67.3 296.6 55.9 11.0</td>
</tr>
<tr>
<td>132.0 67.3 228.0 67.3 11.0</td>
</tr>
<tr>
<td>63.3 55.9 132.0 67.3 11.0</td>
</tr>
<tr>
<td>0 0 1 3 10 0 0 20 10270.0 4.4</td>
</tr>
</tbody>
</table>

3 TEST CASE FOR FRAGM CHECKOUT

Figure 32. Typical Input Data for Program FRAGM
6. OUTPUT FORMAT

a. Description of Problem

Across the top of the first page of printout for each problem one line of alphanumeric print is used to describe the problem being solved.

b. Table 1. Control Data.

This table prints a record of the variables and program options used for each problem.

(1) Table 1. Heading

Lines 1, 2 and 3 print the heading for the table columns. These headings appear as follows:

<table>
<thead>
<tr>
<th>TABLE 1. CONTROL DATA</th>
<th>TABLE NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

(2) Table 1. Data

Under these headings are printed the number 0 to indicate that new data are read into Tables 2, 3, or 4 on the current problem or a 1 to indicate that data from the preceding run of a multiple run is retained. If data is read into Tables 2, 3, and 4 on the current problem, the program prints

| PRIOR DATA OPTIONS (1 = HOLD) | 0 | 0 | 0 |
(3) Table 1. Number of Cards

When data are read into Table 2, 3, or 4, the number of cards read into each table is printed. If 3, 10, and 7 data cards are read into Tables 2, 3, and 4, respectively, the program will print

NUM CARDS INPUT THIS PROBLEM
3    10    7

(4) Table 1. Barricade Data

If Barricade Data are not read into the current problem or to either omit the previous barricade and read new barricade or solve for the distribution without a barricade a 1 or 0, respectively, is printed with the following statement.

BARRICADE DATA (1 = NO)    0 or 1

(5) Table 1. Increment Theta

The number of degrees used in the current problems for the increments on azimuth angle theta is printed as

INCREMENTS OF THETA, DEGREES

(6) Table 1. Increment Beta

The number of degrees used in the current problem for the increments on departure angle BETA is printed as

INCREMENTS OF BETA, DEGREES

209
(7) Table 1. Angle

The angle measured from Theta = 0° to the centerline out the nose of the bombs in the stack is printed as

ANGLE BETWEEN COORDINATES OF BOMB AND BARRICADE

(8) Table 1. Height

The height of the geometric center of the bomb stack is printed as

HEIGHT OF STACK CENTER

c. Table 2. Barricade Data

This table is printed only on problems where barricade data is read from data cards. If data are retained from the previous problem, this table is not printed

(1) Table 2. Heading

The heading for the table to contain data defining the geometry of the barricade is printed as

TABLE 2. BARRICADE DATA

<table>
<thead>
<tr>
<th>THETA DEGREES</th>
<th>DISTANCE, FT.</th>
<th>BARRICADE HEIGHT, FT.</th>
</tr>
</thead>
</table>

(2) Table 2. Data

The data used to define a segment of the barricade geometry are printed in pairs for each segment. Data for segment 1, 2, ..., N, ..., are contained in lines 1 and 2
3 and 4, ..., 2N-1 and 2N, ..., respectively. The first line of information for a particular segment will print the angle to the start of the segment, the radial distance from the bomb stack geometric center to the start of the segment, and the height of the segment. The second line of information for a particular segment will print the angle to the end of the segment, the radial distance from the bomb stack geometric center to the end of the segment, and the height of the segment. The height of any segment is to be constant between its end points. When segment K meets segments K+1, the printed output for the first line of segment K+1 will be the same as the last line of segment K with the possible exception of the height.

d. Table 3. Fragment Data

This table is printed only on problems where the fragment data is to be read from data cards. If data is retained from the previous problem, this table is not printed.

(1) Table 3. Heading

This heading for the table to contain data defining the initial condition for the fragments ejected by a single bomb as a function of polar angle measured from the nose of the bomb, is printed as:

<table>
<thead>
<tr>
<th>TABLE 3. FRAGMENT DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>THETA, DNG</td>
</tr>
<tr>
<td>(WRT BOMB COORD)</td>
</tr>
</tbody>
</table>
Table 2. Data

For each angle where data are input, starting with $0^\circ$ and increasing in steps equal to the increment of theta to maximum of $180^\circ$, the program will print out the angles where the data are input. The fragment mass in grams, initial velocity in ft./sec., and the number of fragments per steradian are printed beside the appropriate angle to indicate the average initial condition used in the current problem at that angle.

e. Table 4. Experimental Fragment Dispersion Data

This table is printed on problems where there is experimental fragment dispersion data available that have been read into the program. If data are retained from the previous problem, this table is not printed.

(1) Table 4. Heading

The heading for Table 4 containing experimental fragment dispersion data is printed as:

<table>
<thead>
<tr>
<th>TABLE 4. EXPERIMENTAL FRAGMENT DISPERSION DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>COORDINATES, FT.</td>
</tr>
<tr>
<td>XC YC</td>
</tr>
</tbody>
</table>

(2) Table 4. Data

For each recovery area of dimensions XH by YV at coordinates XC and YC the number of fragments per weight range is printed for the three heaviest fragment ranges.
f. Table 5. Range and Velocity Data

This table is printed for all problems run.

(1) Table 5. Heading

The heading for Table 5, Range and Velocity Data, is printed as:

TABLE 5. RANGE AND VELOCITY DATA

THETA  BETA  RANGE, FT.  IMP VEL, FPS  NUM  AVG FRAG MASS, G

(2) Table 5. Data

For each combination of azimuth angle, theta, and departure angle, beta, the range to the impact point, ft., the impact velocity, ft./sec., number of fragments expected to impact at that range, and the average fragment mass, grams, are printed in tabular form. There will be one Table 5 for each azimuth angle, theta, where trajectories are computed and one entry in Table 5 for each value of departure angle, beta.

The entries for any single line of Table 5 will be in one of two forms.

(a) If the fragment does not clear the top of the barricade wall for the launch angles \( \theta \) and \( \beta \), the program will print the launch angles and indicate that the fragment does not clear the barricade. This appears as:

\( \theta  \  \beta \ FRAGMENT\ DOES\ NOT\ CLEAR\ BARRICADE \)
(b) If the fragment clears the barricade or if there is no barricade in the direction $\theta$ for the launch angles $\theta$ and $\beta$, the program will compute the range to the impact point, $X_1$, impact velocity, $V_1$, number of fragments expected to impact, $NUM$, and average fragment mass, $FM$.

The printed output appears as:

$$\theta \quad \beta \quad X_1 \quad V_1 \quad NUM \quad FM$$

(g) Table 6

This table is printed for all problems run.

(1) Table 6. Heading

For each azimuth angle, $\theta$, used in the current problem solution a Table 6 will be printed. Each Table 6 will give the distribution in a direction $\theta$ for an area bounded by lines symmetric about $\theta$ and separated by the angular increment of $\theta$, $\Delta\theta$. Let $\theta$ be the azimuth angle and $\theta_1$, $\theta_2$, be the symmetric lines about $\theta$.

Then the Table 6 heading will be printed as:

TABLE 6. DISTRIBUTION DATA

$\theta(1) = \theta_1$ DEGREES $\quad \theta(2) = \theta_2$ DEGREES

RANGE 1 RANGE 2 IMP VEL, FPS NUM/SQ FT GRAMS/SQ FT

(2) Table 6. Data

Along an azimuth angle the impact ranges are computed at discrete points. From these discrete impact points
a representative impact area is defined by the angles $\theta_1$, and $\theta_2$ mentioned in g. (1) and average ranges between impact points. For impact point number 1 call these ranges $R_{A1}$ and $R_{A2}$. Only impact areas where $R_{A1}$ is greater than zero (0) are of interest. Therefore, for the first impact area $0 \leq R_{A1} \leq R_{A2}$. In the printed Table 6 this would appear as:

\[ \begin{array}{ccccc}
R_{A1} & R_{A2} & V_1 & N_{PA} & G_{PA} \\
\end{array} \]

where $R_{A1}$, $R_{A2}$, $N_{PA}$, and $G_{PA}$ are numbers corresponding to ranges defining the representative impact area, average impact velocity, number of fragments per sq. ft., and number of grams of fragments per sq. ft. in the impact area.
h. Typical Output

The following pages are indicative of the output format and type of information that is presented.
### TABLE 1. CONTROL DATA

<table>
<thead>
<tr>
<th>TABLE NUMBER</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRIOR-DATA OPTICS (1=ON)</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>NUM CARDS INPUT THIS PROBLEM</td>
<td>3</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

| HARRICADE DATA ( 1=NO ) | 0 |
| INCREMENTS OF THETA, DEGREES | 20 |
| INCREMENTS OF BETA, DEGREES | 10 |
| ANGLE BETWEEN COORDINATES OF BOMB AND HARRICADE | 270 |
| HEIGHT OF STACK CENTER | 4.4 |

### TABLE 2. BARRICADE DATA

<table>
<thead>
<tr>
<th>THETA, DEGREES</th>
<th>DISTANCE, FT</th>
<th>BARRICADE HEIGHT, FT</th>
</tr>
</thead>
<tbody>
<tr>
<td>61.3</td>
<td>55.9</td>
<td>11.0</td>
</tr>
<tr>
<td>132.0</td>
<td>67.3</td>
<td>11.0</td>
</tr>
<tr>
<td>132.0</td>
<td>67.3</td>
<td>11.0</td>
</tr>
<tr>
<td>229.0</td>
<td>67.3</td>
<td>11.0</td>
</tr>
<tr>
<td>296.6</td>
<td>55.9</td>
<td>11.0</td>
</tr>
</tbody>
</table>

### TABLE 3. FRAGMENT DATA

<table>
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<tr>
<th>THETA, DEGREES (WRT BOMB COORD)</th>
<th>AVG FRAG MASS, GRAMS</th>
<th>INITIAL VEL, FPS</th>
<th>FRAGS PER STERADIAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>4000</td>
<td>5000</td>
</tr>
<tr>
<td>20</td>
<td>17</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>40</td>
<td>14</td>
<td>5776</td>
<td>3800</td>
</tr>
<tr>
<td>60</td>
<td>10</td>
<td>6666</td>
<td>3800</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>7552</td>
<td>6000</td>
</tr>
<tr>
<td>120</td>
<td>9</td>
<td>7816</td>
<td>11000</td>
</tr>
<tr>
<td>140</td>
<td>16</td>
<td>5662</td>
<td>3000</td>
</tr>
<tr>
<td>160</td>
<td>23</td>
<td>4108</td>
<td>5000</td>
</tr>
<tr>
<td>180</td>
<td>31</td>
<td>2554</td>
<td>7000</td>
</tr>
</tbody>
</table>

### TABLE 5. RANGE AND VELOCITY DATA

<table>
<thead>
<tr>
<th>THETA</th>
<th>BETA</th>
<th>RANGE, FT</th>
<th>IMP VEL, FPS</th>
<th>NUM FRAGS</th>
<th>AVG FRAG MASS, GRAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
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<td>7216.0</td>
<td>30929</td>
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<tr>
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<tr>
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<tr>
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<td>7552.0</td>
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<td>6.0</td>
<td></td>
</tr>
<tr>
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<td>-10.0</td>
<td>7552.0</td>
<td>121655</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>1100.0</td>
<td>127495</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>10.0</td>
<td>1917.6</td>
<td>127495</td>
<td>6.0</td>
<td></td>
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</tbody>
</table>
TABLE 6. DISTRIBUTION DATA

<table>
<thead>
<tr>
<th>THETA(1) = 10,000 DEGREES</th>
<th>THETA(2) = 30,000 DEGREES</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANGE 1</td>
<td>RANGE 2</td>
</tr>
<tr>
<td>215</td>
<td>630</td>
</tr>
<tr>
<td>630</td>
<td>991</td>
</tr>
<tr>
<td>991</td>
<td>1164</td>
</tr>
<tr>
<td>1164</td>
<td>1320</td>
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<td>1320</td>
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<tr>
<td>1581</td>
<td>1790</td>
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<tr>
<td>1790</td>
<td>1997</td>
</tr>
</tbody>
</table>

TABLE 5. RANGE AND VELOCITY DATA

<table>
<thead>
<tr>
<th>THETA</th>
<th>BETA</th>
<th>RANGE, FT</th>
<th>IMP VEL, FPS</th>
<th>NUM</th>
<th>AVG FRAQ MASS, G</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0</td>
<td>-80.0</td>
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<td>7552.0</td>
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</tr>
<tr>
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</tr>
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<td>0.</td>
<td>7552.0</td>
<td>64739</td>
<td>6.0</td>
</tr>
<tr>
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<td>-50.0</td>
<td>0.</td>
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<td>112119</td>
<td>6.0</td>
</tr>
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<td>64739</td>
<td>6.0</td>
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<td>-30.0</td>
<td>0.</td>
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<td>112119</td>
<td>6.0</td>
</tr>
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<td>-20.0</td>
<td>0.</td>
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<td>44229</td>
<td>6.0</td>
</tr>
<tr>
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<td>22943</td>
<td>6.0</td>
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<td>64739</td>
<td>6.0</td>
</tr>
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<td>112119</td>
<td>6.0</td>
</tr>
<tr>
<td>20.0</td>
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<td>0.</td>
<td>7552.0</td>
<td>44229</td>
<td>6.0</td>
</tr>
<tr>
<td>20.0</td>
<td>40.0</td>
<td>0.</td>
<td>7552.0</td>
<td>22943</td>
<td>6.0</td>
</tr>
<tr>
<td>20.0</td>
<td>50.0</td>
<td>0.</td>
<td>7552.0</td>
<td>64739</td>
<td>6.0</td>
</tr>
<tr>
<td>20.0</td>
<td>60.0</td>
<td>0.</td>
<td>7552.0</td>
<td>112119</td>
<td>6.0</td>
</tr>
<tr>
<td>20.0</td>
<td>70.0</td>
<td>0.</td>
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<td>6.0</td>
</tr>
<tr>
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<td>0.</td>
<td>7552.0</td>
<td>22943</td>
<td>6.0</td>
</tr>
</tbody>
</table>

TABLE 4. DISTRIBUTION DATA

<table>
<thead>
<tr>
<th>THETA(1) = 10,000 DEGREES</th>
<th>THETA(2) = 30,000 DEGREES</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANGE 1</td>
<td>RANGE 2</td>
</tr>
<tr>
<td>215</td>
<td>630</td>
</tr>
<tr>
<td>630</td>
<td>991</td>
</tr>
<tr>
<td>991</td>
<td>1164</td>
</tr>
<tr>
<td>1164</td>
<td>1320</td>
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<td>1320</td>
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<td>1790</td>
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<tr>
<td>1790</td>
<td>1997</td>
</tr>
</tbody>
</table>

TABLE 5. RANGE AND VELOCITY DATA

<table>
<thead>
<tr>
<th>THETA</th>
<th>BETA</th>
<th>RANGE, FT</th>
<th>IMP VEL, FPS</th>
<th>NUM</th>
<th>AVG FRAQ MASS, G</th>
</tr>
</thead>
<tbody>
<tr>
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<td>22943</td>
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</tr>
<tr>
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</tr>
</tbody>
</table>

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### Table 5: Range and Velocity Data

<table>
<thead>
<tr>
<th>Theta</th>
<th>Beta</th>
<th>Range, ft</th>
<th>Imp Vel, fps</th>
<th>Num Avg Frag Mass, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.0</td>
<td>-80.0</td>
<td>Fragment does not clear barricade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60.0</td>
<td>-70.0</td>
<td>Fragment does not clear barricade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60.0</td>
<td>-60.0</td>
<td>Fragment does not clear barricade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60.0</td>
<td>-50.0</td>
<td>Fragment does not clear barricade</td>
<td></td>
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</tr>
<tr>
<td>60.0</td>
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<td>60.0</td>
<td>-30.0</td>
<td>Fragment does not clear barricade</td>
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<tr>
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<td>-20.0</td>
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</tr>
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### Table 6: Distribution Data

<table>
<thead>
<tr>
<th>Theta(1) = 50,000 degrees</th>
<th>Theta(2) = 70,000 degrees</th>
<th>Range 1</th>
<th>Range 2</th>
<th>Imp Vel, fps</th>
<th>Num/ft</th>
<th>Grams/ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
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<td>600</td>
<td>117.3</td>
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<td>2.485E+00</td>
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<td>1000</td>
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<td>3.170E+01</td>
<td>1.902E+00</td>
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<td>2463</td>
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<td>1.040E+01</td>
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</tbody>
</table>
APPENDIX III

CRATER PROGRAM

1. FORTRAN PROGRAM DESCRIPTION

The program on cratering follows the theory summarized in Section IV-4. The basic values for the parameters that form part of the program are either assumed \( W_L = 500 \text{ tons}, E^D_s = 0.3, \beta = 0.3 \) or result from the detonation of a 100-ton hemispherical bare charge on a silty clay at the Suffield Experimental Station \( (D_a = 21 \text{ ft.}, R_a = 70 \text{ ft.}, \text{soil density} = 94 \text{ lb/ft}^3) \).

New reference values for the charge weight, crater dimensions, and soil density are read into the program by statement 45. The following statements compute new values for the dissipation ratio and the ejecta parameter according to the formulas given by Equations (123), (124), (125a) and (125b).

For charge weights that are part of the input data, the program computes apparent depths and radii according to Equations (117), (119), (120), (121a) and (121b). The only difficulty in this procedure is solving the transcendental equation (121a) for the ratio \( R_a/R_a^0 \). The solution is obtained by means of the subroutine TRANS. Since a traditional iterative procedure did not work, it was necessary to write the equation in an alternate form. Suppose we define a function \( FR(\hat{R}) \) by

\[
FR(\hat{R}) = \frac{K}{(E^D_s)^2} \left[ 1 - \frac{(1 - E_s^D)}{K^{1+\xi}} (R^{4+\xi}) \right]^2 - R
\]

(III-1)
where

\[ \hat{R} = \frac{R_a}{R_a^0} \quad \text{(III-2)} \]

Then after some algebraic manipulations, it can be shown that Equation (121a) is satisfied if \( PR(\hat{R}) \) is zero.

Essentially, all that the subroutine TRANS does is to find that value of \( \hat{R} \) for which \( PR(\hat{R}) \) is zero for given values of \( K, E_s^D \) and \( \zeta \).
2. CRATER PROGRAM FLOW DIAGRAM

SET REFERENCE VALUES
FROM SUFFIELD TEST AND
SET ASSUMED VALUES

COMPUTE VARIABLES USED
IN PROGRAM
ZET1, ZET4, ZET41, TZET1, CDEN

READ NDATA, NW

IF NDATA

SET
REFERENCE
VALUES

READ CHARGE WEIGHTS,
NUMBER OF CHARGE
WEIGHTS = NW

1
FOR EACH CHARGE WEIGHT

COMPUTE k, APPARENT

RADIUS AND APPARENT DEPTH

PRINT TITLES AND
REFERENCE VALUES

PRINT APPARENT RADIUS
AND APPARENT DEPTH
FOR EACH CHARGE WEIGHT
3. LIST OF VARIABLES IN CRATER PROGRAM

a. Main Program

<table>
<thead>
<tr>
<th>Program Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BETH</td>
<td>$\hat{\beta}$</td>
</tr>
<tr>
<td>BETHST</td>
<td>$\hat{\beta}^*$</td>
</tr>
<tr>
<td>BETREF</td>
<td>Reference value for $\hat{\beta}$</td>
</tr>
<tr>
<td>Bl</td>
<td>$\frac{\hat{\beta} - 2}{\hat{\beta} - 3} \cdot 15$</td>
</tr>
<tr>
<td>B1ST</td>
<td>$\frac{\hat{\beta}^* - 2}{\hat{\beta}^* - 3} \cdot 15$</td>
</tr>
<tr>
<td>B2ST</td>
<td>$\frac{\hat{\beta}^* - 2}{\hat{\beta}^* - 3}$</td>
</tr>
<tr>
<td>CDEN</td>
<td>$2 - \left(\frac{W_o}{W_L}\right)^{1/3}$</td>
</tr>
<tr>
<td>CDEN1</td>
<td>$WREF \cdot \left[2 - \frac{W_o}{W_L}\right]^{1/3}$</td>
</tr>
<tr>
<td>DEN</td>
<td>Weight density of earth media, $\rho g$ (lb./ft.$^3$)</td>
</tr>
<tr>
<td>DENREF</td>
<td>Reference value for density of earth media (lb./ft.$^3$)</td>
</tr>
<tr>
<td>DENST</td>
<td>New weight density of earth media, $\rho^* g$ (lb./ft.$^3$)</td>
</tr>
<tr>
<td>DREF</td>
<td>Reference value for apparent depth (ft.)</td>
</tr>
<tr>
<td>DT</td>
<td>$D_a/D_o^0$</td>
</tr>
<tr>
<td>Program Variable</td>
<td>Description</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>DV(I)</td>
<td>Apparent diameter vector</td>
</tr>
<tr>
<td>D1</td>
<td>$D_a^O$ (ft.)</td>
</tr>
<tr>
<td>D2</td>
<td>$D_a^{*O}$ (ft.)</td>
</tr>
<tr>
<td>D5</td>
<td>$C_{FO}/C_{Fo}$</td>
</tr>
<tr>
<td>D6</td>
<td>$(1 - E_s^D) / (1 - E_s^D)$</td>
</tr>
<tr>
<td>D7</td>
<td>$\frac{\rho}{\rho^F} \left( \frac{R_a^O}{R_a^{*O}} \right) \left( \frac{C_{a}^O}{C_{a}^{*O}} \right)$</td>
</tr>
<tr>
<td>EDS</td>
<td>$E_s^D$</td>
</tr>
<tr>
<td>EDSREF</td>
<td>Reference value for dissipation ratio</td>
</tr>
<tr>
<td>EDSST</td>
<td>$E_s^D$</td>
</tr>
<tr>
<td>K</td>
<td>K</td>
</tr>
<tr>
<td>NDATA</td>
<td>IF NDATA is positive, new reference values are to be read in</td>
</tr>
<tr>
<td>NW</td>
<td>Number of charge weights that are to be read in</td>
</tr>
<tr>
<td>RATDST</td>
<td>$D_{a}^O/D_{a}^O$</td>
</tr>
<tr>
<td>RATRST</td>
<td>$R_{a}^O/R_{a}^{*O}$</td>
</tr>
<tr>
<td>RREF</td>
<td>Reference value for apparent radius (ft.)</td>
</tr>
<tr>
<td>RT</td>
<td>$R_{a}/R_{a}^O$</td>
</tr>
<tr>
<td>RV(I)</td>
<td>Apparent radius vector</td>
</tr>
<tr>
<td>RZA</td>
<td>$R_{a}^O$ (ft.)</td>
</tr>
</tbody>
</table>
### Program Variable

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RZAST</td>
<td>$R^0a$</td>
</tr>
<tr>
<td>TZETI</td>
<td>$1/2$</td>
</tr>
<tr>
<td>WL</td>
<td>$W_L$ (tons)</td>
</tr>
<tr>
<td>WREF</td>
<td>Reference value for $W_0$</td>
</tr>
<tr>
<td>WV(I)</td>
<td>Charge weight vector</td>
</tr>
<tr>
<td>WZ</td>
<td>$W_0$ (tons)</td>
</tr>
<tr>
<td>WZST</td>
<td>$W_0^*$ (tons)</td>
</tr>
<tr>
<td>ZETA</td>
<td>$\zeta$</td>
</tr>
<tr>
<td>ZET1</td>
<td>$\zeta + 1$</td>
</tr>
<tr>
<td>ZET4</td>
<td>$\zeta + 4$</td>
</tr>
<tr>
<td>ZET4I</td>
<td>$1/(\zeta + 4)$</td>
</tr>
</tbody>
</table>

### Subroutine TRANS

#### Subroutine Variable

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$\frac{K}{(E_s^D)^2}$</td>
</tr>
<tr>
<td>ALPHH</td>
<td>$\zeta$</td>
</tr>
<tr>
<td>ALP11</td>
<td>$\zeta + 1$</td>
</tr>
<tr>
<td>ALP4II</td>
<td>$1/(\zeta + 4)$</td>
</tr>
<tr>
<td>ALP44</td>
<td>$\zeta + 4$</td>
</tr>
<tr>
<td>B</td>
<td>$(1 - E_s^D)/(E_s^D)^{\zeta+1}$</td>
</tr>
<tr>
<td>DEL</td>
<td>Absolute value of FR(R)</td>
</tr>
<tr>
<td>EDTT</td>
<td>$E_s^D$</td>
</tr>
<tr>
<td>FNEW, FN</td>
<td>New value of FR(R)</td>
</tr>
<tr>
<td>FP</td>
<td>Previous value of FR(R)</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Subroutine Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PR(R)$</td>
<td>$\frac{K}{(E_s)^2} \left[ 1 - \frac{(1 - \frac{E^D}{E_s})}{K + 1} R^{\zeta+1} \right]^2 - R$</td>
</tr>
<tr>
<td>$KK$</td>
<td>$K$</td>
</tr>
<tr>
<td>$R$</td>
<td>$R_a/R^O_a$</td>
</tr>
<tr>
<td>$RP$</td>
<td>Previous value of $R$</td>
</tr>
<tr>
<td>$RNEW, RH$</td>
<td>New value of $R$</td>
</tr>
</tbody>
</table>
4. PRINTOUT OF CRATER PROGRAM
PROGRAM NAME: (INPUT = OUTPUT)

00001 DIMENSION V(25), RV(25), X(25)

00001 YELL K

00001 5 FOR AT (111)

00001 10 FOR AT (111,103,34) REFERENCE PARAMETERS FOR THIS RUN

1 REFERENCE YIELD = 9F7, 25.9 TONS 15X

2 YIELD = 9F7, 25.9 TONS //X50.1 X 1 EX 47 TONS 15X

3 HEIGHT = 9F7, 25.9 TONS //X50.1 X 1 EX 47 TONS 15X

4 % HARMONIZED RADIUS AND DEPTH VERSUS YIELD

5 % 1 ST ZETA = ZETA (TONS) 1/2, 9X4 AND (X4 RADIUS)

00041 20 FOR AT (110, 3, 19, 2)

C FOR SOIL AND PROGRAM CONSTANTS

00001 DATA 0.502, .41/100, 0.02/21, .94/70, ZETA/0.3, 0.35/3, 1/6, DEH/0.0, 0.01/0.333333, 0.02/0.333333

00011 ZETA = ZETA + 10

00001 ZETA = ZETA + 20

00001 ZETA = ZETA + 30

00001 ZETA = ZETA + 40

00001 ZETA = ZETA + 50

00001 ZETA = ZETA + 60

00001 ZETA = ZETA + 70

00001 ZETA = ZETA + 80

C IF (DATA) > 10000

00001 IF = 0.0

00001 IF = 0.1

00001 IF = 0.2

00001 IF = 0.3

00001 IF = 0.4

C NOT REPRODUCIBLE

00001 END
FUNCTION TRANS(KK,EDIT,T*ALPHA1,ALPHA2,ALPHA3,ALPHA4,ALPHA5,ALPHA6)

REAL KK

P = (-1)**(1-(MOD(KK,10)+**2))

FUNCTION = IF (K = 0) 0.0, 1.0

IF (K = 1) 1.0, 0.0

IF (K = 2) 0.0, 1.0

IF (K = 3) 1.0, 0.0

I = [I] + 1

RETURN

IF (K = 4) 0.0, 1.0

IF (K = 5) 1.0, 0.0

IF (K = 6) 0.0, 1.0

RETURN

IF (K = 7) 0.0, 1.0

IF (K = 8) 1.0, 0.0

IF (K = 9) 0.0, 1.0

RETURN

IF (K = 10) 0.0, 1.0

IF (K = 11) 1.0, 0.0

IF (K = 12) 0.0, 1.0

RETURN

IF (K = 13) 0.0, 1.0

IF (K = 14) 1.0, 0.0

RETURN

IF (K = 15) 0.0, 1.0

RETURN

IF (K = 16) 1.0, 0.0

RETURN

RETURN
5. INPUT FORMAT

Each set of Input Data consists of either two or three groups of information. The integers NDATA and NW are read in on the first card according to the format 2I10. If NDATA is a positive integer, then the following new reference values are read in on the next card:

a. WZST - the new reference charge \( W^* \) (tons),

b. DZAST - the new reference apparent depth \( D^{*0} \) (ft.),

c. RZAST - the new reference apparent radius \( R^{*0} \) (ft.),

d. DENST - the new weight density of the earth media, \( \rho^* g \) (lb./ft.\(^3\)).

The format for these variables is 4F10.2. If NDATA is negative or zero, this card is omitted.

The last group of input data consists of NW charge weights for which predicted values of apparent radii and depths are desired. The format for the charge weights is (8F10.2).
6. OUTPUT FORMAT

The output format is illustrated by the sample runs shown on the following pages. In addition to the reference values that formed part of the input, values for the dissipation ratio $E_D$ and the ejecta parameter $\hat{B}$ (beta) are given. The apparent depth and radius for each of the charge weights are shown in the table following the reference parameters.

To obtain the ejecta depth at a given position, $\hat{B}$, and the apparent depth and radius are used in connection with Figure 28 of Section V.
**REFERENCE PARAMETERS FOR THIS RUN**

REFERENCE YIELD = 100.00 TONS

APPEARANT DEPTH = 21.00 FT

APPEARANT RADIUS = 70.00 FT

DISSIPATION RATIO = .10

ZETA = .30

META = 3.10

**APPEARANT RADIUS AND DEPTH VERSUS YIELD**

<table>
<thead>
<tr>
<th>YIELD (Tons)</th>
<th>DEPTH</th>
<th>RADIUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.00</td>
<td>14.72</td>
<td>32.75</td>
</tr>
<tr>
<td>20.00</td>
<td>16.76</td>
<td>42.11</td>
</tr>
<tr>
<td>30.00</td>
<td>17.89</td>
<td>40.27</td>
</tr>
<tr>
<td>40.00</td>
<td>18.66</td>
<td>52.76</td>
</tr>
<tr>
<td>50.00</td>
<td>19.25</td>
<td>56.44</td>
</tr>
<tr>
<td>60.00</td>
<td>20.11</td>
<td>63.71</td>
</tr>
<tr>
<td>100.00</td>
<td>21.00</td>
<td>70.00</td>
</tr>
<tr>
<td>200.00</td>
<td>22.66</td>
<td>84.83</td>
</tr>
<tr>
<td>400.00</td>
<td>23.57</td>
<td>94.98</td>
</tr>
<tr>
<td>700.00</td>
<td>24.14</td>
<td>100.75</td>
</tr>
<tr>
<td>1000.00</td>
<td>24.62</td>
<td>105.37</td>
</tr>
</tbody>
</table>

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REFERENCE PARAMETERS FOR THIS RUN

REFERENCE YIELD = 500.00 TONS

APPEARANT DEPTH = 38.00 FT

APPEARANT RADIUS = 79.00 FT

DISSIPATION RATIO = .66

WL = 500.00 TONS

ZETA = .30

BETA = 3.34

APPEARANT RADIUS AND DEPTH VERSUS YIELD

<table>
<thead>
<tr>
<th></th>
<th>(TUNS)</th>
<th>DEPTH</th>
<th>RADIUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.00</td>
<td>3.76</td>
<td>6.13</td>
</tr>
<tr>
<td>2</td>
<td>20.00</td>
<td>7.27</td>
<td>11.04</td>
</tr>
<tr>
<td>3</td>
<td>30.00</td>
<td>10.49</td>
<td>17.11</td>
</tr>
<tr>
<td>4</td>
<td>40.00</td>
<td>13.74</td>
<td>21.87</td>
</tr>
<tr>
<td>5</td>
<td>50.00</td>
<td>15.76</td>
<td>26.05</td>
</tr>
<tr>
<td>6</td>
<td>60.00</td>
<td>19.65</td>
<td>33.09</td>
</tr>
<tr>
<td>7</td>
<td>100.00</td>
<td>23.74</td>
<td>41.11</td>
</tr>
<tr>
<td>8</td>
<td>200.00</td>
<td>30.76</td>
<td>57.36</td>
</tr>
<tr>
<td>9</td>
<td>300.00</td>
<td>34.27</td>
<td>67.06</td>
</tr>
<tr>
<td>10</td>
<td>400.00</td>
<td>36.47</td>
<td>73.88</td>
</tr>
<tr>
<td>11</td>
<td>500.00</td>
<td>38.00</td>
<td>79.00</td>
</tr>
</tbody>
</table>
REFERENCES


10. Thomas, L. H.; Computing the Effects of Distance on Damage by Fragments, Report No. 468, Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland.


12. Cratering from High Explosive Charges, Analysis of Crater Data, TR No. 2-547, U. S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, June 1961.


Analytical models and subsequent computer codes have been developed for predicting peak overpressure, positive unit impulse, the distribution and impact velocity of bomb fragments, crater dimensions and ejecta thickness from the detonations of typical bomb stacks used by the Air Force. These models consider aboveground barricaded stacks with an equivalent net weigh: high-explosive range of 10 to 500 tons of TNT. The peak overpressure and impulse from a detonation are obtained by modifying the known results of a bare hemispherical charge to take into account the stack and barricade geometries and the interaction effect of bombs. Fragment dispersion patterns are predicted by combining experimental results for single bombs and using the trajectory equations for the motion of a steel fragment in air. By using basic principles and experimental data, crater and ejecta dimensions are predicted. Based on output from the computer codes, illustrative examples are given together with recommendations for future tests to obtain needed data. Programs for optimizing munition storage areas are also suggested.
<table>
<thead>
<tr>
<th>KEY WORDS</th>
<th>LINE A</th>
<th>LINE B</th>
<th>LINE C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Munitions storage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mathematical model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analytical model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional explosives</td>
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<td></td>
</tr>
<tr>
<td>Fragmentation</td>
<td></td>
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