A MODEL OF ANTIFRATRICIDE SHIELD INTERACTION WITH JETS FORMED BY MULTIPLE ARTILLERY ROUND DETONATIONS

Evan Harris Walker

January 1983
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This report presents a theoretical model of certain influence attenuation effects involved in round to round detonation propagation. The purpose of the model is to provide guidance in the design of structures to safely store and transport HE filled munitions. Such structures employing isolation panels or shields between artillery shells or groups of artillery shells are to prevent the propagation of detonations in the event that one or several shells are detonated by other means. The most severe effect to be shielded against is the...
metal jetting produced when neighboring shells are simultaneously detonated. The present report deals with the interaction that occurs between such metal jets and multi-layered shields composed of inert materials, explosive layers, or semiactive (hydrated) materials that derive their energy from the kinetic energy of the impacting metal jet and shell casing fragments. The study finds that the model correctly reproduces most features found in experiments with isolation panels, that present semiactive materials such as gypsum show only minor enhancement of shield performance, and that the use of proper positioning of panels and distribution of shield material is a significant parameter for the design of such structures.
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I. INTRODUCTION

This report deals with the problem of optimizing the packaging for artillery shells to provide protection against influence initiation in the metal jetting environment produced by shell casing impacts. The initiation of a shell stored or transported with other shells produces high speed casing fragments that on impact with nearby shells can cause shocks, penetration, and/or fracture resulting in the initiation of the explosive fill in the neighboring shells. In addition, the detonation of two adjoining shells can, as their casings impact, produce significant metal jetting. In the case of 155 mm artillery shells this metal jet can cut through as much as 15 cm of steel. As such, this latter mechanism represents the most severe fratricide environment constraining shield design. Neighboring shells can be protected from this jet of material by inserting layers of material to intercept and disrupt the metal jet. The insertion of material, however, greatly increases the total amount of material required for the safe packaging of munitions. It becomes important, therefore, to develop a model of the shield interaction with such shell casing jets to facilitate the development of optimum packaging designs capable of inhibiting influence initiation of shells in this severe environment.

The design of an optimum packaging involves variation of numerous parameters such as number, thickness, composition, and placement of the shield materials. Extensive experimental work has been carried out to determine good potential designs. Still, determination of an optimum design requires the development of a mathematical model to minimize the total number of experimental tests necessary for the development of the influence suppression configuration. The purpose of the present report is to provide a model of the antifratricide shield panels subjected to the most severe environment, jets produced by simultaneously detonating neighboring rounds. A subsequent report will deal with the problem of shock attenuation by panels separating neighboring rounds.

II. DESCRIPTION OF THE ARTILLERY SHELL METAL JET

The mechanism causing influence initiation of concern in the present report is the jetting of metal due to the impact of shell casing material from two neighboring shells initiated at approximately the same time. An example of the formation of a jet resulting from the simultaneous detonation of two Comp B filled steel pipe bombs (15.2 cm long, 4.83 cm diameter, 3.2 mm thick wall) is seen in the end-on flash X-ray photograph, Fig. 1. The details of the jets formed by this mechanism vary considerably from shot to shot (largely because the pipe bombs are not precision items). Typically, the jets travel at about 2 km/s with the lowest velocity material effective in penetrating metal plates traveling at about 0.5 km/s. Material in the jet is confined to a fan of material about 0.1 radian in angular width.

The design of an optimum suppressive structure requires that this type of jet be either interrupted, dissipated or inhibited. We describe below the model used to calculate the effect of jet collision with elements of the suppressive structure.

III. ARTILLERY SHELL INFLUENCE INITIATION EFFECTS

Impact of explosively accelerated metal on artillery shells can produce influence initiation by any of the following mechanisms:

(1) Shock loading of the explosive arising from metal on metal impact leading to the incidence of a strong shock propagating into the explosive.

(2) Adiabatic compression or plastic flow heating of the explosive (or entrapped gas) due to compressive deformation of the impacted shell or to fragment penetration.

(3) Plastic flow heating of explosive injected into shell fissures formed by metal on metal impact.

(4) Direct exposure of the explosive fill to hot fragments in the explosive environment due to shell wall failure or penetration.

These mechanisms entail different quantitative criteria to determine if initiation will be produced in a given test situation. These include:

(1) The time integral of the shock pressure $p$ squared, $\int p^2 dt$. This quantity can be compared with critical values for different explosives.

(2) The maximum pressure to which the explosive is subjected during shock loading, $p_{\text{max}}$, and the rate of loading $dp/dt$ of the explosive or entrapped gas.

(3) A shell deformation characteristic measure $\Delta$,

$$\Delta = \int \int \frac{\rho - \sigma}{\rho} \, dt \, dt$$
Figure 1. Flash X-ray photograph of two Comp B filled steel pipe bombs from end-on view. The pipe bombs are 15.2 cm long, 4.83 cm in diameter with 3.2 mm thick walls and separated by a distance of 6.35 mm. The flash X-ray was taken 50.1 µs after detonation of the rounds. The vertical stripe in the X-ray photograph is caused by the metal jet, which of course, is traveling with a velocity gradient.
where $\sigma$ is the effective strength of the shell wall material (taking account of moment arm effects in the loading), and $\rho$ is the density of the material.

(4) Depth of penetration of impacting fragments or jets into the casing of the artillery shell.

In the present report we will only be concerned with the last of these, the penetration depth into the wall, as from the experimental data it appears that this is the most critical measure in determining whether or not metal jetting will lead to HE initiation.

IV. DESCRIPTION OF THE INFLUENCE SUPPRESSIVE STRUCTURE PARAMETERS FOR THE ARTILLERY SHELL PACKAGING AND STORAGE SHIELDS

Experimental tests$^{3,4}$ have demonstrated that the use of multiple sheets of material (perpendicular to the line joining the center of the detonated or donor shell and the protected or acceptor shell) proves to be effective in suppressing influence initiation. Plaster, containing water of hydration, has appeared to be a particularly good material for use in these experiments.$^{4}$ In addition the use of explosive material sandwiched between layers of inert material may prove to be a good material to shield artillery shells from metal jets. As such, a typical shield design may have as many as six layers, each of which must be designed to be of optimum thickness and placement. Figure 2 shows the general configuration to be treated in the present paper. Since plaster contains water of hydration, there is the possibility for it to behave as an active material in these structures. The high velocity impact of metal from an exploding shell gives rise to shocks in the plaster, producing shock heating of the material. This heating can liberate water from the gypsum in the form of steam, driving the material as though it had exploded.

In the following treatment of the suppressive structure, Fig. 2 will be used as the basis for the physical configuration to be treated by the model. For the most part, materials, dimensions, etc. will be represented parametrically. Subsequently the model will be exercised to determine those characteristics yielding the best results under various constraints (such as total weight or volume).
Figure 2. General configuration of shields treated in the present paper. The donor shells are assumed placed in the worst case position relative to the acceptor shell. Two shields each of up to three layers of any thickness are assumed placed at any position between the donor and acceptor shells. The middle layer of each shield is assumed to consist of an inert material, a semiactive material such as plaster with water of hydration, or an explosive material.
V. SHOCK ACTIVATION AND JET PENETRATION OF HYDRATED OR EXPLOSIVE SOLIDS

Use of gypsum in the form of plaster panels has yielded some experimental data⁴, suggesting that under shock loading the material responds in an explosive manner. Sufficiently strong shock can give rise to the heating of the granular solid material comprising these panels. The heat acts to calcine the plaster giving rise to a high temperature steam under elevated pressures. As a result some of the original shock energy can be dissipated in the plaster. The subsequent explosive expansion of the plaster, however, may give rise to shocks in neighboring materials. Shocks propagating through water, however, have not exhibited any increased ability to attenuate shocks from donor rounds. Thus, there may exist an effect due to shock induced calcination that involves the "solid residuum" serving as the source of the heat available for the generation of the steam.

Let us assume that we have a completely inelastic collision between a plate of areal density \( \sigma_1 \) (volumetric density \( \rho_1 \)) traveling at an initial velocity \( v_1 \) and a stationary plaster plate of areal density \( \sigma_2 \) (volumetric density \( \rho_2 \)) containing a fraction \( g \) of moisture as shown in Fig. 3. After the collision the velocity (of the center of mass) is \( v_2 \). The energy absorbed per unit area \( E \) is given by

\[
E = \frac{\rho_2}{\rho_2} \left[ \frac{P_1}{\sigma_1} - \frac{P_2}{(\sigma_1 - \sigma_2)} \right]
\]

where

\[
P_1 = \sigma_1 v_1
\]

and

\[
P_2 = (\sigma_1 + \sigma_2) v_2
\]

The specific energy \( \epsilon_2 \), per unit mass in the second (plaster) plate before expansion is

\[
\epsilon_2 = \frac{E}{\sigma_2}
\]

This energy gives rise to the heating of the "solid residuum" of specific heat \( C_{v_s} \) (which for plaster has a value of 0.210 cal/g°C), and the water of specific heat \( C_{v_{H_2O}} \) (=0.48 cal/g*K) that is liberated as the gypsum is heated. The heat of liberation is represented by \( h_f \). For gypsum, \( h_f \) is 58.1 cal/g; for water, 79.7 cal/g. We obtain

\[
\epsilon_2 = (1 - g) C_{v_s} \Delta T + C_{v_{H_2O}} \Delta T + gh_f
\]
Figure 3. Schematic of an inelastic collision between an inert plate, A, traveling with velocity $v_1$ impacting on a plate containing water content, B. The resultant combination of plates, C, travels away with a velocity $v_2$, the kinetic energy absorbed by the inelastic collision being converted to heat with the evolution of steam.
(This expression represents the unexpanded condition of the heated plaster so that the heat of vaporization does not occur here.) where $\Delta T = T - T_i$, $T_i$ being the initial temperature of the plaster and $T$ the temperature to which an amount $e_2$ of energy heats the plaster. Of this, an energy (specific) \( e_{H_2O} \) will be available as the explosively released energy of the steam. Where \( gC_v \Delta T \) is the energy that goes into heating the liberated water, the available energy is

\[
e_{H_2O}^2 = gC_v \frac{\Delta T}{H_2O} \tag{6}
\]

where $n$ is the work efficiency. We will use for $n$ the ideal thermodynamic efficiency (for a Carnot cycle) although the actual efficiency is lower. The ideal efficiency is

\[
n = \frac{T - T_i}{T} \tag{7}
\]

Where $T$ is high, Eq. (8) serves as a good approximation. Thus, we can write

\[
2e_{H_2O}/n = \left[ \left( \sigma_1 v_1^2 - (\sigma_1 + \sigma_2) v_2^2 \right) / \sigma_2 - 2[(1 - g)C_v \Delta T + gh_f] \right] \tag{8}
\]

or substituting for $\Delta T$ from Eq. (6) and solving for $e_{H_2O}$ we have

\[
2e_{H_2O} = n \left[ \left( \sigma_2 [\sigma_1 v_1^2 - (\sigma_1 + \sigma_2) v_2^2] - 2gh_f \right) / \left[ 1 + \frac{(1 - g)C_v}{C_v H_2O} \right] \right] \tag{9}
\]

The quantity $2e_{H_2O}$ can be used as the energy constant in the Gurney equation in order to calculate the subsequent expansion of the plaster plate as it drives adjoining plates. It should be noted that the assumption of complete inelastic collision leads to Eq. (5) giving the energy available for calcination of the gypsum. In the case where a given shock propagates into a panel, it is necessary to determine the rate at which shock energy is converted to heat which will be a function of $(1 - g)$. The value for dry gypsum (water of hydration) is 0.209. Measurements by Gould Gibbons, Jr. (TBD - EEB) yielded a value of 0.290 for wet plaster as tested.

Let us now consider what occurs when a high velocity jet of material impacts a material such as plaster which explosively releases energy. Figure 4 shows the flow of jet material and target material in the coordinate system moving with the stagnation point in a target under steady state flow conditions. Letting $v_j$ be the velocity of the jet and $v_s$ the velocity of the stagnation point, in the frame of reference moving with the stagnation point, the jet approaches the stagnation point $S$ with a velocity $v_j - v_s$ while the target material approaches with a velocity $v_s$. To maintain steady state
Figure 4. Schematic of a jet interaction with a target material under conditions of hypervelocity flow. Velocity vectors give velocities with respect to a coordinate system moving to the right with the stagnation velocity $V_s$. 

flow, the forces acting on the stagnation point must be balanced. Therefore, we can write, noting that the shocked plaster gives rise to a pressure $p_{H_2O}$,

$$1/2 \rho (v_j - v_s)^2 = 1/2 \rho_1 v_s^2 + p_{H_2O}$$

We note that $p_{H_2O}$ is simply equal to the energy density of the steam, $\varepsilon_{H_2O}$, as given by Eq. (9). By reference to Fig. 3 and recognizing that in jet penetration to an incremental depth $dP$ an incremental length of penetrator $dL$ impacts with the target and is consumed, we see that the quantities $\sigma_1$ and $\sigma_2$ of Eq. (9) take the values

$$\sigma_1 \rightarrow dL \rho_j$$

and

$$\sigma_2 \rightarrow dP \rho_p$$

Where

$$v_1 = v_j$$

we have

$$\sigma_1 v_1 = (\sigma_1 + \sigma_2) v_2$$

or

$$v_2 = v_j / (1 + \sigma_2 / \sigma_1) = v_j (1 + \frac{dP \rho_p}{dL \rho_j})$$

Therefore, we have the integral expression for $P$

$$P = \int_0^L dL \sqrt{\rho / (1 + \alpha)}$$

where

$$\rho = \rho_j / \rho_p$$

$$\alpha = 2p_{H_2O} / \rho_p v_s^2$$

and

$$p_{H_2O} = \rho_p \varepsilon_{H_2O}$$
Where \( \rho \) and \( \alpha \) are constant, we can write (16) as

\[
P = L \sqrt{\rho/(1 + \alpha)}.
\]

(20)

Substituting from (13) and (14) into (9) gives

\[
\varepsilon_{H_2O} = \frac{\sigma_1}{\sigma_2} \left( \frac{\sigma_1}{\sigma_2} - \frac{\sigma_2}{\sigma_1 + \sigma_2} \right) - 2gh_f.
\]

(21)

where

\[
k = \left[ 1 + \frac{(1 - g)C_v}{gC_{H_2O}} \right]^{-1}.
\]

(22)

Defining

\[
f = \frac{\sigma_1}{\sigma_2} = \frac{dL}{dF},
\]

(23)

we can write (21) as

\[
\varepsilon_{H_2O} = \frac{\sigma_1}{\sigma_2} \left( \frac{\sigma_2}{1 + \frac{f}{f}} - 1 \right) - 2gh_f.
\]

(24)

Substituting (24) into (19) and then into (18) gives

\[
\alpha = \begin{cases} 
\frac{\sigma_1}{\sigma_2} \left( \frac{\sigma_2}{1 + \frac{f}{f}} - 1 \right) - \frac{\sigma_1}{\sigma_2} \left( \frac{\sigma_2}{1 + \frac{f}{f}} - 1 \right) - 2gh_f & \text{if } \frac{\sigma_1}{\sigma_2} \left( \frac{\sigma_2}{1 + \frac{f}{f}} - 1 \right) - 2gh_f < 0 \\
0 & \text{otherwise}
\end{cases}
\]

(25)

where \( v = v_j/V_s \) and

\[
\delta = 2gh_f/v_s^2.
\]

(26)

If we take the effects of the steam evolution to be small then

\[
f = \frac{\rho}{dF/dL}, \quad \frac{d}{\rho} = \sqrt{\rho}.
\]

(27)

With this value as an approximation, Eq. (25) can be solved iteratively allowing the integration of Eq. (16). It may be seen that Eqs. (20) and (28) abridge the usual penetration density law for hypervelocity target penetration, giving rise to a term that increases the effective density of the target material. Thus, in the case of impact activated materials the usual hypervelocity penetration density law differs from that appropriate for inert materials.
VI. DESIGN OPTIMIZATION FORMULATION FOR INFLUENCE ATTENUATION PANELS TO SUPPRESS SHELL - SHELL IMPACT JET INDUCED INITIATION

Assume a jet formed by the impact of two simultaneously initiated shells, as shown in Fig. 1, attacks an influence suppression structure of the kind shown in Fig. 2. Figure 5 illustrates the specific jet and suppressive structure concerned together with parameters representing the important dimensions and quantities. Assume the jet formed by the impact of the shells has an initial length \( l \) of density \( \rho_0 \), the density of the shell walls, and that subsequently the jet increases in length linearly with the difference between the jet tip velocity \( v_t \) and jet back velocity \( v_b \). We assume also that the jet width increases from an initial value \( e \) with a velocity \( a \nu(x) \), where \( a \) is a constant equal to the angle of spread in jet material measured in radians and \( \nu(x) \) is the forward velocity of the jet at any distance \( x \) along the initial jet length. The density of the jet is assumed to decrease inversely with the product of the fractional increase in width and local stretching in length.

We assume a linear velocity gradient given at any point \( x \) by

\[
v = v_b + (v_t - v_b)x/l\tag{28}\]

where \( l \) is the length of the jet at which the density is that of the steel. The time for material to reach any distance \( L \) will be referred to the time of initial jetting (virtual origin of the jet at \( x=0 \)). Thus,

\[
t(x) = L/v(x).\tag{29}\]

The jet element of length \( dx \) at \( x \) increases in length to \( dx' \) as of its arrival at \( L \) as given by

\[
dx' = dx + tdv\tag{30}\]

Differentiating Eq. (28) to substitute for \( dv \) and using (29) to substitute for \( t \) in (30) gives on integrating

\[
x' = \left[1 + C_1 L/(1 + C_1 x)\right]dx\tag{31}\]

\[
= L + L \ln(1 + C_1 L)\]

where

\[
C_1 = (v_t - v_b)/\nu_b.\tag{32}\]

This gives the length of the jet at any distance \( L \) from its origin.
Figure 5. Schematic of the jet formed by simultaneously initiated artillery shells and antifracture panels of the type shown in Fig. 2 defining the important parameters governing the interaction. Jet tip and base velocities \(v_t\), \(v_b\), width \(e\), angular spread \(\alpha\), initial length \(\ell\) and jet density \(\rho_j\); panel densities \(\rho_a\), \(\rho_b\), \(\rho_c\), \(\rho_{a'}\), \(\rho_{b'}\), and \(\rho_{c'}\), as well as the spacial configurational parameters, \(c', h, d, d_s\), and \(L\) are shown. Density of the target is \(\rho_t\).
The penetration of the unimpeded jet at L in a target (such as steel) of density $\rho_t$ must be calculated in terms of the density of the jet as it arrives at the target. Since the jet initially forms a sheet of metal, its density drops as it expands laterally, i.e., normally to the surface of that sheet, and as it lengthens. Thus, we have for the density:

$$\rho_j(x, t) = \rho_0 \frac{e}{e + \alpha v(x) t(x)} \left( \frac{dx}{dx} \right)^{-1}$$  \hspace{1cm} (33)$$

$$= \rho_0 \left( 1 + \frac{C_1 L}{1 + C_1 x} \right)^{-1} \frac{e}{e + \alpha v t}.$$  \hspace{1cm} (33)

The penetration factor is $\sqrt{\rho_j/\rho_t}$. Thus, without influence suppression panels, the penetration $P$ in the target at L will be

$$P = \int_0^L dx \sqrt{\rho_j/\rho_t} \left[ 1 + \frac{C_1(L + P(x))}{1 + C_1 x} \right]$$  \hspace{1cm} (34)

where we have included the penetration into the target $L + P(x)$ as a correction to more accurately give the distance to the target. This correction is to be included in the expression for $\rho_j$ as well, but only for the longitudinal extension of the jet:

$$\rho_j(x, t) = \rho_0 \left( 1 + \frac{C_1(L + P(x))}{1 + C_1 x} \right)^{-1} \frac{e}{e + \alpha L}.$$  \hspace{1cm} (35)

This gives for the penetration into the target in the absence of suppressive layers:

$$P = \int_0^L dx \sqrt{\rho_0/\rho_t} \left( 1 + \frac{C_1(L + P_x)}{1 + C_1 x} \right)^{1/2} \left( 1 + \frac{a}{e} \right)^{1/2}$$  \hspace{1cm} (36)

where the notation $P_x$ means

$$P_x = \int_0^x dx \sqrt{\rho_0/\rho_t} \left( 1 + \frac{C_1(L + P_x)}{1 + C_1 x} \right)^{1/2} \left( 1 + \frac{a}{e} \right)^{1/2}.$$  \hspace{1cm} (37)

We now calculate the effects due to the presence of two suppressive structure panels through which the jet must pass before encountering the target plate. Assume panel I consists of the three layers of thickness $a$, $c$, and $b$ as shown in Fig. 6. We have for the losses of jet length $\Delta l_a$, 
\[ a = \sqrt{\frac{p_0}{\rho_a}} \int_{\Delta \xi_a}^{\Delta \xi_a + \Delta \xi_c} dx \left[ 1 + \frac{C_1(h + p_a)}{1 + C_1x} \right]^{1/2} \left( 1 + \frac{a}{\rho} h \right)^{1/2} \]  

(38)

\[ c = \sqrt{\frac{p_0}{\rho_a}} \int_{\Delta \xi_a}^{\Delta \xi_a + \Delta \xi_c} dx \left[ 1 + \frac{C_1(h+a+P_c)}{1 + C_1x} \right]^{1/2} \left[ 1 + \frac{a}{\rho} (h+a) \right]^{1/2} \]  

(59)

and

\[ b = \sqrt{\frac{p_0}{\rho_b}} \int_{\Delta \xi_a - \Delta \xi_c}^{\Delta \xi_a - \Delta \xi_c + \Delta \xi_b} dx \left[ 1 + \frac{C_1(h+a+c+p_b)}{1 + C_1x} \right]^{1/2} \left[ 1 + \frac{a}{\rho} (h+a+c) \right]^{1/2} \]  

(40)

where \( P_a, P_c, \) and \( P_b \) are defined as the instantaneous penetration as in Eq. (37). The density \( \rho_1 \) is from (20), the "effective" value

\[ \rho_1 = \rho_c(1 + \alpha) \]  

(41)

For high velocity jet penetration, stagnation point temperatures are high, so that the efficiency \( \eta \) can be nearly unity. In this case (41) becomes

\[ \rho_1 = \rho_c \left\{ 1 + k \left[ \frac{v^2}{\frac{f^2+f-1}{f+1}} - \delta \right] \right\} \]  

(41a)

which is to be solved recursively. The total loss in length passing through panel 1 is therefore \( \Delta \xi_1 \) where

\[ \Delta \xi_1 = \Delta \xi_a + \Delta \xi_c + \Delta \xi_b \]  

(42)

During the jet's penetration of panel 1, a shock builds up in the jet as shown in Fig. 4. When the jet exits panel 1, the rarefaction wave from the newly formed free surface of the jet propagates into this region of high pressure, disrupting the jet material. Let us obtain an approximate expression for the loss of jet material due to this effect. There are two cases to be considered. First, if the penetration is supersonic an amount proportional (and approximately equal) to the jet thickness is lost, i.e., and amount \( k_1 \), where \( k \) is a proportionality constant approximately equal to unity. Since this should be expressed so that a zero thickness panel removes no jet material we will write for the loss length
\[ y_1 = ke_1 / [1 + e_1 \rho_j / (a_1 \rho_a + b_1 \rho_b + c_1)] \] (43)

where \( e_1 \) is the jet width given in terms of the initial width by

\[ e_1 = e / [1 + a \over e (h + a + b + c)] \] (44)

and \( \rho_j \) is the density of the jet on exit from the first panel. In this length \( y_1 \), shocks of pressure \( p_1 \) given by

\[ p_1 = \frac{\rho_1 \rho_j}{2(\sqrt{\rho_1} + \sqrt{\rho_j})^2} \] (45)

where \( \rho_1 \) should be taken to be the average density within a mass column equal to \( e_1 y_1 \), act on the mass column. In essence this means \( \rho_1 = \rho_b \) unless \( b \ll e \) or \( \rho_b \ll \rho_j \). Also, \( \rho_j \) should be taken to be the jet density at exit from panel 1:

\[ \rho_j = \rho_0 \left( \frac{C_1 (h+a+b+c)}{1 + C_1 (L-\Delta L_1)} \right)^{-1} \frac{e}{e+\alpha (L-\Delta L_1)} \] (46)

Here \( v_1 \) is the corresponding velocity at \( x = L - \Delta L_1 \) as given by Eq. (38). Now the pressure \( p_1 \) causes the jet to spread laterally and thus drop in effectiveness against the next plate. This loss in effective length \( \Delta y_1 \) is calculated from density considerations to be

\[ \Delta y_1 = -y_1 [1 - \sqrt{(1 + ad/e) / (1 + af_1 d/e)}] \] (47)

where

\[ f_1 = \frac{av_1}{av_1 + (p_1/\rho_j)^{1/2}} \] (48)

In the case of subsonic penetration of the panel, the shock zone in the jet will increase with penetration distance. However, the strength of the shock will decrease. Thus, Eq. (47) will serve as an approximation of the jet length loss in that case as well. This length loss is equivalent to an initial length decrement \( \Delta L_1 \) given by
\[ \Delta y_1 = \int_{x=(\Delta x_1 + \Delta x_1')}^{x-(\Delta x_1 + \Delta x_1')} dx \left[ 1 + \frac{C_1 (h + a + b + c + d)}{1 + C_1 x} \right]. \] (49)

At panel 2 the length loss is to be computed in the same fashion as for the first panel. We have in the appropriate order:

\[ b' = \sqrt{\rho_0/\rho_b} \int_{x-(\Delta x_1 + \Delta x_1')}^{x-(\Delta x_1 + \Delta x_1')} dx \left[ 1 + \frac{C_1 (L_2 + p_b')}{1 + C_1 x} \right]^{1/2} \left[ 1 + \frac{a}{e} L_2 \right]^{1/2} \] (50)

where

\[ L_2 = h + a + b + c + d \] (51)

\[ c' = \sqrt{\rho_0/\rho_b} \int_{x-(\Delta x_1 + \Delta x_1')}^{x-(\Delta x_1 + \Delta x_1')} dx \left[ 1 + \frac{C_1 (L_2 + b' + p_c)}{1 + C_1 x} \right]^{1/2} \left[ 1 + \frac{a}{e} (L_2 + b') \right]^{1/2} \] (52)

and

\[ a' = \sqrt{\rho_0/\rho_a} \int_{x-(\Delta x_1 + \Delta x_1')}^{x-(\Delta x_1 + \Delta x_1')} dx \left[ 1 + \frac{C_1 (L_2 + b' + c')}{1 + C_1 x} \right]^{1/2} \left[ 1 + \frac{a}{e} (L_2 + b' + c') \right]^{1/2} \] (53)

where

\[ \Delta x_2 = \Delta x_a' + \Delta x_b' + \Delta x_c' \] (54)

As in the case for Eq. (41), we write for \( \rho_2 \)

\[ \rho_2 = \rho_c, \quad (1 + a') = \rho_c, \quad \left\{ 1 + k \left[ \frac{\epsilon^2}{\epsilon + 1} + \frac{\epsilon - 1}{\epsilon} - \delta \right] \right\}. \] (55)

Again we calculate the effective loss in jet length due to shocks in the jet on exit from the second panel. Corresponding to Eq. (43) to (49) we have

\[ y_2 = ke_2/\left[ 1 + e_2 \sum_j/(a' \rho_a' + b' \rho_b' + c' \rho_2) \right] \] (56)
with
\[ e_2 = e/[1 + \frac{a}{e}(L_2 + a' + b' + c')] \].
(57)

The shock pressure \( p_2 \) is
\[ p_2 = \frac{\rho_2 \rho_{j2}}{2(\sqrt{\rho_2 + \rho_{j2}})^2} v_2^2 \]
(58)

where
\[ \rho_{j2} = \rho_0 \left( 1 + \frac{C_1(L_2 + a' + b' + c')}{1 + C_1(x - \Delta L_1' - \Delta L_2')} \right)^{-1} \]
(59)

and \( v_2 \) is the velocity at \( x = \lambda - \Delta L_1' - \Delta L_2' \) as given by Eq. (38). The spread in the jet produces the effective loss
\[ \Delta y_2 = -y_2 [1 - \sqrt{(1 + ah'/e)/(1 + af'h'/e)}] \]
(60)

where
\[ f' = \frac{av_2}{av_2 + (p_2/\rho_{j2})^{1/2}} \]
(61)

Therefore, \( \Delta L_2' \), the effective loss in initial rod length due to the gap \( h' \) is
\[ \Delta y_2 = \frac{\int_{L - (\Delta L_1' + \Delta L_2') - \Delta L_2}^{L - (\Delta L_1' + \Delta L_2' + \Delta L_2')} dx \left[ 1 + C_1(L_2 + a' + b' + c' + h') \left/ \left[ 1 + C_1x \right] \right. \right]}{L - (\Delta L_1' + \Delta L_2') - (\Delta L_2 + \Delta L_2')} \]
(62)

Finally, the remaining rod material penetrates into the target a distance
\[ p' = \sqrt{\frac{\rho_0}{\rho_r}} \int_{0}^{L - (\Delta L_1' + \Delta L_2') - (\Delta L_2 + \Delta L_2')} dx \left[ 1 + \frac{C_1(L + p'_{j2})}{1 + C_1x} \right]^{1/2} / \left( 1 + \frac{L}{\rho_c} \right)^{1/2} \]
(63)
VII. COMPUTATIONS

A computer code designated "Main" to compute $P^1$ has been developed and is given in Appendix A. This code has been used to compute shield effectiveness curves. The effectiveness of a single homogeneous panel to suppress jet induced influence is shown in Figs. 6-9. The nondimensional penetration (in units of donor round radius) $P^1$ as a function of the nondimensional panel thickness (also in units of donor round radius) is plotted for the case of separation distance $d_s$ equal to 1.0 R (Fig. 6), 2.0 R (Fig. 7), 3.0 R (Fig. 8), and 4.0 R (Fig. 9). The shield panel is taken to be equidistant between the donor and acceptor rounds. Panel density $\rho_c$ is taken as a parameter for Figs. 6-9. Values of specific parameters have been taken to provide an optimum fit to experimental data obtained from pipe bomb tests as discussed below.

X-rays made during these pipe bomb tests were employed to obtain the jet characteristic parameters' values. Specific values used are:

Jet Characteristics: $\rho_o = 8.0 \text{ g/cm}^3$
- $t = 0.2$
- $e = 0.4$
- $a = 0.1$
- $v_t = 2.0 \text{ km/s}$
- $v_b = 0.5 \text{ km/s}$

Target: $\rho_t = 8.0 \text{ g/cm}^3$

Other: $k = 2.0$
- $v_s = 3.0 \text{ km/s}$
- $g = 0.0$ and $0.209$

The results obtained for the two values of $g$ were nearly the same. The values of jet characteristic parameters are dependent on the donor rounds used. For rounds that do not scale to the approximate values of the pipe bombs used in Ref. 4, scaling test should be made before the results of Figs. 6-9 are used for applications. The curves offer no surprises, but simply show that increased thickness and increased density both decrease monotonically the penetration in an acceptor round. The curves can be used to obtain the requirements to just stop a jet from penetrating into the acceptor.
Figure 6. Nondimensional penetration $P'/R$ versus nondimensional shield thickness $C/R$, where shield is placed at midpoint between donor and acceptor rounds (or witness plate, as shown in inset) separated by 1.0 R. Shield density $\rho_c$ is parameter for the family of curves.
Figure 7. Nondimensional penetration $P'/R$ versus nondimensional shield thickness $C/R$, where shield is placed at midpoint between donor and acceptor rounds separated by 2.0 $R$. Shield density $\rho_c$ is a parameter for the family of curves.
Figure 8. Nondimensional penetration $P'/R$ versus nondimensional shield thickness $C/R$, where shield is placed at midpoint between donor and acceptor rounds separated by 3.0 $R$. Shield density $\rho_c$ is parameter for the family of curves.
Figure 9. Nondimensional penetration $P'/R$ versus nondimensional shield thickness $C/R$, where shield is placed at midpoint between donor and acceptor rounds separated by 4.0 R. Shield density $\rho_c$ is parameter for the family of curves.
Figure 10 shows the results obtained for the nondimensional penetration depth as a function of the separation distance D/R for two panels placed symmetrically about the midpoint between the donor and acceptor (or target) rounds. The result is obtained for several densities and for panels 0.53 R thick (this corresponds to panels 1/2" or 1.27 cm thick in the pipe bomb experiments). Separation between donor and acceptor rounds is taken to be 4.0 R in these calculations. These curves show that the penetration versus separation distance drops as the separation increases. This is easily understood as an effect of jet elongation with travel distance. As a result, it is concluded that for a fixed amount of buffer material it is better to separate the material into two panels placed close to or against the shells. Figures 11-14 incorporate the optimum shield material distribution, i.e., separation of the shield material, into two panels as indicated by the results shown in Fig. 10. Comparison with Figs. 6-9 shows the improvement afforded by such an arrangement of shield material. Note that the curves in Figs. 6-9 give the same value at zero total shield thickness and for shields completely filling the donor-acceptor round gap as the corresponding curves in Figs. 11-14. At points in between, however, the curves in Figs. 11-14 dip below their counterparts in Figs. 6-9. These results show that the improvement noted in Fig. 10 as to the optimum placement of shield material under the symmetry constraint is general.

Figure 15 gives data showing that a further improvement in buffer material efficiency is achieved using a "foam" (a low density material) filling the gap between the shells. The curve gives the penetration as a function of the density of the "foam" buffer filling the entire gap. It is seen that the penetration in the target plate is zero at a density of about 0.21 g/cm³ for a gap of 4.0R. This is equivalent to a 1.05 R thick panel of density 0.80 g/cm³ which placed at the midpoint will not protect the target plate (penetration P'/R=0.15); divided into two 0.525 R thick panels the penetration is P'/R=0.13. Therefore, the best panel design appears to be a low density "foam" filling the available gap.

VIII. COMPARISON WITH EXPERIMENTAL RESULTS

An extensive series of shield tests using 4.82 cm (1.9") diameter pipe bombs has been run employing a wide variety of shields. The data obtained in these tests has been used to validate the "Main" code. Figure 16 shows a comparison between the experimental and theoretical code results. In Fig. 16 the penetration depth (maximum depth in the target plate) is used for the ordinate while the individual test code numbers (these are the same code numbers used to designate the tests in Ref. 4) are listed along the abscissa. The order of the tests listed along the abscissa is not important. As listed, however, they imply a decreasing function of penetration with increasing shield material. Beneath each entry is a small picture indicating the test arrangement of the shield along with the shield thickness in mm together with symbols indicating shield materials used. Additional test details may be found in Ref. 4. All tests employed Comp B filled 4.82 cm diameter pipe bombs 15 cm in length placed 4 radii above a steel witness plate. The reference case shows the results for no shield between the two pipe bombs and the witness plate. The error bars (obtained from the test data for three shots) indicate the considerable variability of the results obtained in these tests.
Figure 10. Nondimensional penetration $P'/R$ versus nondimensional panel separation distance $D/R$ for two symmetrically placed 0.53 R thick panels in a 4.0 R space between donors and target plate for various panel densities. The inset shows the geometry. These results indicate that if symmetry must be maintained in packaging, the best placement of shield material is midway between donor and acceptor rounds.
Figure 11. Nondimensional penetration $P'/R$ versus nondimensional total shield thickness $(C + C')/R$, where the shield consists of two panels symmetrically placed about the midpoint, one against the donor rounds, one against the acceptor rounds (or witness plate, as shown in the inset). Donor-acceptor separation is 1.0 $R$. Shield density $\rho_c$ is parameter for curves.
Figure 12. Nondimensional penetration $P'/R$ versus nondimensional total shield thickness $(C + C')/R$, where the shield consists of two panels symmetrically placed about the midpoint, one against the donor rounds, one against the acceptor rounds (or witness plate as shown in inset). Donor-acceptor separation is 2.0 R. Shield density $\rho_c$ is parameter for curves.
Figure 13. Nondimensional penetration $P'/R$ versus nondimensional total shield thickness $(C + C')/R$, where the shield consists of two panels symmetrically placed about the midpoint, one against the donor rounds, one against the acceptor rounds (or witness plate, as shown in inset). Donor-acceptor separation is 3.0 $R$. Shield density $\rho_c$ is parameter for curves.
Figure 14. Nondimensional penetration $P'/R$ versus nondimensional total shield thickness $(C + C')/R$, where the shield consists of two panels symmetrically placed about the midpoint, one against the donor rounds, one against the acceptor rounds (or witness plate as shown in inset). Donor-acceptor separation is 4.0 R. Shield density $\rho_c$ is parameter for curves.
Figure 15. Nondimensional penetration versus density of shield material for a "foam" filling the space between the donor rounds and target plate (acceptor rounds) for a gap of 4.0 R.
Figure 16. Penetration depth in mm charted for the several experimental shield tests. Theoretical and experimental data points have been plotted for all pipe bomb tests having bombs in contact 4.0 R above the witness plate. Schematics of each test shot with shield thickness, position and composition notes are shown below shot number. Note the error bars on the reference (no shield) test indicating the variability of the test results. Within these limits agreement between the experimental and theoretical results is good. Note also that the data trend is an artifact of the ordering of test shot data. As expected from theory, the smallest penetrations occurred for shields placed against donor rounds.
In tests 26T and 30B Detasheet was employed between thin sheets of steel to form the shield. The code computed shielding assuming both detonation of the Detasheet and no detonation. The results assuming no detonation are seen to agree satisfactorily with the observed results. At the right side of Fig. 16 are located all the tests in which a shield panel is placed against the donor rounds. It will be noticed that these six tests yielded the best shielding (least penetration into the witness plate) results. This is in general agreement with the predictions of the code as indicated by the results in Fig. 10. Overall the theoretical results given by the code correspond well with the experimental results in Fig. 16. (The reader should keep in mind that in some cases the penetration data is a measurement taken for two or three fragment craters in the witness plate that may be no more than 2-3 mm in diameter.) The experimental data must be regarded as having significant error bars reflecting the variability of these test results. Within these limitations, therefore, the model works well.

The results obtained in matching the experimental and theoretical data indicated that the effects observed were due to the mass column of shield material, and placement of that material alone. The code indicated no significant effect due to the use of hydrates in the shield. Several shots to test this hypothesis have been carried out by G. Gibbons. In these shots equal mass columns of steel, aluminum, plaster, and water were used as shields. Damage to the witness plates was almost identical in these four shots, although in the shot using steel for the shield, the shield material itself produced some pitting in the witness plate (these pits were located to either side of the area usually damaged by the jet from the donor rounds).

IX. CONCLUSIONS

If two neighboring artillery shells in an ammunition pallet are simultaneously detonated, a high velocity metal jet is formed that can detonate other neighboring shells, even if these shells are protected by a significant thickness of armor (for example 15 cm of armor can be penetrated by the jet from two simultaneously detonated 155 mm HE artillery rounds). Equations to model the interaction of shield panels with such jets have been derived and employed to write a computer code to calculate penetration depth of the jet after passing through up to two panels consisting of sandwiches of up to three layers of material. In the code one layer in each panel (the middle layer in three layer panels) can consist of an explosive or a hydrated material that may be activated to yield enhanced pressures under the shock loading of the jet.

Computations using the code have indicated:

(1) The primary effect produced by inert or hydrated materials depends on the mass column of material in the panel and panel placement. Water of hydration produces only minor effects.

(2) The optimum placement for the shield panel to suppress jets is against the donor shells.
(3) Under symmetry requirements (i.e., where all shells must be equally shielded) the best placement employs two shields of equal thickness, one against the donor, one against the acceptor rounds.

(4) Use of explosive material sandwiched in the shields can significantly enhance the effectiveness of the shields. (Such material, however, may enhance impact shock initiation.)

(5) The best symmetric shield design (minimum weight basis) for inhibiting fratricide jets would employ a single panel filling the entire available space between donor and acceptor rounds with the lowest density material capable of inhibiting the jet (as given by the curves in Figs. 6-9) in the available space.

ACKNOWLEDGEMENTS

I would like to thank Gould Gibbons, Jr. of the EEB, TBD for furnishing much of the data used to compare the theoretical calculations with experimental results. I would also like to thank Toni Dorsey for extensive assistance in developing and exercising the computer code "Main." Finally, I wish to acknowledge Dr. Philip M. Howe for proposing this research problem and for his constructive suggestions regarding this task.
APPENDIX

PROGRAM "MAIN"
PROGRAM MAIN(INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT, TAPE9)
DIMENSION GG(20), DD(20), RHO(20)
DIMENSION LAB(4), PLC(50), PLPP(50)

*** FORMATS ***
1 FORMAT(5X, 'GAP = ', E11.4, ' //')
2 FORMAT(3X, 'ICL = ', I10, 'X', 'PLC = ', E11.4, 'X', 'PLPP = ', E11.4, ' //')
4 FORMAT(A10)
5 FORMAT(A10,10X, 'LL = ', I5)
10 FORMAT(I10)
15 FORMAT(1H)
20 FORMAT(E10.3)
25 FORMAT(1H0)
30 FORMAT(VE10.3)
35 FORMAT(1H0)
55 FORMAT(A10,10X, 'LM = ', I5)
60 FORMAT(1H)
75 FORMAT(1H)

*** CALCULATIONS ***
CVH2D = 2.007E7 $ CV = 6.78E6 $ VDET = 7.0E8
WRITE(6,10)
10 BX = 1.0 $ BY = 1.0
15 LAB(1) = 10H TONTHMA $ LAB(2) = 10H X5742~309
20 LAB(3) = 10H PLOT $ LAB(4) = 10H SCOOP
25 XPAGE = 8.0 $ YPAGE = 8.0
30 CALL PLOT(XPAGE, YPAGE, 1, 0, 9, LAB)
35 CALL PLOT(BX, BY, 3)
40 BX = 0.0 $ BY = 0.0
45 CALL FACTOR(0.5)
50 DO 3000 IC = 1, 2
55 DO 3000 IC = 2, 2
60 READ(5,20) A, B, BP, AP, CP, RADIUS, HP, AL, RHODZ, E, VT, VB
65 1 ALPHA, RHOD = VS, AK, HP
70 A = 0.0 $ B = 0.0 $ AP = 0.0 $ BP = 0.0 $ CP = 0.0 $ HP = 0.0
75 RADIUS = 1.0 $ AL = 0.20 $ E = 0.40
80 READ(5, 25) ICOUNT
85 READ(5, 4) TITLE
90 DO 700 LL = 1, ICOUNT
95 700 \(\)
WRITE(6,5) TITLE= LL
WRITE(6,15) MAIN 66
READ(5,20) C, D, H, RHODA, RHOB, RHOC, RHODAP, RHODBP, RHUCP, G MAIN 67
READ(5,20) (GG(I), I=1,2) MAIN 69
READ(5,20) (RRHO(I), I=1,9) MAIN 70
DO 680 IG = 1, 2
G = GG(IG) MAIN 71
DO 670 I = 1, 4
CALL AXIS(0, 0, 0, 0.5, RRHO(I)+2, 0.0, 0.0, 0.0, 0.0) MAIN 72
CALL AXIS(0, 0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0) MAIN 73
READ(5,20) (RRHO(I), I=1,9) MAIN 74
DO 660 IRHO = 1, 9
RHOC = RRHO(IRHO) MAIN 75
RHOCP = RHOC CORRB 2
ACC = 0.0 MAIN 76
DO 655 ICC = 1, 9
CM(ICC-1) = 2.0, 40.0 MAIN 77
IF(CM = 0.0) CM = 0.001 MAIN 78
IF(CM .GT. GAP) GO TO 655 MAIN 79
GAP = FLOAT(ID) MAIN 80
DO 640 IP = 1, 2
G = GG(IP) MAIN 81
DO 630 IG = 1, 2
G = GG(IG) MAIN 82
DO 620 I = 1, 4
CALL AXIS(0, 0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0) MAIN 83
CALL AXIS(0, 0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0) MAIN 84
READ(5,20) (RRHO(I), I=1,9) MAIN 85
DO 610 IRHO = 1, 9
RHOC = RRHO(IRHO) MAIN 86
RHOCP = RHOC CORRB 2
ACC = 0.0 MAIN 87
DO 600 IG = 1, 2
HRHO = IG CORRB 3
DO 590 J = 1, 5
CALL AXIS(0, 0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0) MAIN 88
CALL AXIS(0, 0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0) MAIN 89
READ(5,20) (RRHO(I), I=1,9) MAIN 90
DO 580 IRHO = 1, 9
RHOC = RRHO(IRHO) MAIN 91
RHOCP = RHOC CORRB 4
HP = 0.0 MAIN 92
DO 570 I = 1, 4
CALL AXIS(0, 0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0) MAIN 93
CALL AXIS(0, 0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0) MAIN 94
READ(5,20) (RRHO(I), I=1,9) MAIN 95
DO 560 IRHO = 1, 9
RHOC = RRHO(IRHO) MAIN 96
RHOCP = RHOC CORRB 5
RP = 0.0 MAIN 97
DO 550 I = 1, 9
CALL AXIS(0, 0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0) MAIN 98
CALL AXIS(0, 0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0) MAIN 99
READ(5,20) (RRHO(I), I=1,9) MAIN 100
DO 540 IRHO = 1, 9
RHOC = RRHO(IRHO) MAIN 101
RHOCP = RHOC CORRB 6
CAPPL = RAD + H A + C + D + AP + BP + CP + HP MAIN 102
C1 = (VT-VB) / (AL*VB) MAIN 103
P = 0.0 MAIN 104
DX = AL / 100.0 MAIN 105
X = DX / 2.0 MAIN 106
DO 100 I = 1, 99
CAPL1 = H A + C / 2.0 MAIN 107
PA = 0.0 MAIN 108
DX = AL / 100.0 MAIN 109
X = AL - DX / 2.0 MAIN 110
DO 200 I = 1, 99
IF(RHOD .EQ. 0.0 OR. RHOA .EQ. 0.0) GO TO 150 MAIN 111
P = P + (SORT(RHOS/RHOD)) * DX * (1.0+(C1*CAPL1+C1*PA)/(1.0+C1*X))**0.5 MAIN 112
10.9/(1.0+ALPHA*CAPL/E)** 0.5 MAIN 113
X = X + DX MAIN 114
100 CONTINUE MAIN 115
C 150 WRITE(6,4b) P, C1, BETA MAIN 116
150 CONTINUE MAIN 117
CAPPL1 = H A + C / 2.0 MAIN 118
PA = 0.0 MAIN 119
DX = AL / 100.0 MAIN 120
X = AL - DX / 2.0 MAIN 121
DO 200 I = 1, 99
IF(RHOD .EQ. 0.0 OR. RHOA .EQ. 0.0) GO TO 210 MAIN 122
P = PA + (SORT(RHOS/RHOD)) * DX * (1.0+(C1*CAPL1+C1*PA)/(1.0+C1*X))**0.5 MAIN 123
10.9/(1.0+ALPHA*CAPL/E)** 0.5 MAIN 124
X = X - DX MAIN 125
100 CONTINUE MAIN 126
200 CONTINUE MAIN 127
DELLES = AL - X MAIN 128
PC = 0.0 MAIN 129
TEST = 1.0 MAIN 130
CAPPL1 = 5.0E5 MAIN 131
DX = (AL-DELLAS) / 100.0 MAIN 132
X = (AL-DELLA) - DX / 2.0 MAIN 133
DO 220 I = 1, 99
IF(RHOD .EQ. 0.0) GO TO 1050 MAIN 134
C MAIN 135
C *** NEGATIVE BETA FOR DETONATION LAYER. MAIN 136
C *** INCLUDES PRESSURE DROP WITH EXPANSION. MAIN 137
C
IF((G .LT. 0.0) BETA = 1.0 - G * (C/(C+PC*VDET/CAPVS)) / (0.5*RHOC) MAIN 131
1 RHOZ*V'T*V'/(SQRT(RHOC)+SQRT(RH0Z))**2) MAIN 132
IF(BETA .LT. 0.0) BETA = 0.0 MAIN 133
IF(G .LT. 0.0) GO TO 1050 MAIN 134
RHOJ = RHOZ * E / ((E+ALPHA*(H+A+C))*(1.0+C1*(H+A+PC))/(1.0+C1*X)) MAIN 135
RO = RHOJ / RHOC MAIN 136
V8 = V8 + (V'T-V8) * X / AL MAIN 137
CAPV5 = VJ / (1.0+SQRT(RHOC/RHOJ)) MAIN 138
DGREEK = 2.0 * G * HF / CAPV5**2 MAIN 139
AKK = 1.0 MAIN 140
IF(G .GT. 0.0) AKK = 1.0 * (1.0+(1.0-G)*CVF(G+CVH2O)) MAIN 141
C
IF(G .EQ. 1.0) GO TO 1000 MAIN 142
TEMP = (0.5*RHOJ*RHOC*VJ*VJ/(2.0*(SQRT(RHOJ)+SQRT(RHOC))**2)) / ((11.0-G)*CV) MAIN 143
IF(TEMP .LT. 373.0) GO TO 1000 MAIN 144
GO TO 1010 MAIN 145
1000 TEM1 = 373.0 MAIN 146
1010 WORKF = (TEMP-373.0) / TEMP MAIN 147
GAM = WORKF * AKK MAIN 148
TFAC = 1.0 - (GAM/RD) * (1.0-GAM/RD) * (1.0-DGREEK) MAIN 149
IF(TFAC .LE. 0.0) GO TO 1030 MAIN 150
GO TO 1040 MAIN 151
1030 BETA = 1.0 MAIN 152
GO TO 1050 MAIN 153
1040 V = (1.0-SQRT(TFAC)) / (1.0-GAM/RD) MAIN 154
FRHO = SQRT(RD) MAIN 155
FRHO = (FRHO*FRHO*FRHO-1.0) / (1.0+FRHO) MAIN 156
BETA = 1.0 / ((1.0+GAM*(V*V*FRHO-DGREEK))) MAIN 157
IF(BETA .LT. 0.0) BETA = 0.0 MAIN 158
1050 RHO = BETA * RHOC MAIN 159
IF(RH01 *LT. RHOC) RH01 = RHOC MAIN 160
IF(RHO1 .EQ. 0.0 .OR. RH01 .EQ. 0.0) GO TO 230 MAIN 161
PC = PC + (SQRT(RH01/RH01)) * DX *(1.0+(C1*(H+A+PC))/(1.0+C1*X)) MAIN 162
1**0.5 / (1.0+ALPHA*(H+A)/E) ** 0.5 MAIN 163
X = X - DX MAIN 164
IF(PC .GE. C) GO TO 230 MAIN 165
220 CONTINUE MAIN 166
230 DELLC = AL - DELLA - X MAIN 167
PB = 0.0 MAIN 168
DX = (AL-DELLA-DELLC) / 100.0 MAIN 169
X = (AL-DELLA-DELLC) - DX / 2.0 MAIN 170
DO 240 I = 1,99 MAIN 171
IF(RHOZ .EQ. 0.0 .OR. RHOB .EQ. 0.0) GO TO 250 MAIN 172
PB = PB + (SQRT(RH0Z/RH0B)) * DX *(1.0+(C1*(H+A+C+PB))/(1.0+C1*X)) MAIN 173
1**0.5 / (1.0+ALPHA*(H+A+C)/E) ** 0.5 MAIN 174
X = X - DX MAIN 175
IF(PB .GE. B) GO TO 250 MAIN 176
240 CONTINUE MAIN 177
250 DELIB = AL - DELLA - DELLC - X MAIN 178
DELLH = DELLA + DELLB + DELLC MAIN 179
C
WRITE(6,92) DELI MAIN 180
C
WRITE(6,82) DELI, DELLB, DELLC MAIN 181
RHOJ = RHOZ * E / (((1.0+C1*(H+A+B+C))/(1.0+C1*(AL-DELL1))) * (E+AL MAIN 182
1PHA*(AL-DELL1))) MAIN 183
E1 = E / ((1.0+ALPHA*(H+A+B+C))/E) MAIN 184
QCOL = AK * E1 * RHOJ1 MAIN 185
RCOL = RHOB * B MAIN 186
DIS = B MAIN 187
DIS = B MAIN 188
RHOP = RHOB MAIN 189
IF(QCOL .LE. RCOL) GO TO 260 MAIN 190
RCOL = RCOL + RHOC * C MAIN 191
DIS = DIS + C MAIN 192
DIS = C MAIN 193
45
RHOP = RHOC
IF(QCOL .LE. RCOL) GO TO 260
RCOL = RCOL + RHODA + A
DISS = DISS + A
DIS = A
RHOP = RHODA
IF(QCOL .LE. RCOL) GO TO 260
IF(A+B+C .EQ. 0.0) GO TO 253
RHOP = RCOL / (A+B+C)
GO TO 259
253 RHOP = 0.0
255 GO TO 270
259 GO TO 270
260 IF(RCOL .EQ. 0.0) GO TO 265
FF = (QCOL-RCOL) / RCOL
GO TO 267
265 FF = 0.0
267 RCOL = RCOL - RHOP * DIS * FF
DISS = DISS - DIS * FF
IF(DISS .EQ. 0.0) GO TO 268
RHOP = RCOL / DISS
GO TO 270
268 RHOP = 0.0
270 CONTINUE
V1 = VB + (VT-VB) * (1.0-DELL1/AL)
PREL = 0.5 + RHOP + RHOD1 + V1 + V1 / (SQRT(RHOP)+SQRT(RHOD1))**2
WRITE(6F5O) CAPL2 PA, PB, PC, VL, RHOP, RHOD1, RHOD2, PRES
F = 1.0 / (1.0+(SQRT(PRES/RHOD1))/(ALPHA*V1))
IF(A=RHODA+B*RHOD+C*RHOI .EQ. 0.0) GO TO 274
V1 = AK + E1 * RHOD1 / (1.0+E1/(A*RHODA+B*RHOD+C*RHOI))
GO TO 276
274 V1 = 0.0
276 DELY1 = -Y1 * (1.0-SQRT((1.0+ALPHA*D/E)/(1.0+ALPHA*D/F/E)))/P2
C = 0.0
CAPL2 = H + A + B + C + D
DX = (AL-DELL1) / 100.0
X = (AL-DELL1) - DX / 2.0
DO 300 I = 1,99
P2 = P2 + DX * (1.0+C1*CAPL2/(1.0+C1*X))
X = X - DX
IF(P2 .GE. DELY1) GO TO 310
300 CONTINUE
310 DELLP = AL - DELL1 - X
C = WRITE(6F5O) F, Y1, DELY1, P2, DELLP
C = WRITE(6F5O) RHOZ
PB = 0.0
DX = (AL-DELL1-DELLP) / 100.0
X = (AL-DELL1-DELLP) - DX / 2.0
DO 400 I = 1,99
IF(RHOZ .EQ. 0.0 .OR. RHORP .EQ. 0.0) GO TO 410
PB = PB + (SQRT(RHOD/RHORP)) * DX * (1.0+(C1*(CAPL2+PB))/(1.0+C1**X1))**0.5 / (1.0+ALPHA*CAPL2/E) ** 0.5
X = X - DX
IF(PB .GE. BP) GO TO 410
400 CONTINUE
410 DELLP = AL - DELL1 - DELLP - X
C = WRITE(6F5O) PB, BP, DELLP
PCP = 0.0
BETA = 1.0
DX = (AL-DELL1-DELP-DELLP) / 100.0
X = (AL-DELL1-DELP-DELLP) - DX / 2.0
DO 420 I = 1,99
C = *** NEGATIVE BETA FOR DETONATION LAYER.
C = *** INCLUDES PRESSURE DROP WITH EXPANSION
RCOL = RHOBP * AP
DISS = AP
DIS = AP
RHOPP = RHODP
IF(QCOL .LE. RCOL) GO TO 460
RCOL = RCOL + RHODP * CP
DISS = DISS + CP
DIS = CP
RHOPP = RHODP
IF(QCOL .LE. RCOL) GO TO 460
RCOL = RCOL + RHODP * CP
DISS = DISS + CP
DIS = AP
RHOPP = RHOBP
IF(QCOL .LE. RCOL) GO TO 460
IF(AP+BP+CP .EQ. 0.0) GO TO 493
RHOPP = RCOL / (AP+BP+CP)
GO TO 495
453 RHOP = 0.0
455 GO TO 470
460 IF(RCOL .EQ. 0.0) GO TO 465
FF = (QCOL-RCOL) / RCOL
GO TO 467
465 FF = 0.0
467 RCOL = RCOL - RHODP * FF * DIS
DISS = DISS - DIS * FF
IF(DISS .LE. 0.0) GO TO 468
RHOPP = RCOL / DISS
GO TO 470
468 RHOP = 0.0
470 CONTINUE
PRES = 0.5*RHOPP*RHODP2*V2*V2/(SRT(RHODP)+SRT(RHODP2))*2
WRITE(6,98) RHOPP, RHODP, V2
FP = 1.0 / (1.0+(SRT(PRES/RHODP2))/(ALPHA*V2))
IF((AP+RHODP+BP)*RHODP+CP*RHODP) .EQ. 0.0) GO TO 474
Y2 = AK * E2 / (1.0+E2*RHODP2/(AP+RHODP+BP)*RHODP+CP*RHODP)
GO TO 476
474 Y2 = 0.0
476 DELY2 = -Y2 * (1.0-SRT((1.0+ALPHA*HP/E)/(1.0+ALPHA*FP+HP/E)))
P4 = 0.0
DX = (AL-(DELL1+DELL1P+DELL2)) / 100.0
X = 99.5 * DX
DO 500 I = 1,99
P4 = P4 + DX * (1.0+C1*CAPL/(1.0+C1*X))
X = X - DX
IF(P4 .GE. DELY2) GO TO 510
500 CONTINUE
510 DELL2P = AL - (DELL1+DELL1P+DELL2) - X
C WRITE(6,80) Y2, V2, PRES, F, DELY2, P4, DELL2P, FP
PP = 0.0
DX = AL - (DELL1+DELL1P+DELL2+DELL2P)
DX = DX / 100.0
X = DX / 2.0
DO 600 I = 1,99
IF(RHOD2 .EQ. 0.0) GO TO 690
P4 = PP + (SRT(RHOD2/RHODT)) * DX * (1.0+(C1*CAPL+C1*PP)/(1.0+C1*X))
1)**0.5/(1.0+ALPHA*CAPL/E) ** 0.5
X = X + DX
600 CONTINUE
PPIN = PP / 2.54
650 CONTINUE
IF(C .GT. 2.0) GO TO 655
IPCC = IPCC + 1
PLPP(ICC) = C + CP * PLPP(ICC) = PP
CONTINUE MAIN
PLC(IPCC+1) = 0.0
PLPP(IPCC+1) = 0.0
PLC(IPCC+2) = 0.2
PLPP(IPCC+2) = 0.2
CALL LINE(PLC,PLPP,IPCC,1,0.0)
CONTINUE MAIN
CALL PLTPGE
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