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EXPLOSIVE OUTPUT FOR DRIVING METAL*

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Abstract

In using explosives to drive metal, a designer is often interested in delivering some particular impulse, acceleration, or final velocity to the metal. Design variables under his control may include the system configuration, the choice of the explosive material and its density, and the direction of detonation propagation relative to the metal. This paper reviews two simple methods for calculating the effects of these variables on system performance. The more powerful of these methods, the Gurney model, is critically reviewed and diverse applications are presented to illustrate the range of the model.

Values of performance parameters are listed for some explosive materials.

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INTRODUCTION

A large fraction of the problems that engineers encounter in the utilization of explosives center around the calculation of energy transfer to metal. This paper presents a review of simple methods for estimating the acceleration history, total impulse, and final velocity imparted to metal elements by the detonation of an adjacent explosive charge.

The stress pulse driven into a material body by a detonation is characterized by a rapid rise to a very high peak amplitude followed by a gradual decay to a protracted tail of relatively low amplitude. The amplitude of the peak stress is independent of the thickness of the explosive but depends on the properties of the explosive, the shock impedance of the adjacent material, and the direction of detonation propagation relative to the interface, as discussed by Jones.¹ Explosives derive much of their power to destroy or damage individual metal elements from the early, high-amplitude portion of the stress pulse. The gross response of structures to explosive loading, on the other hand, is usually dependent on the total impulse or momentum ($\int F(t)dt$, where $F(t)$ denotes the imposed force history) delivered by the entire stress pulse. Most of the momentum delivered to a body by detonation of a contact charge is accumulated during the protracted expansion of the detonation product gases, the duration of which is very much affected by the size of the charge.

Determination of the acceleration history of explosively-driven metal requires information about the shock wave dynamics within the metal for very early time behavior, and about the expansion behavior of the detonation product gases for later time response and approach to final velocity. Detailed analysis of transient behavior also indicates energy partitioning throughout the system and serves to test the validity of simplifying assumptions which may be considered.

To solve the shock interaction and flow problems in detail using the most realistic models of material behavior available it is necessary to invoke complex computer codes of the sort discussed in the papers of Mader² and of Sedgwick, Gittings, and Walsh³ in this symposium. Some large wave-propagation codes have been put into user-oriented form so that engineers can employ them simply by preparing input data which defines a particular problem. This method is highly recommended where it is necessary to obtain the best possible prediction of system behavior.

For many applications, however, less sophisticated methods give satisfactory results with much less expenditure of time and money. If one is interested only in the final state after acceleration is completed, overall energy and momentum balances often yield the needed information with very modest effort.

In this paper we first consider a simple gasdynamical model for acceleration of a metal plate by normally-incident detonation of a planar explosive charge. This treatment is somewhat oversimplified and is applicable only to a limited class of problems, but does provide insight into the metal acceleration process.

The second model we consider is one developed in 1943 by R. W. Gurney⁴ to predict the terminal velocity of fragments from grenades

and artillery shells. It is based on an energy balance in which energy released in the explosion is assumed to be converted into kinetic energy of the metal shell fragments and the detonation product gases. This model provides a framework for calculating the final velocity and delivered impulse, but says nothing about the acceleration history of the driven metal. It does, however, permit derivation of explicit expressions for metal velocity for a wide variety of system configurations. Gurney equations for several simple geometries are given, and values of a characteristic parameter needed to apply the equations are listed for a number of explosives. Gurney equations are applied to a few situations of general interest to illustrate the versatility of these explicit forms. Finally the important assumptions of the Gurney model are examined by comparison with the results of the gasdynamical analysis.

GASDYNAMICAL MODEL

Let us consider the uniaxial flow problem sketched in Fig. 1. In this problem a planar detonation is initiated at the free face of an explosive slab, propagates through the slab, and interacts with a metal plate in contact with its downstream face. As the detonation wave passes through it, the explosive undergoes an exothermic chemical decomposition converting it to gaseous detonation products in a state of high temperature and pressure. Since the products are unconfined at the upstream face of the slab, they will begin to expand to the rear immediately upon initiation of the charge, allowing a pressure-release wave to propagate downstream into the products immediately behind the detonation wave itself. (This flow system is called a Taylor wave, after G. I. Taylor.⁵⁾)

When the detonation reaches the metal plate (which, for simplicity, we assume to be incompressible) an interaction will take place resulting in acceleration of the plate away from the exploding charge and reflection of a recompression wave into the detonation products. Many additional wave interactions occur as the flow develops, with the eventual result that the cloud of detonation products gases expands to the ambient conditions of the environment. The sustained pressure applied to the plate during this expansion process can accelerate it to a very high velocity.

The details of the process discussed above are described by a system of equations representing balance of mass, momentum, and energy. An additional condition, called the Chapman-Jouguet hypothesis, is imposed to ensure steady detonation. We require that

$$D = u_j + c_j \quad , \quad (1)$$

where D represents the detonation wavespeed and u_j and c_j are the particle velocity and sound speed, respectively, for the detonation products at the Chapman-Jouguet (CJ) state (i.e. reaction completed, but no subsequent expansion).

Before solution of the governing equations can be attempted, an equation of state for the detonation products must be selected. Much research has gone into the development of suitable equations of state, and detailed representations are available for several high-density explosives. For the present discussion, however, it will be sufficient to assume that the detonation product gases behave in accordance with the γ -law,

$$E = \frac{P}{\rho(\gamma-1)} \quad , \quad (2)$$

where E is the specific internal energy, P is the pressure, ρ is the density, and γ is a material constant usually having a value in the range $1.3 \leq \gamma \leq 3$. For adiabatic reversible flows such as the isentropic expansion of the detonation product gases, the relation

$$P \rho^{-\gamma} = \text{constant} = P_j \rho_j^{-\gamma} \quad (3)$$

applies in every region of the material. In a gas governed by Eq. (1) the sound speed c is given by

$$c = \sqrt{\gamma P / \rho} \quad (4)$$

Escape Velocity of Product Gases

At the CJ state the product gases possess kinetic energy associated with a particle velocity u_j in the direction of detonation propagation, and potential energy associated with the very high pressure of the gases. As the gases expand, their potential energy is converted into work performed on the surroundings (e.g. acceleration of surrounding metal or other materials) and into increased kinetic energy of the gases themselves.

The potential energy content of the high-pressure gases is determined by the form of their expansion isentrope, as illustrated in Fig. 2. If the product gases are unimpeded in their expansion into vacuum, they attain their maximum possible velocity which is known as ^{the} escape velocity. The magnitude of the escape velocity is also governed by the expansion isentropes of the gases. The particle velocity of the gas at the downstream face of a bare charge obtained by expansion from the CJ pressure - particle velocity state (P_j, u_j) can be

calculated from the integral⁶

$$u = u_j + \int_{P_f}^{P_j} \frac{dP}{\rho c} \quad , \quad (5)$$

where P_f is the final expanded pressure.

Evaluation of this integral for a gas expanding along the isentrope given by Eq. (3) is readily accomplished, and the result can be placed in the form

$$u_f - u_j = \frac{2}{\gamma-1} (c_j - c_f) \quad , \quad (6)$$

showing that the increase in particle velocity of the detonation products upon expansion is proportional to the decrease in sound speed in the gas. For $\gamma = 3$ the change in particle velocity is, in fact, equal to the change in the sound speed and also, as we shall see below, the detonation velocity of the explosive. Using the Chapman-Jouguet condition (1) this result can be placed in the form

$$u_f = D + \frac{3-\gamma}{\gamma-1} c_j - \frac{2}{\gamma-1} c_f \quad . \quad (7)$$

For the case of expansion into a vacuum, $c_f = 0$ and we see that the escape velocity exceeds the detonation velocity by the amount $[(3-\gamma)/(\gamma-1)]c_j$. For expansion to a final pressure of one atmosphere, where $c_f \approx 340$ m/sec, the maximum gas velocity would be slightly less than the escape velocity. For $\gamma = 3$ the escape velocity is just the detonation velocity D . Real detonation gases usually have an effective value of γ which is somewhat less than 3 at the CJ state and which,

contrary to the assumption of the foregoing calculation, decreases substantially (toward a lower limit of ~ 1.3 at atmospheric pressure) as expansion proceeds. The escape velocity from the downstream face of the charge can thus be expected to exceed the detonation velocity. The escape velocity is the limiting velocity to which an infinitesimally thin foil can be accelerated by the detonation.

Computer Example

To gain some insight into the entire flow problem, it is helpful to examine a solved example. The example chosen is one in which the explosive is a slab of Composition B of thickness such that its mass is three times that of the driven plate. In the computation the value $\gamma = 2.85$ was chosen.⁷ Some results are shown in Fig. 3. The spatial distribution of the gas velocity and the density are each shown at three particular times during the computed expansion. The gas velocity distribution is also plotted as a function of the material position of the gas in Fig. 3, to facilitate consideration of simplified models of the gas flow. Material position X is defined as the original spatial position occupied by the given particle before detonation initiation (i.e. $X = X_0$). Thus in material coordinates neither the density distribution nor the material position X for a given particle changes with time during flow.

Let us define t_0 at the instant at which detonation reaches the metal plate; the flow in the detonation product gases at t_0 is a Taylor wave. At later times, the effects of the shock reflected from the metal surface back into the product gases may be seen. Note that the reflected shock produces a flow field in which the density of the gas is approximately constant, and with only a slight disturbance to the nearly linear gas velocity profile. By the time the metal has attained 90% of its final velocity (a time between $t_0 + 10 \mu\text{sec}$ and $t_0 + 33 \mu\text{sec}$ as shown on Fig. 3), over 80% of the mass of the gas possesses essentially a constant density.

Closed Form Solution

In the case $\gamma = 3$ the equations describing the problem at hand possess particularly simple solutions. For this case the acceleration of the metal plate can be calculated in closed form,⁸ and the result of this calculation is depicted graphically in Fig. 4. In this figure time is plotted in units of the time interval L/D required for detonation wave passage through the charge, and acceleration histories are given for several values of M/C . The quantity L is the explosive charge length, M is the mass of the driven metal plate, and C is the mass of the explosive charge. From this figure we see that acceleration of the plate, once begun, is essentially complete after a time interval equal to that required for detonation to traverse the charge.

It should be noted here that the true acceleration history of the metal possesses substantial, discontinuous jumps, as a consequence of stress wave interactions within the metal.⁹ (See the papers of Mader² and Jones¹ in this symposium.) The gasdynamic model⁸ which generated Fig. 4 did not admit such interactions because the metal plate was assumed to be incompressible.

The final plate velocity v can be expressed⁸ as

$$v = D(z - 1)/(z + 1) \quad (8)$$

where

$$z = \left(1 + \frac{32}{27} \frac{C}{M}\right)^{1/2}.$$

Deribas et al.¹⁰ compared experimental data with Eq. (8) for low density (1 g/cm^3) explosives of the sort used in cladding operations, and concluded that the actual metal velocity was 20% higher than predicted by this formula.

For purposes of simple explosive output calculations, gasdynamic

analysis of the sort presented above are limited in scope. A change in the geometric configuration or of the boundary conditions will generally yield a different mathematical problem which must be solved independently. Very few problems lead to results which can be expressed algebraically; most problems can be solved only by numerical computation.

Nevertheless, some gasdynamic results can be very useful in developing insight into flow phenomena and for testing the validity of results obtained by consideration of simplified models. For example, the escape velocity calculations provide a limit for metal velocity against which the predictions of simpler models may be compared. In the final section of this paper we shall use gasdynamic results for examination of the Gurney model, which we now introduce.

THE GURNEY MODEL

The Gurney approach to explosive system performance is based upon energy and momentum balances. In contrast to the gasdynamic model, this treatment yields only the final velocities of the gaseous and metal elements of a system being calculated; accelerations experienced by the components in approaching the final state are not considered.

The Gurney model may be applied to any explosive/metal system of simple geometry. It is assumed that the driven metal is projected in a direction normal to its surface, regardless of the direction of detonation propagation. Two further assumptions are made to obtain mathematical tractability and are crucial to the method. First, a specific energy (denoted the "Gurney energy" E , in kcal/g), with a characteristic value for each explosive, is assumed to be converted from chemical energy in the initial state to kinetic energy in the final state. Secondly, this kinetic energy is partitioned between the metal and the detonation product gases in a manner prescribed by an assumed velocity distribution linear in space in the uniform density product gases. Figure 5 illustrates such a gas velocity profile for a cylindrical charge in a metal tube. The velocity of the metal is assumed to be constant throughout its thickness. The velocity of each gas element or metal particle is taken to be normal to the axis.

Linear Velocity Distribution Assumption

The gas velocity distribution and density assumptions described above can be restated in a manner which is consistent with Fig. 5 and consistent with the original Gurney assumption, but which substitutes a single, more general condition for the two-part assumption stated above regarding the gas velocity and density distributions. We choose to regard

the y-coordinate scale of Fig. 5 as a material position scale, in which coordinate positions are identified with the original spatial position of given material points (i.e. "marked" particles) rather than with spatial positions, as introduced earlier.

The assumption of a linear gas velocity distribution in a material coordinate system does not require that the gas density remain uniform; some density variation is admissible subject to the constraint that velocity is distributed linearly over the assembly of mass increments that make up the gas. This restated assumption has the further benefit that it can conveniently be compared with the output of Lagrangian code computations.

Based on the assumptions of a known Gurney energy and a linear gas velocity distribution, we can write a total energy balance for any simple geometry. For a symmetric configuration such as a cylinder or sphere or flat sandwich, the momentum balance requirement is automatically satisfied, so the energy balance equation fully defines the final state. For asymmetric configurations such as a sandwich of explosive between layers of metal of differing mass, an explicit momentum balance equation must be solved simultaneously with the energy balance equation. For each geometry, the result is an analytical expression for the final metal velocity as a function of the Gurney energy, E , and M/C . The dimensionless quantity M/C is the ratio of the total metal mass to the total explosive mass in a representative portion of a metal/explosive assembly. This portion could be the volume normal to a unit area for a flat configuration, a unit length or a solid sector for a cylindrical configuration, or a spherical sector or spherical wedge for a spherical

configuration. End conditions such as a metal plate which extends beyond the edge of the charge cannot be handled separately in this method; the designer must assume (or determine experimentally) either that the extensions will separate from the driven portion of the plate or that the extensions will remain with the driven portion, and calculate the metal mass M accordingly.

As an example, we now derive the equations which result from these assumptions for an open-faced sandwich geometry. As sketched in Fig. 6, the velocity distribution in the detonation product gases as a function of material position y is

$$v_{\text{gas}}(y) = (v_o + v) \frac{y}{y_o} - v \quad , \quad (9)$$

and the velocity of the metal plate is v across its entire thickness.

A given particle is assumed to move at constant speed at all times in constructing energy and momentum balances. Note that the assumed linear velocity profile thus is maintained at all times during the product gas expansion.

The initial thickness and density of the explosive are y_o and ρ_e , respectively. Energy and momentum balances for a unit area may be written respectively as

$$CE = \frac{1}{2} Mv^2 + \frac{1}{2} \rho_e \int_0^{y_o} \left[(v_o + v) \frac{y}{y_o} - v \right]^2 dy \quad (10)$$

and

$$0 = -Mv + \rho_e \int_0^{y_o} \left[(v_o + v) \frac{y}{y_o} - v \right] dy \quad (11)$$

Integration of these equations and introduction of the charge mass

$C \equiv \rho_e y_o$ yields

$$v = \sqrt{2E} \left[\frac{\left(1 + 2\frac{M}{C}\right)^3 + 1}{6\left(1 + \frac{M}{C}\right)} + \frac{M}{C} \right]^{-1/2} \quad (12)$$

and

$$\frac{v_o}{v} = 2\frac{M}{C} + 1, \quad (13)$$

which are called the Gurney equations for the open-faced sandwich geometry.

It may be noted that the balances and results are of exactly the same form if the original Gurney assumptions, requiring a spatially linear velocity distribution and uniform gas density, are utilized.

Gurney Equations

Henry¹² provided a comprehensive review of the Gurney method and derivation of formulae for many other geometries. Gurney equations for some common symmetric and asymmetric configurations are presented in Fig. 7. The equations were derived on the assumption that side or end losses are negligible. The quantity $\sqrt{2E}$ occurs in each expression; its units are those of velocity and it is known as the Gurney constant or Gurney characteristic velocity for a given explosive. The ratio of final metal velocity v to the characteristic velocity $\sqrt{2E}$ is an explicit function of the metal to charge mass ratio, M/C ; in the case of the asymmetric sandwich where the second plate may be considered to be a tamper, the metal velocity is a function also of tamper mass to charge mass ratio, N/C . In all cases the velocity derived is that of the metal plate M .

Gurney equations can also be derived for other geometries. In some cases additional parameters will enter the equations. For example, for an annular cylindrical explosive charge with metal sleeves on both the interior and exterior surfaces, the Gurney equations will involve the initial radii of the explosive-metal interfaces.

Figure 8 presents a plot of the dimensionless velocity, $v/\sqrt{2E}$, of metal M as a function of the loading factor M/C for the geometries shown in Fig. 7. Values of the Gurney velocity and density are tabulated for several common explosives in Table 1, hence Fig. 8 can be used directly to estimate the metal velocity to be expected from any given explosive/metal system of simple geometry. Table 1 also lists values of the specific impulse I_{sp} and heat of detonation ΔH_d (where known) for each explosive. The relation of these quantities to the Gurney energy E will be discussed later in this paper.

The values of Gurney energy listed in Table 1 were calculated using terminal velocity data obtained from carefully conducted experiments in which end losses and gas leakage through fractures in metal were minimized. Occurrence of end losses or fracturing of driven metal early in the acceleration period may decrease the effective value of $\sqrt{2E}$ by as much as 20%. We shall discuss such losses in the next section.

Impulse

Impulse imparted to metal may be of interest in some engineering applications, e.g. the impulse testing or the calculation of the response of a structure to explosive loading. Since the Gurney model provides a means of estimating the final velocity imparted to an explosively loaded body, the total

momentum $\mathcal{M}$ of the body can be readily calculated as the product of its mass and velocity. We divide by the total charge mass C to derive the specific impulse delivered by the explosive,²²

$$I_{sp} = \mathcal{M}/C = \frac{M}{C} v . \quad (18)$$

Specific Impulse from Unconfined Surface Charges. Light explosive charges are often detonated directly on the surface of relatively very heavy bodies in order to deliver a desired impulse for testing purposes. If we consider the loaded body to be rigid and immovable, all detonation gases will flow away from the surface and maximum specific impulse will be delivered to the body. For a very large ratio of body mass to explosive mass, $M/C \gg 1$, Eq. (12) reduces to

$$v \approx \sqrt{2E} . \quad \sqrt{\frac{3}{4}} \frac{C}{M} . \quad (19)$$

By substituting this expression for v into Eq. (18), the specific impulse is found to be dependent only on the Gurney energy of the explosive:

$$I_{sp} = \sqrt{1.5 E} . \quad (20)$$

Because the gas is perfectly confined on the metal side in this configuration, the peak backward velocity v_o along the linear gas velocity profile should assume a maximum value. By equating the specific momentum of this flowing gas to the specific impulse driven into the metal according to Eq. (20),

$$\frac{C v_o/2}{C} = I_{sp} = \sqrt{1.5 E} ,$$

we derive a relation for the maximum gas velocity:

$$v_{o, \max} = \sqrt{6 E} . \quad (21)$$

Impulse Modification. The impulse imparted to a body by detonation of explosive at a given areal density (grams explosive/cm² of body surface) can be increased by tamping the explosive with an outer layer of metal. The Gurney model can be used to estimate the functional dependence of impulse on tamper areal density. If the heavy body surface is considered to be rigid, it resembles the symmetry plane in a symmetrical sandwich configuration. The velocity of the tamper plate will then be given by Eq. (18), (where we insert N in place of M, to remind ourselves that the moving plate is the tamper) and the impulse imparted to the heavy body per unit mass of explosive will be equal to the momentum of the tamper and the gas following it. The effective specific impulse of the explosive when the tamping ratio is N/C can be shown to be

$$I_{sp, \text{ tamped}} = \sqrt{2E} \left(\frac{N}{C} + \frac{1}{2} \right) / \left(\frac{N}{C} + \frac{1}{3} \right)^{1/2} . \quad (22)$$

Note that when no tamper is present (N/C = 0), this expression reduces to that for an untamped charge as given in Eq. (21).

Benham and Shirey²³ have demonstrated further that impulse can be varied as a function of position on a surface by appropriate gradual variation of either the charge thickness or the tamper thickness, or both.

APPLICATIONS OF THE GURNEY MODEL

In this section the Gurney approach is applied to derive several results which illustrate the value of this model in guiding explosive system design, and which provide useful insight in their own right. As examples of parametric studies we analyze the effectiveness of tamping in enhancing performance and the efficiency of energy transfer to metal. We then suggest ways of utilizing Gurney equations in situations where side losses cannot be ignored.

Tamping Effectiveness

The form of the Gurney equations (explicit in $v/\sqrt{2E}$) is well suited to directly reveal the effect of a change in configuration (i.e. M/C or N/C) on the velocity imparted to metal. The effect of the mass of a metal tamper plate N in an asymmetric sandwich in increasing the velocity of plate M can be calculated from Eq. (17) and is shown in Fig. 9, a plot of the proportionate velocity increase of plate M as a function of the tamping mass ratio for various loading ratios M/C . This figure shows that, for every value of M/C , diminishing returns are received as one continues to increase the relative tamper mass, N/C . Also, tamping a relatively heavy charge ($M/C \leq 0.2$) increases the velocity of plate M by very little, whereas adding tamping to a light charge ($M/C \geq 5$) increases the velocity considerably, particularly in the range of $N/C < 5$.

Efficiency of Energy Transfer

An explicit general equation may be derived to express the efficiency of energy transfer from explosive to metal for any configuration. Let us define efficiency, ϵ , as the ratio of the kinetic energy of plate M to the explosive energy, which is the product of the heat of detonation, ΔH_d , of the explosive and the charge mass, C. By introducing the Gurney energy E and rearranging, we derive the following expression.

$$\epsilon \equiv \frac{Mv^2}{2C\Delta H_d} \cdot \frac{E}{E} = \left[\left(v/\sqrt{2E} \right)^2 \cdot \frac{M}{C} \right] \frac{E}{\Delta H_d} \equiv \epsilon_m \frac{E}{\Delta H_d} \quad (23)$$

Mechanical Efficiency. The mechanical efficiency, ϵ_m , is the fraction of the total Gurney energy which is in the form of kinetic energy of plate M. This term is a function of M/C (and N/C where applicable), and can be evaluated for any given configuration using the form of $v/\sqrt{2E}$ appropriate for the geometry of interest. Let us calculate the mechanical efficiency for the asymmetric sandwich configuration discussed previously. Variation of ϵ_m as a function of C/M and N/M (an alternative form for expressing tamping ratio) is illustrated in Fig. 10, in a form following that used by Hoskin et al.⁷ The condition N/M = 0 corresponds to an open-faced sandwich, and N/M = ∞ corresponds to a rigid rear support of the charge. Efficiency is seen to be influenced strongly by the tamping ratio at low values of C/M, but only slightly at high values of C/M where the charge effectively provides its own confinement, but the efficiency decreases because of the large proportion of kinetic energy remaining in the large amount of gas.

In Fig. 10 note the general agreement between the solid curves which are based on the Gurney model and the computed points based on a $\dot{\gamma}$ - law gasdynamic model. Efficiency is clearly not strongly dependent upon the value of γ . The Gurney model can be seen to slightly overestimate the efficiency (i. e. the metal velocity) in the open-faced sandwich configuration.

Chemical Efficiency. The second factor, $E/\Delta H_d$, is the ratio of Gurney energy (the total kinetic energy per unit mass of charge) to the specific chemical energy of the explosive. Since chemical energy data are available for some explosives for which Gurney velocities have not been measured, we should like to devise a method for estimating the value of this ratio of Gurney energy to chemical energy. For chemical energy we shall use the experimental value of the heat of detonation, where available.

Values of Gurney energy E and heat of detonation ΔH_d , both in kcal/g, are given in Table 1 for several explosives. Note that the ratio $E/\Delta H_d$ lies in the range from 0.61 to 0.76 for all but one of the high-density explosives listed.²⁴ In the absence of suitable performance data from which to calculate E , one might then empirically estimate that, for high-density explosives undergoing ideal detonation,

$$E \approx 0.7 \Delta H_d \quad . \quad (24)$$

Ideal detonation implies a very short reaction zone length such that chemical reaction can be assumed to be instantaneous in solving the hydrodynamic and chemical equilibrium equations which determine the detonation state. Most monomolecular explosives detonate ideally, but multiple component explosives (e.g. blasting agents) usually detonate nonideally.²⁵

The value of $E/\Delta H_d$ appears to be lower than 0.7 for low-density explosives, for reasons related to gasdynamics, and for nonideally detonating explosives, since the driven metal can begin to move appreciably before the chemical energy release is complete. Tritonal is an example of a high-density explosive which has a low energy conversion efficiency ($E/\Delta H_d$) because it detonates nonideally. Trimonite No. 1 is a picric acid composition used in Great Britain for explosive welding,¹⁷ and displays very low values of $\sqrt{2E}$ and $E/\Delta H_d$ because it is used at low density and also detonates nonideally. Wittman²⁶ has observed that $E/\Delta H_d$ can be as low as 0.2 to 0.4 for low-density blasting agents of types often used in explosive metalworking.

Scaling

Explosives are often used in configurations which do not permit direct application of a Gurney equation. Perhaps an explosive is to be used for which neither E nor ΔH_d is known, or very significant side losses may be expected which will degrade performance substantially.

In such cases it is recommended that metal velocity and M/C measurements taken in the first shot of a series be utilized to calculate an effective value of $\sqrt{2E}$, based on the equation for the nearest "ideal" one-dimensional geometry as sketched in Fig. 7. This effective value of $\sqrt{2E}$ will usually be no more than 20% lower than the ideal value. The effective value of $\sqrt{2E}$ can then be used to estimate the metal velocity when the value of M/C is changed.

Effective use of scaling in configurations with substantial end losses is illustrated in the following examples. Weinland¹³ has correlated the effective value of $\sqrt{2E}$ with the L/D ratio of open-ended tubes filled with

Composition B explosive. For long slender tubes ($L/C \geq 6$), the value of $\sqrt{2E}$ is the limiting or ideal value quoted in Table 1, whereas the effective value of $\sqrt{2E}$ decreases at an increasing rate as L/D is reduced below 6.

As a second example, the implosive collapse of thin-walled cylindrical tubes driven by an explosive charge wrapped about the tube exterior was treated by use of the Gurney open-faced flat sandwich equation by Kennedy.²⁷ There were significant edge losses from the rather short length wrapped with the charge. For two experiments in which the value of M/C was changed by 40%, the effective values of $\sqrt{2E}$ calculated from the measured velocities agreed within 1%, although the values of $\sqrt{2E}$ were over 10% lower than that pertaining to the same explosive in configurations free of edge losses. Those experiments demonstrated that the open-faced sandwich equation with an effective value of $\sqrt{2E}$ determined by a single experiment represented a good scaling law.

Discounting for Side Losses

For high-loss configurations, an alternative approach to scaling from experimental data is to devise a criterion for "discounting" the mass of the explosive to account for side losses. This smaller effective mass of the explosive can then be utilized in applying Gurney equations.

Based on gasdynamic arguments involving lateral rarefaction waves,²⁸ Baum et al. have suggested that explosive material within 30° of the normal from an edge of the charge cannot contribute to metal acceleration. This approach toward discounting is sketched in Fig. 11 and is similar to the "detonation head" argument developed by Cook.²⁹ Both of these models indicate that, for charges with side losses, there exists a

finite charge height which will drive metal at a velocity which cannot be increased by further increases in charge height.

Following reasoning similar to Baum's, Weber³⁰ considered angles of various values and found the best correlation with experimental data whenever a discounting angle indeed equal to 30° was used, as suggested by Baum. Thus this approach can be used effectively in working with experimental data for lossy configurations.

EXAMINATION OF GURNEY MODEL ASSUMPTIONS

The comparisons in Fig. 10 between computed results (which represent experimental observations rather well) and calculations based on the Gurney model may leave the reader with the impression that the Gurney model is quite accurate for a wide range of conditions. This indeed is the case. In this section we shall examine the validity of the Gurney assumptions. We shall try to discover why this simple model works so well, and to define its limitations.

The Gurney model assumptions are recalled to be:

- Linear gas velocity distribution in Lagrangian (material) coordinate system
- Gurney energy E (total final kinetic energy) independent of system configuration and direction of detonation propagation.

Gas Velocity Distribution

To see whether the assumed flow field on which the Gurney model is based is in reasonable accord with that actually present in a detonation we may examine the problem solved in an earlier section of

this article using the gasdynamical model. We recall that this problem involved accelerating a plate by the normally-incident detonation of a charge of Composition B explosive having a mass three times that of the plate. This open-faced sandwich configuration represents a very severe test of the Gurney assumptions. The severity of the test is further increased by the fact that the low value of M/C used leads to rapid attainment of the final metal velocity (See Fig. 4), and hence allows little time for gas flow stabilization.

The results of the calculation were shown in Fig. 3 and, as discussed previously, they are well represented by the Gurney assumptions of linear gas velocity distribution in material space. It was previously shown that the Gurney model indicates that the maximum backward velocity of the gas in an open-faced sandwich arrangement is

$$v_{\text{gas, max}} = \sqrt{6E} \quad . \quad (21)$$

The value of this quantity for Composition B is 4.69 mm/ μ sec, compared with a computed value of 4.70 mm/ μ sec. While the extremely close agreement of these two calculated values is fortuitous, agreement within $\sim 10\%$ is common.

Computations for most other geometries and M/C values show closer approaches to meeting the Gurney model assumptions than the example discussed above.

Direction of Detonation Propagation

Lee and Pfeifer³¹ found in two-dimensional computer calculations that a tubular cylinder was driven to the same final velocity (within a few percent) whether it was simultaneously initiated all along the axis so as to provide normal incidence of detonation on the wall, or end-initiated so as to provide tangential incidence. However, the acceleration history of the metal is strongly affected by the angle of incidence. Kury et al.¹¹ have found that metal has been accelerated essentially to its final velocity by the time the detonation products have expanded to twice the original volume of the explosive whenever detonation is normally incident against the metal surface; on the other hand, whenever detonation propagates in a direction tangential to the metal surface, the metal approaches its final velocity only after the product gases have expanded to approximately seven times the original volume of the explosive. The reason for the slower approach to final velocity in the latter case is that tangentially incident detonation subjects the metal to a shock pulse of longer duration but only half the peak pressure in comparison with the pulse driven by normally incident detonation; this point has been reviewed by Jones¹ in this symposium.

Within the context of the overall approximations contained in the Gurney method, the difference of a few percent in final velocity as a consequence of detonation direction is considered to be negligible.

M/C Range of Applicability

To define the range of values of M/C over which the Gurney model is applicable, it is helpful to compare the Gurney model with the gasdynamic model described earlier. The Gurney model expresses the final velocity in the form $v = f(\sqrt{2E}, M/C)$, whereas the gasdynamic model leads to the equation $v = g(D, M/C)$. To link these two models, we shall utilize the expression

$$\frac{\sqrt{2E}}{D} = \frac{0.605}{\gamma - 1} \quad (25)$$

derived from gasdynamics by Roth¹⁴, which relates Gurney energy and detonation parameters.

This correlation is quite closely satisfied for the parameter values^{32,11} for Composition B ($D = 8.03$ mm/ μ sec, $\gamma = 2.76$, and $\sqrt{2E} = 2.71$ mm/ μ sec). We shall consider the detonation of a Composition B charge accelerating a metal plate in the open-faced sandwich configuration as depicted in Fig. 1. Equations (8) and (12) were derived for this configuration using the gasdynamic model (for normal incidence with $\gamma = 3$) and the Gurney model, respectively. The final plate velocity has been presented as functions of M/C according to each of these models in Fig. 12. The results obtained from the two models are quite close at large values of M/C , but diverge as M/C becomes small. The experimental results of Hoskin et al.⁷ for tangential incidence of detonation show agreement with the Gurney model all the way to the lower limit of their observations, where $M/C < 0.1$.

These results, and others, suggest that very accurate treatment of the gas flow is necessary if the performance of heavy charges is to be predicted, and that the Gurney method should not be used when $M/C < 0.1$.

Geometry

A practical demonstration of the observation that the same value of E applies for very different geometries can be seen in Table 1. Considering Composition B explosive, the value of $\sqrt{2E}$ derived by Kury et al.¹¹ from grazing detonation experiments in tubes (2.71 mm/ μ sec) is quite close to the value derived from the data of Hoskin et al.⁷ from grazing detonation experiments on flat plates in an open-sandwich configuration (2.77 mm/ μ sec). The flows in fully confined tubes and in open sandwiches are about as different as any pair of configurations considered in Fig. 7, yet the values of E derived from these different experiments are nearly the same.

Development of a rather complete rationalization and insight concerning the reasons that the Gurney model works well for many geometries, using the same value of the Gurney energy, might be gained by study of computation of the gas flows and states in several different configurations. To our knowledge, no such study has been done.

Based on our examination of computed results for a small number of cases, it appears that the chemical energy is not fully converted to Gurney energy principally because of a "communication" problem. The time required to transfer energy through an expanding gas cloud to a moving metal plate increases rapidly as the gas density decreases. The energy transfer process is eventually terminated by side losses in any real system before the transfer is completed. This results in an apparent inefficiency in conversion of the chemical energy.

DIRECTION OF METAL PROJECTION

In the derivation of Gurney equations, it has been assumed that the metal moves in a direction normal to its surface. This is true when the detonation wave encounters the metal at a normal angle of incidence, but is not true when the metal is driven by "grazing detonation," which propagates parallel to the metal surface. In certain applications, notably explosive welding and ordnance, it is important to know the direction in which driven metal will move and its inclination to this path.

Figure 13 depicts grazing detonation driving a metal plate. Acceleration of the plate to its final velocity is assumed to be instantaneous for purposes of analysis. Upon launch, the plate is deflected at an angle θ to its original rest plane.

At steady state, the plate is assumed to undergo no net shear flow, and therefore will undergo no change in length or thickness as a result of being launched. From the geometry of Fig. 13, we recognize that

$$v = 2D \sin \frac{\theta}{2} \quad . \quad (27)$$

A first order estimate of the actual direction in which metal is projected is the angle $\theta/2$ from its original plane. This angle can be evaluated from Eq. (27) if v and D are known. Gurney Eq. (12), (14) and (17) can be used to estimate v from knowledge of M/C , N/C , and E . As the plate travels, it will be tilted at an angle θ to its rest position and, according to this model, will not be rotating. These results are in accord with those deduced by Deribas et al.¹⁰ and are discussed in more detail in Ref. 33.

SUMMARY

Gasdynamic computations can yield accurate solutions for the launching of metal by explosive detonation. These solutions include detailed information about flow phenomena and metal acceleration histories, but require carefully calibrated equations of state for the detonation products and elaborate computer codes.

This report has reviewed and extended the Gurney model, an alternative method for calculation of the velocity and impulse imparted to metal by the detonation of explosives in contact operations. This model assumes simplified gasdynamics which permit algebraic solution of a wide range of system configurations. The Gurney method is approximate, usually within 10% of the true velocity and often much better when calibrated for a particular configuration. The Gurney approach is particularly valuable in predicting the effects on performance of changes in system parameters (M/C , N/C , or E) which are under the control of the design engineer. The versatility of this approach in handling various geometries and in addressing diverse design questions has been demonstrated through solution of selected examples.

The Gurney model appears to work well because the assumptions on which it is founded are reasonable simplifications of the actual situation. The most serious restriction is that Gurney equations generally should not be used at very low metal-to-explosive ratios, $M/C < 0.1$.

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TABLE 1

GURNEY ENERGIES AND SPECIFIC IMPULSES OF EXPLOSIVES

Density, g/cm ³	Explosive	$\sqrt{2E}$, mm/ μ sec	(Ref.)	I_{sp} , ktaps/(g expl./cm ²)	E, kcal/g	ΔH_d , kcal/g	(Ref.)	E/ ΔH_d
1.77	RDX	2.93	(16)	254	1.03	1.51	(21)	0.68
		2.83	(12)	245	0.96			0.64
1.60	Composition C-3	2.68	(16)	232	0.86	----		----
				205				
1.63	TNT	2.37	(11)	205	0.67	1.09	(20)	0.61
		2.44	(12)	211	0.71			0.65
1.72	Tritonal* (TNT/Al = 80/20)	2.32	(16)	201	0.64	1.77	(34)	0.36
1.72	Composition B (RDX/TNT)	2.71	(11)	235	0.87	1.20	(21)	0.72
		2.77	(7)	240	0.91			0.76
		2.70	(13)	234	0.87			0.72
		2.68	(12)	232	0.86			0.72
1.89	HMX	2.97	(11)	257	1.06	1.48	(20)	0.72
1.84	PBX-9404	2.90	(11)	251	1.01	1.37	(21)	0.74
1.62	Tetryl	2.50	(16)	217	0.75	1.16	(21)	0.65
1.61	TACOT	2.12	(16)	184	0.54	0.98	(21)	0.55
1.14	Nitromethane	2.41	(11)	209	0.69	1.23	(20)	0.56
1.76	PETN	2.93	(11)	254	1.03	1.49	(19)	0.69
	duPont Sheet:							
1.46	EL506D	2.28		197	0.62	----		----
		2.50	(14)	217	0.75	----		----
1.56	EL506L	2.20	(15)	191	0.58			
1.1	Trimonite No. 1*	1.04	(17)	90	0.13	1.26	(17)	0.10

NOTES:

1. Preferred value of $\sqrt{2E}$ for each explosive is listed first.
2. Corrections were applied to the data of Refs. 11 and 12 as discussed in Ref. 33 to estimate true speed of metal before calculating Gurney energy, E.
3. Equation (20) was used to calculate values of I_{sp} from values of $\sqrt{2E}$, or vice versa. The following identities pertain for conversion from velocity units to specific impulse units in the context of quantities in this table:

$$1 \text{ mm}/\mu\text{sec} = 10^5 \text{ dyn-sec/g explosive} = 10^5 \text{ taps}/(\text{g explosive}/\text{cm}^2).$$

* Detonates nonideally.

FIG. 1 Infinite slab of explosive driving metal plate.

FIGURE 2

EXPANSION ISENTROPES FOR γ -LAW GAS.
 Area under curve represents potential
 $P\Delta v$ work for expansion to final
 pressure P_f .

Fig. 4 PLATE ACCELERATION PER γ -LAW
GASDYNAMIC ANALYSIS (after Ref. 6,
for $\gamma = 3$)

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Fig. 5 Linear gas velocity profile assumed by Gurney.

Fig. 6 VELOCITY DISTRIBUTION IN
OPEN-FACED SANDWICH

ASYMMETRIC CONFIGURATIONS

ED SANDWICH:

$$\left[\frac{\left(1 + 2 \frac{M}{C}\right)^3 + 1}{6 \left(1 + \frac{M}{C}\right)} + \frac{M}{C} \right]^{-1/2}$$

RIC SANDWICH:

$$= \frac{1 + 2 \frac{M}{C}}{1 + 2 \frac{N}{C}} ;$$

(TAMPER)

$$\left[\frac{1 + A^3}{(1 + A)} + \frac{N}{C} A^2 + \frac{M}{C} \right]^{-1/2}$$

ERGY/UNIT EXPLOSIVE MASS

$$= \frac{\text{TOTAL TAMPER MASS}}{\text{TOTAL EXPLOSIVE MASS}}$$

GEOMETRIES

Fig. 9 TAMPING EFFECTIVENESS IN ASYMMETRIC SANDWICH

EFFICIENCY OF ENERGY PARTITIONING
TO PLATE M IN ASYMMETRIC SANDWICH
(DUE TO N. HOSKIN, AWRE)

Fig. 10 EFFICIENCY OF ENERGY PARTITIONING
TO PLATE M IN ASYMMETRIC SANDWICH
(due to Hoskin et al⁷)

FIG. 11 DISCOUNTING ANGLE TO ACCOUNT FOR SIDE LOSSES. Dotted regions are not counted in calculating effective charge mass C . Note that charge extension above height h is completely discounted.

Fig. 12 COMPARISON OF GASDYNAMIC AND GURNEY MODELS FOR
REFLECTED SHOCKWAVE CONFIGURATION COMPOSITION B EXPLOSIVE

Fig. 13 DIRECTION OF METAL PROJECTION
BY GRAZING DETONATION