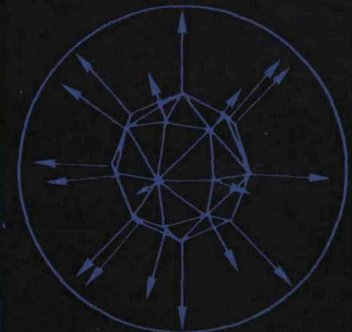


Research Report

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DECEMBER 1970

GURNEY ENERGY OF EXPLOSIVES:

ESTIMATION OF THE VELOCITY AND

IMPULSE IMPARTED TO DRIVEN METAL

J. E. KENNEDY, 5133

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Gurney Energy of Explosives:
Estimation of the Velocity and
Impulse Imparted to Driven Metal*

J. E. Kennedy
Sandia Laboratories
Albuquerque, New Mexico 87115

December 1970

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ABSTRACT

The Gurney method, which yields simple equations for evaluating the velocity of metals driven by detonating explosives in many geometries, is reviewed. The method is extended by relating the specific impulse of an explosive to its Gurney energy parameter, and by noting that for most explosives the Gurney energy is a nearly constant proportion of the chemical energy. Several diverse examples illustrate application of the Gurney equations in the utilization of explosives.

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* This work was supported by the U. S. Atomic Energy Commission.

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Suggestions by Dr. Fritz Herlach of the Illinois Institute of Technology provided the incentive for developing these extensions of the Gurney method. Helpful discussions concerning applications with T. J. Tucker and E. C. Cnare of Sandia Laboratories are also acknowledged.

1. INTRODUCTION

The motion of metal driven by detonating explosive can be very accurately calculated by complex computer codes^{1,2} using detonation product equations of state which have been calibrated to reproduce precise experimental data.^{2,3} On the other hand, the Gurney method for estimating the velocity imparted to a metal by an explosive is simple and approximate (nominally 10% uncertain).

The method, based on energy and momentum balances, was devised in 1943 by R. W. Gurney⁴ of BRL to correlate fragment velocities from artillery shells and grenades of widely varying sizes and proportions. It is a simple, but rational, approach to explosive system performance calculations in which the main interest is the final velocity imparted to the metal elements. Calculations done by this method show excellent correlation with experimental data, in spite of two gross assumptions made to obtain mathematical tractability.

The Gurney method is reviewed in detail in the next section of this report, and equations resulting for several simple geometries are given. We then derive a relationship between the Gurney energy and the specific impulse of an explosive. An empirical basis for estimating the Gurney energy of an explosive from calorimetric data is suggested in Section 3. Finally, examples are given to show that the Gurney method can be profitably used in many diverse engineering applications, principally because the equations permit direct calculation of the effect of changing the value of any system parameter.

2. THE GURNEY METHOD

The Gurney method may be applied to any explosive/metal system with a cross-section admitting one-dimensional translational motion of the metal normal to its surface, regardless of the direction of detonation propagation. A specific 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. This final kinetic energy is partitioned between the metal and the detonation product gases in a manner dictated by an assumed linear velocity profile in the gases. Figure 1 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 and metal element is taken to be normal to the axis.

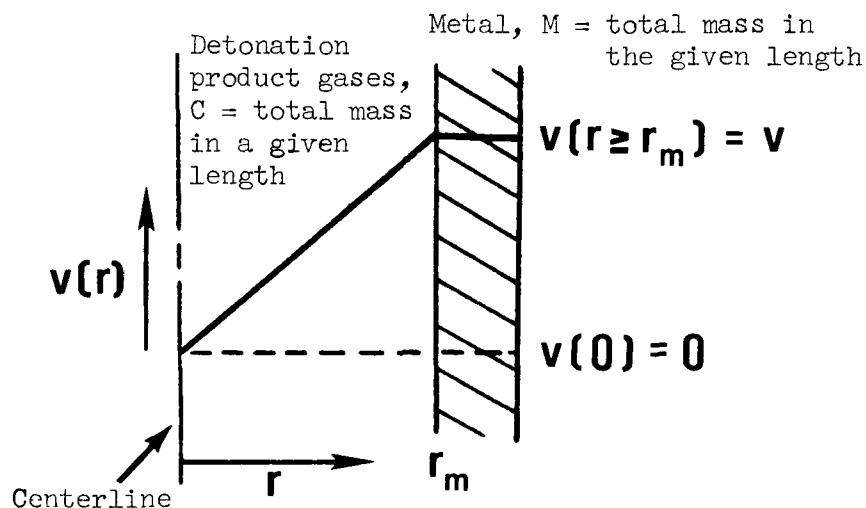


FIG. 1

Linear Gas Velocity Profile.

Based on these assumptions we can write an energy balance for any simple geometry which can be easily integrated to provide an analytical expression for the final metal velocity v as a function of Gurney specific

energy, E , and the ratio of total metal mass to total explosive mass, M/C . In addition, asymmetric one-dimensional configurations such as a sandwich of explosive between layers of metal of differing thickness require a momentum balance, which is solved simultaneously with the energy balance.

The quantity M/C is dimensionless because it is the ratio of the total metal mass to the total explosive mass in a metal/explosive assembly. For purposes of calculating M/C it will often be convenient to consider a representative volume element of the assembly. This 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.

While some assumptions upon which the Gurney method is based indeed deviate significantly from reality, these deviations usually affect the correlation only at extreme values of M/C (i.e., $M/C > 10$ or $M/C < 0.2$). Restrictions on the range of applicability of the Gurney methods due to the assumptions are collected and discussed later in this section. At this point, allow us to develop the equations which result from these assumptions, for various simple geometries. As sketched in Fig. 2, the velocity distribution in the detonation product gases as a function of Lagrangian position* y is

$$v_{\text{gas}}(y) = (v_o + v) \frac{y}{y_o} - v \quad (1)$$

*Coordinate positions are identified with particles rather than spatial position. A given particle is assumed to move at constant speed at all times in constructing energy and momentum balances.

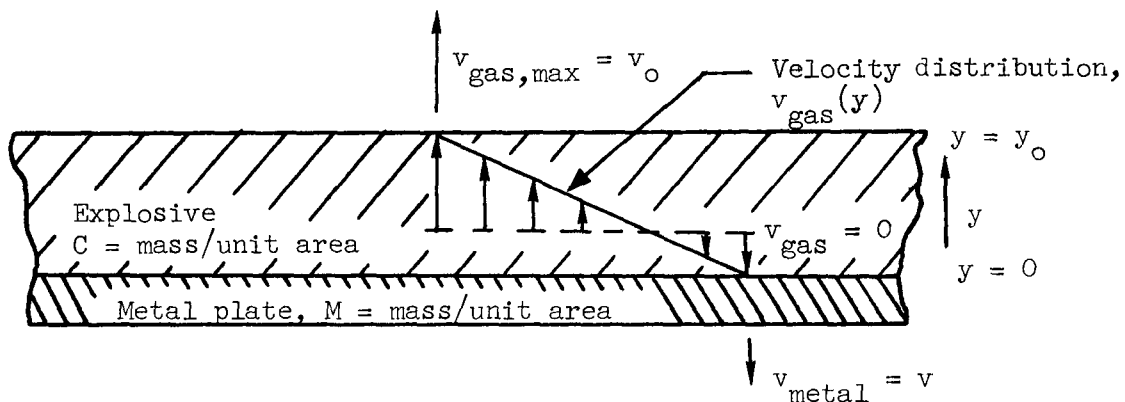


FIG. 2

Assumed Velocity Distribution in Open-Faced Sandwich Configuration.

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

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

and

$$0 = -Mv + \rho_e \int_0^{y_o} \left[(v_o + v) \frac{y}{y_o} - v \right] dy \quad (3)$$

Integration of these equations and substitution of M/C for the equivalent ratio $M/\rho_e y_o$ yields

$$v = \sqrt{2E} \left[\frac{\left(1 + 2\frac{M}{C}\right)^3 + 1}{6\left(1 + \frac{M}{C}\right)} + \frac{M}{C} \right]^{-1/2} \quad (4)$$

and

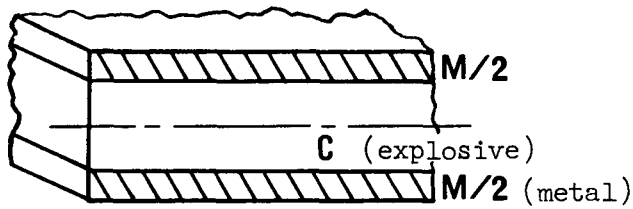
$$\frac{v_o}{v} = 2\frac{M}{C} + 1 \quad (5)$$

2.1 Gurney Equations

Henry⁵ provided a comprehensive review of the Gurney method and derivation of many formulae. Gurney equations for some common symmetric and asymmetric configurations are presented in Fig. 3. The quantity $\sqrt{2E}$ occurs in each expression; its units are velocity and it is known as the 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 , and, in the case of the asymmetric sandwich where the second plate may be considered to be a tamper, 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 .

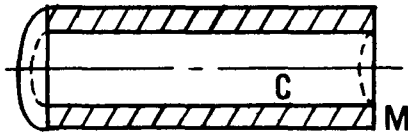
Figure 4 presents a plot of the dimensionless velocity, $v/\sqrt{2E}$, of metal M as a function of the loading factor M/C for the geometries shown in Fig. 3. Values of the Gurney velocity, $\sqrt{2E}$, are tabulated for several common explosives in Sec. 3 of this report, hence Fig. 4 can be used directly to estimate the metal velocity to be expected from any given explosive/metal system of simple geometry.

SYMMETRIC CONFIGURATIONS



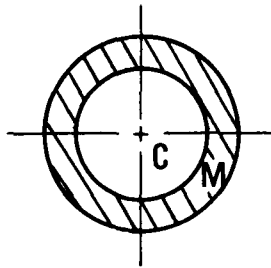
Flat Sandwich:

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



Cylindrical Case:

$$\frac{v}{\sqrt{2E}} = \left[\frac{M}{C} + \frac{1}{2} \right]^{-1/2} \quad (7)$$



Spherical Case:

$$\frac{v}{\sqrt{2E}} = \left[\frac{M}{C} + \frac{3}{5} \right]^{-1/2} \quad (8)$$

ASYMMETRIC CONFIGURATIONS

Open-faced Sandwich:

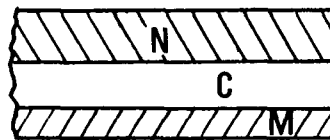
$$\frac{v}{\sqrt{2E}} = \left[\frac{\left(1 + 2 \frac{M}{C}\right)^3 + 1}{6 \left(1 + \frac{M}{C}\right)} + \frac{M}{C} \right]^{-1/2} \quad (4)$$



Asymmetric Sandwich:

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

(tamper)



$$\frac{v}{\sqrt{2E}} = \left[\frac{1 + A^3}{3(1 + A)} + \frac{N}{C} A^2 + \frac{M}{C} \right]^{-1/2} \quad (9)$$

Symbols: $\frac{M}{C} = \frac{\text{total metal mass}}{\text{total explosive mass}} ; \quad \frac{N}{C} = \frac{\text{total tamper mass}}{\text{total explosive mass}}$
 v = metal velocity
 Gurney energy, E = kinetic energy/unit explosive mass

FIG. 3 Gurney Equations for Common Geometries

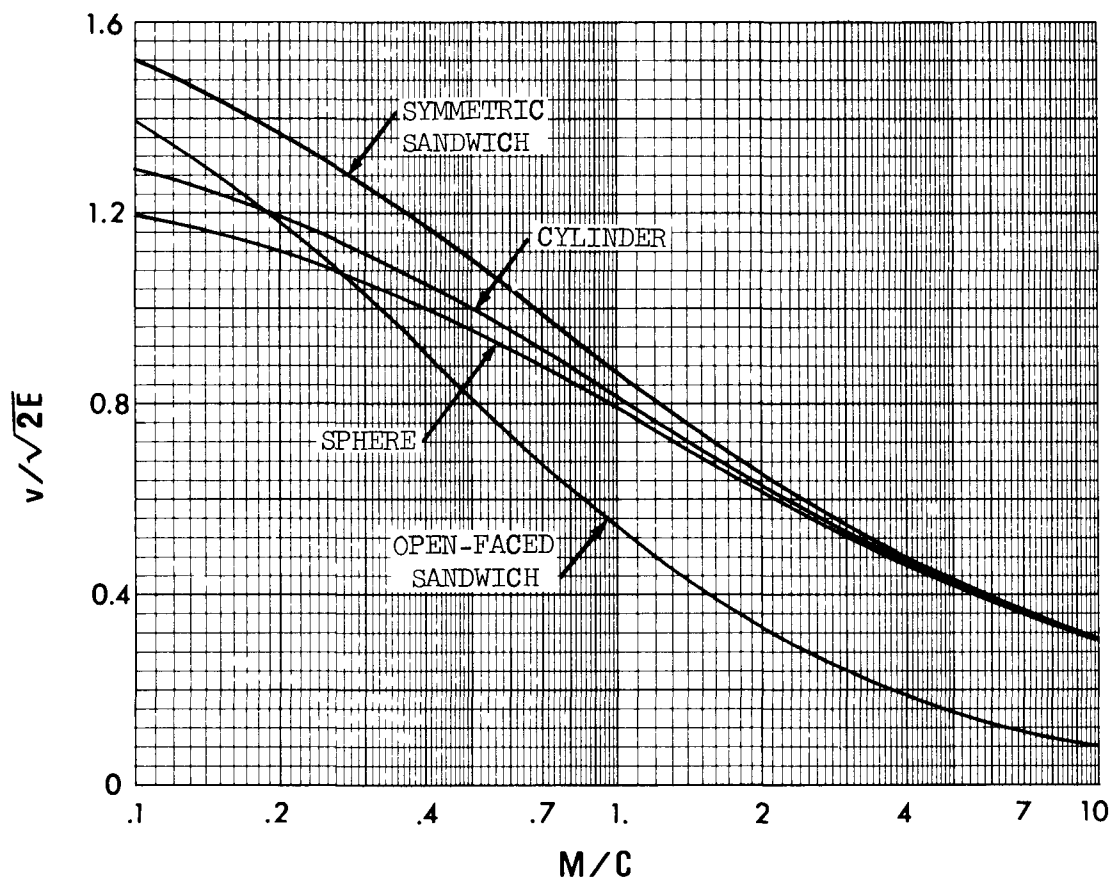


FIG. 4

Dimensionless Velocity of Metal as Function of Loading Factor M/C .

The calculated velocity of the driven plate in an open-faced sandwich configuration is plotted in Fig. 5 as a function of M/C for a few common explosives. Estimates for other explosives can be read from the graph by interpolation between curves based on appropriate values of $\sqrt{2E}$.

Equations can be derived for other geometries and conditions by use of the Gurney model.⁵

2.1.1 Division of Gas Flow. The partitioning of gas flow in the symmetric sandwich configuration is obvious -- half the detonation product gases flow in the direction of each metal plate. However, for asymmetric sandwich configurations, the proportion of gas flowing in the direction of plate M varies with M/C and N/C . In view of the linear velocity profile assumed for constant-density gases in the Gurney method, the proportion of the total detonation product gases which flows in the direction of plate M may be seen to be $v_M / (v_N + v_M)$. The two velocities, v_M and v_N , may be evaluated by individual applications of Eq. (9). For an open-faced sandwich, the proportion of gas flowing in the direction of plate M is found to be $v_M / (v_O + v_M)$, which may be evaluated from Eqs. (4) and (5).

2.1.2 Range of Applicability. A restricted range of applicability pertains for the Gurney method as a result of the simplifying assumptions made explicitly or implicitly in the model. Effects of many of these assumptions and limitations are presented briefly in Table 1.

The Gurney assumption of a linear velocity profile of constant density detonation product gases is a substantial departure from gasdynamic theory, and merits additional attention. This assumption introduces the largest errors in configurations involving a free explosive surface such as the open-faced sandwich, for which the Gurney approach may overestimate the

TABLE 1 APPLICABILITY OF THE GURNEY APPROACH

RESTRICTION	REMARKS AND RECOMMENDATIONS
1. Range of M/C Ratio	Henry ⁵ recommends restriction to the range $0.2 < M/C < 10$ for velocity calculations. Impulse calculations may be done if $M/C > 0.2$ on basis of data from Ref. 1.
2. Acceleration Phase	Gurney method is not capable of analyzing motion during acceleration. Acceleration is completed after detonation products have expanded to twice that original charge volume for normal incidence of detonation onto metal, or to seven times original charge volume for grazing incidence onto metal ² (see Appendix P). The metal will reach its calculated velocity only if no external forces of interactions are applied during acceleration.
3. Direction of Detonation Propagation	Detonation drives metal at a given velocity, within a few percent, for a given M/C regardless of the angle between the detonation front and the metal surface. ¹⁵ The direction in which the metal is driven will vary slightly with the angle (see Appendix A).
4. Gas Velocity Profile Inaccuracy	Assumed linear velocity profile and constant density are gross oversimplifications. Ignoring effects both of rarefaction waves and of pressure peaks near the metal appear to be cancelling errors. ⁵ See text concerning effects of free explosive surface.
5. One-dimensional Motion	Approach cannot be used to estimate variations in local velocities of a plate driven by a charge with a steep taper in its thickness. Some averaged value of M/C could be used to estimate final velocity of entire plate.
6. Metal Strength Effects	No forces exerted by the metal to oppose deformation are considered, other than inertia. Hoop stresses in cylinders and spheres can reduce metal velocity by a few percent ² at moderate M/C values (~ 2.5) in explosions, and by a greater amount in implosions. ¹³
7. Metal Spallation	May occur when $M/C < 2$ for high density explosives and metals. Can be avoided by spacing charge a few millimeters from metal, with very little decrease in metal velocity. ¹
8. Early Case Fracture	Leakage of product gases through fractures in the metal case can decrease the final metal velocity by no more than 10%, the value calculated for a case composed of preformed fragments. ⁵

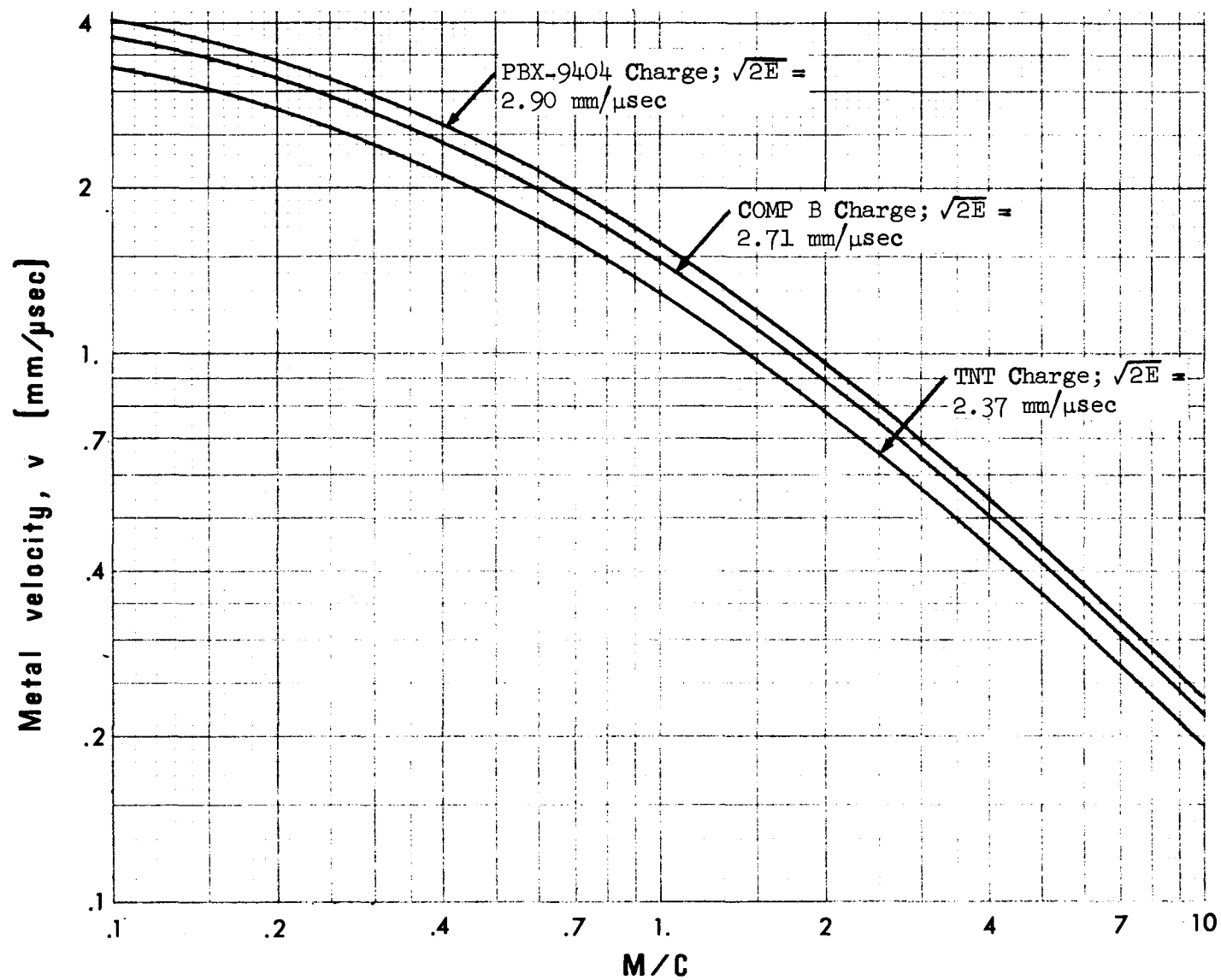


FIG. 5

Driven Metal Velocity for Open-Faced Sandwich.

metal velocity (and impulse) by as much as 7%.¹ Henry⁵ employed a variable pressure profile of a simple mathematical form in the detonation products in an attempt to reduce this discrepancy. He concluded that the additional mathematical complexity, which was inconsistent with the Gurney philosophy of simplicity, was not justified by the small improvement achieved in accuracy.

2.2 Impulse Estimation

Since the Gurney method provides an estimate of 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 the body's mass and velocity. We divide by the total charge mass C to derive the specific impulse delivered by the explosive.⁶

$$I_{sp} = \mathcal{M}/C = \frac{M}{C} v \quad . \quad (10)$$

2.2.1 Specific Impulse of Unconfined Surface Charges. Explosive is often detonated directly on the surface of a very heavy body in order to deliver a desired impulse for testing purposes. If we consider the loaded body to be rigid, all detonation gases will flow away from the surface and maximum specific impulse will be delivered to the body. For a very large body mass to explosive mass ratio, $M/C \gg 1$, Eq. (4) reduces to

$$v \approx \sqrt{2E} \cdot \sqrt{\frac{3}{4}} \frac{C}{M} \quad . \quad (11)$$

By utilizing this expression for v in Eq. (10), the relationship for specific impulse is found to be

$$I_{sp} \approx \sqrt{1.5 E} \quad . \quad (12)$$

Upon detonation of an unconfined surface charge as described above, essentially all the gas must flow backward away from the plate. 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. (12),

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

we derive a relation for the maximum free gas velocity:

$$v_{o, \max} = \sqrt{6 E} . \quad (13)$$

2.2.2 Impulse Modification by Tamping. 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 method can be used to estimate the change in impulse as a function of 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. (6), where the tamper to explosive mass ratio N/C is taken to represent M/C . 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

$$I_{sp, \text{ tamped}} = \sqrt{2E} \left(\frac{N}{C} + \frac{1}{2} \right) \bigg/ \left(\frac{N}{C} + \frac{1}{3} \right)^{1/2} . \quad (14)$$

Note that when no tamper is present ($N/C = 0$), this expression reduces to that for an untamped charge as given in Eq. (13).

3. GURNEY ENERGY OF EXPLOSIVES

Table 2 lists Gurney velocities calculated from data given for carefully conducted experiments in which there were no end losses and no gas leakage through metal walls until after their acceleration was completed. Occurrence of end losses (e.g. charges in short tubes, $L/D < 6$, with open ends) or early fracturing of driven metal may decrease the effective value of $\sqrt{2E}$ by 10% to 20% or more.⁷ Values of specific impulse calculated from Gurney velocities are also tabulated in Table 2.

Explicit forms may be derived to express efficiency of energy transfer from explosive to metal. 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:

$$\epsilon = \frac{Mv^2}{2C\Delta H_d} \cdot \frac{E}{E} = \left[\left(v/\sqrt{2E} \right)^2 \cdot \frac{M}{C} \right] \frac{E}{\Delta H_d} . \quad (15)$$

TABLE 2

ENERGIES AND SPECIFIC IMPULSES OF EXPLOSIVES

Explosive	$\sqrt{2E}$, mm/ μ sec (Ref.)	I_{sp} , ktaps/(g expl./cm ²) (Ref.)	E, kcal/g	ΔH_d , kcal/g (Ref.)	E/ ΔH_d
RDX	2.83 (5)	245	0.96	1.51 (11)	0.64
TNT	2.37 (2)	205	0.67	1.09 (10)	0.61
	2.44 (5)	211	0.71		0.65
Comp. B	2.71 (2)	235	0.87	1.20 (11)	0.72
	2.77 (1)	240	0.91		0.76
	2.70 (7)	234	0.87		0.72
	2.68 (5)	232	0.86		0.72
HMX	2.97 (2)	257	1.06	1.48 (10)	0.72
PBX-9404	2.90 (2)	251	1.01	1.37 (11)	0.74
PETN	2.93 (2)	254	1.03	1.49 (9)	0.69
EL506D	2.28	197 (8)	0.62		
EL506D,* Reconstituted	1.63	141 (8)	0.32		
NM	2.41 (2)	209	0.69	1.23 (10)	0.56

*Density assumed to be 1.46 g/cm³.

NOTES: 1. The following identities pertain for conversion from velocity to specific impulse units in the context of quantities in this table:

$$1 \text{ mm}/\mu\text{sec} = 10^5 \text{ dyn-sec/g explosive.}$$

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

2. Corrections were applied to the data of Refs. 1 and 2 as discussed in Appendix A to estimate the true speed of the metal before calculating Gurney energy, E.

3. Eq. (12) was used to calculate values of I_{sp} from values of $\sqrt{2E}$, or vice versa.

3

The first term of the result is the fraction of the Gurney energy which is in the form of kinetic energy of plate M, and this term is solely a function of M/C (and N/C where applicable). We can evaluate this term immediately for any given configuration, using the appropriate form for $v/\sqrt{2E}$ for the geometry of interest.

The second term, $E/\Delta H_d$, is the ratio of Gurney energy (the total kinetic energy in the direction of metal motion) to chemical energy of the explosive. Since chemical energy data are available for many 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 experimental values of heat of detonation, where available.

Values of Gurney energy E in kcal/g and heat of detonation ΔH_d are tabulated in Table 2 for several explosives. The ratio $E/\Delta H_d$ is observed to lie in the range from 0.61 to 0.76 for all explosives reported,¹² except for nitromethane (NM) for which the ratio was 0.56. In the absence of suitable performance data from which to calculate E, one might estimate that

$$E \approx 0.7 \Delta H_d \quad . \quad (16)$$

A series of one-dimensional computer calculations was conducted to determine whether the efficiency of conversion of chemical to kinetic energy was a sensitive function of the properties of an explosive. Those calculations are explained and their results are presented in detail in Appendix B. In summary, the calculations indicated only a slight dependence of conversion efficiency on the equation of state and sound speed of the detonation products. The slight trends indicated by those

calculations with a constant- γ law equation of state are in fact contrary to the slight trends indicated in the experimental data. It is concluded that an equation of state more accurate than the constant- γ law is needed to permit interpretation of fine details of energy transfer, but that Eq. (16) remains a satisfactory method for estimating E or $E/\Delta H_d$.

4. DESIGN APPLICATIONS

Equations (4) and (6) through (9) represent the metal velocity v as functions of $\sqrt{2E}$, M/C , and N/C for some simple symmetric and asymmetric system geometries. This section discusses diverse engineering applications of these relations, to illustrate the range of problems that can be treated by the Gurney method. General areas include parametric studies of the effects of given variables, scaling laws, and efficiency of energy conversion.

4.1 Parametric Studies

4.1.1 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) upon the velocity imparted to metal. The effectiveness of a metal tamper plate N in an asymmetric sandwich (Eq. (9)) in increasing the velocity of plate M is calculated as an example. Fig. 6 is a plot of the proportionate velocity increase of plate M due to tamping for various loading ratios M/C . The figure illustrates that tamping a relatively heavy charge ($M/C = 0.2$) increases the velocity of plate M by very little, whereas adding tamping to a light charge ($M/C = 5$) increases the velocity considerably, particularly in the range of $N/C < 5$.

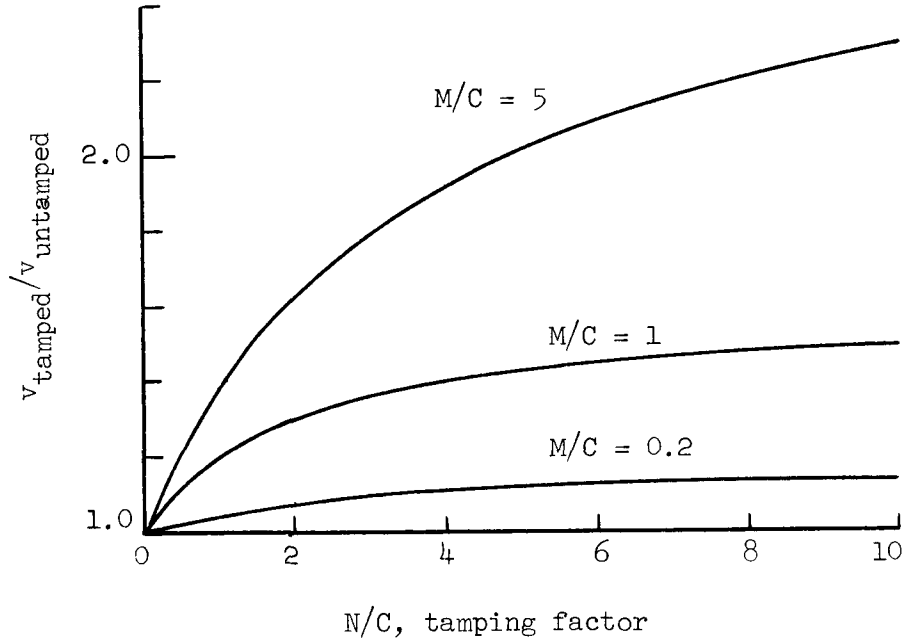


FIG. 6

Effectiveness of Tamping in Increasing Metal Velocity

4.1.2 Efficiency of Energy Conversion. For the same problem discussed above, let us calculate the efficiency of conversion of chemical energy of plate M to kinetic energy. Eq. (15) presented an expression for this overall efficiency, ϵ , which we rewrite here for convenience.

$$\epsilon = \left[(v/\sqrt{2E})^2 \cdot \frac{M}{C} \right] \frac{E}{\Delta H_d} \quad (15)$$

The second factor of this expression, $E/\Delta H_d$, is constant for a given explosive; it can be calculated directly from experimental values of both E and ΔH_d , or can be estimated to be 0.7 according to Eq. (16). The first term in the expression, denoted as ϵ_m , represents the fraction of the Gurney energy (total kinetic energy of gas and metal) which is delivered

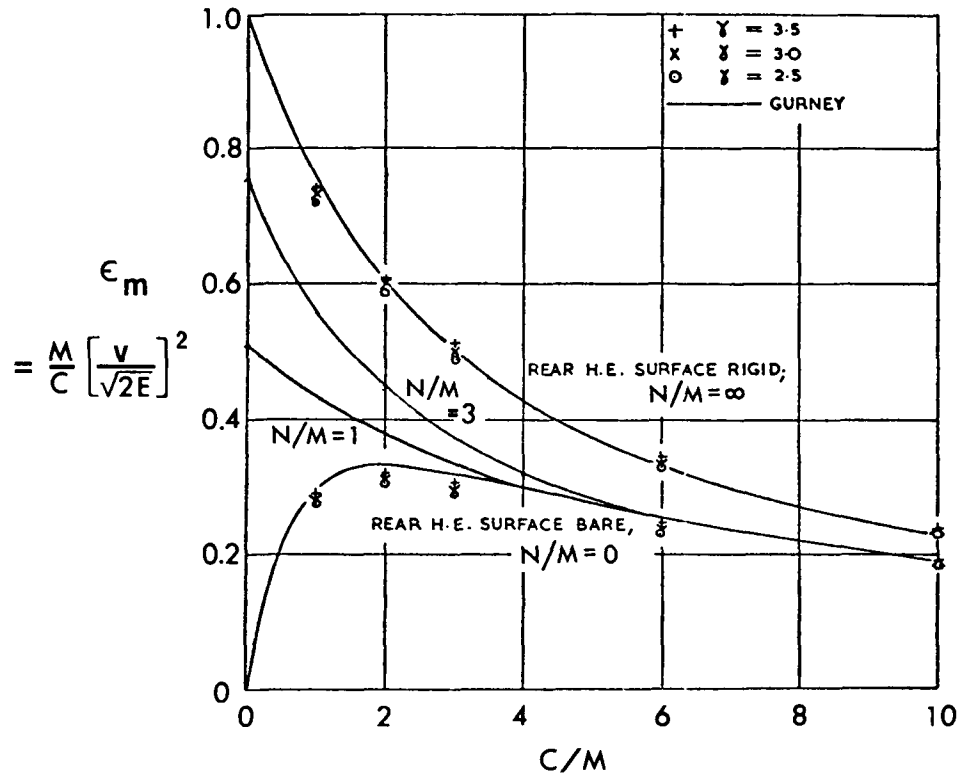
to one driven metal plate M; this term is a function of M/C and N/C (which may alternatively be expressed as N/M) for an asymmetric sandwich configuration and can be evaluated with the aid of Eq. (9). Variation of ϵ_m as a function of C/M and N/M for an asymmetric sandwich is illustrated in Fig. 7, in a form following that used by Hoskin et al.¹ The condition $N/M = 0$ corresponds to a bare charge, $N/M = \infty$ corresponds to a rigid rear support of the charge (or symmetry plane). Efficiency is seen to be strongly influenced by the tamper ratio at low values of C/M , but very slightly at high values of C/M where the efficiency decreases because of the large amount of kinetic energy remaining in the large, moving gas cloud.

4.2 Scaling

Circumstances and configurations often arise in the utilization of explosives 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 significant two-dimensional (edge loss) effects may be present 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 of the nearest "ideal" one-dimensional geometry as sketched in Fig. 3. This effective value of $\sqrt{2E}$ will usually be no more than 30% 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 two examples. Weinland⁷ has correlated the effective value of $\sqrt{2E}$ with the L/D ratio of open-ended tubes filled



- NOTES: 1. Observe that abscissa, C/M , is inverse of loading factor generally used in this report.
2. This figure has been reproduced from Hoskin et al.¹ with addition of the two center curves. Calculated points were obtained by Hoskin using constant- γ law.

FIG. 7

Efficiency of Kinetic Energy Partitioning to Plate M in Asymmetric Sandwich.

with explosive. For tubes of large L/D , the value of $\sqrt{2E}$ is the limiting or ideal value quoted in Table 2, whereas the effective value of $\sqrt{2E}$ decreases at an increasing rate as L/D is reduced below 6. The decrease in effective value of $\sqrt{2E}$ may be estimated from this equation derived by the author to describe Weinland's data, for $L/D > 0.5$,

$$\sqrt{2E}_{\text{effective}} = \sqrt{2E}_{\text{ideal}} (1 - 0.36 e^{-0.68L/D}) \quad . \quad (17)$$

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.¹³ 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 20% 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. After completion of the explosive acceleration of the tube walls, a progressive decrease in kinetic energy of the walls also occurred as a result of plastic work done upon the walls in dynamic deformation.

4.3 Direction of Metal Projection

In the derivation of Gurney equations, it is 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.

A derivation presented in Appendix A shows that the angle at which the metal is driven by grazing detonation is halfway between the normals to the axis and to the deflection angle of the liner as detonation progresses along the charge. The angle of projection, $\frac{\theta}{2}$, is

$$\frac{\theta}{2} \cong \sin^{-1} \frac{v}{2D}$$

off the normal to the original metal surface, in the direction of detonation propagation.^{1,12}

When detonation strikes the metal surface obliquely, at an angle between 0° (grazing or parallel incidence) and 90° (normal incidence), the metal is projected at an angle between 90° and $(90^\circ - \frac{\theta}{2})$.

4.4 Propellant Charges

The Gurney approach may be used also for interior ballistics problems, in which a propellant or a pyrotechnic charge drives a mass.⁵ The appropriate equation for projection of a bullet or shell from a gun, including the recoil effect, is that for the asymmetric flat sandwich, Eq. (9), in which the projectile mass is M, the propellant mass is C, and the gun mass is N. Note that if the gun mass is taken to be infinite, recoil is absent and use of the symmetric sandwich equation is appropriate. Effective Gurney energy values have been determined for some propellants in the presence of barrel friction or rifling; for example, $\sqrt{2E} = 1.7 \text{ mm}/\mu\text{sec}$ for smokeless powder and $\sqrt{2E} = 0.94 \text{ mm}/\mu\text{sec}$ for black powder.⁵ Gurney energy values may be calculated from almost any performance data, and have been

found to apply to systems of similar design but widely different loading factors (M/C) ,⁵ as a scaling law should.

5. SUMMARY

The Gurney method results in explicit algebraic equations for estimating the velocity imparted to metal in contact with detonating explosives. Gurney equations have been presented for several simple explosive/metal system geometries. Specific impulse of an explosive has been related to the Gurney energy of the explosive, and values of both these parameters are tabulated for several high explosives. The Gurney energy of an explosive may be empirically estimated from calorimetric data if suitable performance data on the explosive are not available.

The Gurney method can be applied to many design problems involving the utilization of explosives. Examples have been given to illustrate this point.

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APPENDIX A

Direction of Metal Projection

The one-dimensional Gurney analysis assumes that the metal moves in a direction normal to its surface. For some applications it will be of interest to determine the small angular deflection from the normal which pertains for grazing (parallel) incidence of detonation to the metal surface.

Figure 8 depicts grazing detonation driving a metal plate. Acceleration of the plate to its final velocity is assumed to be instantaneous for purposes of analysis. The plate is deflected at an angle θ to its 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. This requires that the plate element that was at point P at rest will be at point P' after launch and that

$$\overline{AP} = \overline{AP'}$$

where the superior bar ($\overline{\quad}$) denotes length between two points. Next, we construct a line from A normal to line PP'. Note that this bisects angle θ , since APP' is an isosceles triangle. We can now recognize¹ that

$$v = 2D \sin \frac{\theta}{2} . \quad (18)$$

A first order estimate of the actual direction in which metal is projected is the angle $\frac{\theta}{2}$ which can be evaluated from Eq. (18) by knowledge of v and D . Gurney Eq. (4), (6), or (9) 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.

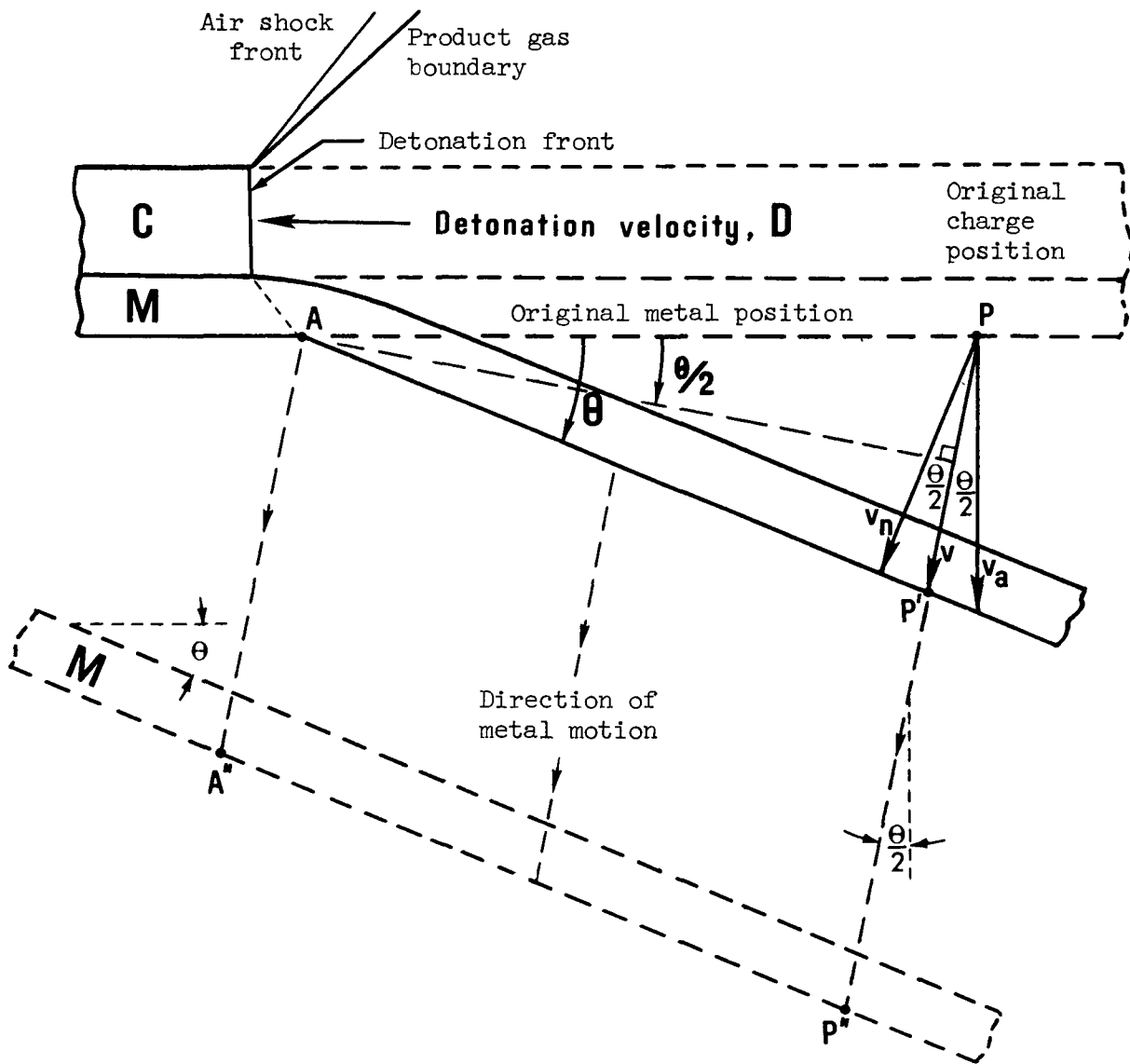


FIG. 8

Direction of Metal Projection by Grazing Detonation.

5 In measuring the velocities of plates driven by grazing detonation it is more convenient to measure components of velocity other than that along PP'. With a streak camera set perpendicular to the rest plane or charge axis, an "apparent velocity" v_a has been measured by Kury et al.² This quantity can be related to v by geometry.

$$v_a = D \tan \theta \quad . \quad (19)$$

$$v/v_a = \cos \theta / \cos \frac{\theta}{2} \quad . \quad (20)$$

Hoskin et al.¹ have expressed their results in terms of v_n , the velocity component normal to the flight plane of the plate, since this velocity component is of interest when the flying plate is used in impact studies. Noting that the angle between v_a and v_n is θ , geometry again allows us to relate v and v_n .

$$v_n = D \sin \theta \quad . \quad (21)$$

$$v/v_n = \sec \frac{\theta}{2} \quad . \quad (22)$$

The difference between v , v_n , and v_a , are in most cases only a few percent. Where data have been extracted from Ref. 1 or Ref. 2 and listed in Table 2, this correction has been made and the velocity v has been used in calculating E in all cases.

APPENDIX B

Effect of Detonation Product Equation of State on Efficiency

Hoskin et al. correlated their experimental results for tubular cylinders and flat plates driven by Comp B very nicely by Gurney equations;¹ their experimental results also agreed well with their computer calculations on those configurations.¹ Our values of chemical to kinetic energy conversion efficiencies ($E/\Delta H_d$) calculated from their Gurney equation showed little variation as the metal to charge mass ratio was varied, as listed in Table 3. This encouraged us to run computer calculations for various explosives in order to study the effect of the detonation product equation of state on energy conversion efficiency.

In our computations a Taylor wave drove a flat metal plate in an open-faced sandwich configuration. The one-dimensional WONDY code¹⁴ was used, with detonation product isentropes represented by the constant γ law, where γ is the polytropic gas exponent. The chemical energy Q was represented as a function of the detonation properties, $Q = D^2/2(\gamma^2 - 1)$, where D denotes detonation velocity.

For late times (large displacements), these WONDY calculations indicated a plate velocity higher by about 10% than was found experimentally by Hoskin et al. It was believed that this discrepancy was due to our use of a constant value of γ rather than a value which decreased as expansion progressed. We therefore chose to interpret our computed results on the basis explained below.

Kury et al.² of LRL have reported that, over a range of common values of M/C , detonation at normal incidence to a metal drives the metal essentially to its final velocity by the time the detonation products have

expanded to twice the original volume occupied by the explosive. The same work reported that the effective value of γ varies as a function of volumetric expansion, V/V_0 . In particular, γ drops off sharply at $V/V_0 = 3$ to 5, probably as a result of chemical recombination and intermolecular potential changes in this dense plasma. This has the effect of retaining most of the remaining internal energy in the gases rather than transferring it to the metal. Because we used a constant γ rather than some more realistic but more complex function, we decided to normalize the results of our calculations on AWRE* Comp B with Hoskin's results. We did this by finding an expansion ratio V/V_0 at which our computed efficiency matched that of Hoskin's observations, and accepted as "final velocity" the value obtained at that expansion ratio in all our calculations. This matching was done at a metal to charge mass ratio of $1/3$, as noted on Table 3, and was attained at a V/V_0 value of 2.7. Our computed efficiencies of energy conversion, E/Q , were subsequently found to be in accordance with the experimental values for Comp B over the range $0 \leq M/C \leq 2$.

Conversion of chemical energy to kinetic energy was calculated by WONDY for three other explosives in addition to Comp B, with gamma values spread over a wide range. All calculations were performed at $V/V_0 = 2.7$, for a metal to charge mass ratio arbitrarily set at one-third ($1/3$). These calculations indicated a correlation between the value of γ and the efficiency of conversion from chemical to kinetic energy as graphed in Fig. 9; for high values of γ , the efficiency was higher. If we consider the ratio of the gas cloud's internal energy, $pV/(\gamma - 1)$, to the initial chemical energy, $D^2/2(\gamma^2 - 1)$, we reach the same general conclusion; that

*Atomic Weapons Research Establishment, Aldermaston, England.

TABLE 3
EFFECTS OF M/C AND γ ON EFFICIENCY

Explosive	D, mm/ μ sec	γ	ΔH_d^* , kcal/g	Computed Results			Experimental Results		
				Configuration	M/C	E/Q	Configuration	M/C	E/ ΔH_d
Comp. B ¹ (AWRE)	7.75	2.85	1.20	Open	2	0.72	Open	2	0.72
				sandwich,	1	0.73	sandwich,	1	0.74
				normal	0.5	0.75	grazing	0.5	0.76
				detonation	0.333	0.76**	detonation ¹	0.333	0.76
				incidence	0.1	0.775		0.1	0.76
					0	0.74		0	0.73
TNT ¹⁶	6.95	3.16	1.09	Open	0.333	0.79	Tube	2.5	0.61
				sandwich,			grazing		
				normal			detonation ²		
				incidence					
Comp. B ¹⁶ (LASL)	8.03	2.76	1.20	Open	0.333	0.725	Tube	2.5	0.73
				sandwich,			grazing		
				normal			detonation ²		
				incidence					
PEX-9404	8.80	2.66 ³	1.37	Open	0.333	0.71	Tube,	2.5	0.74
				sandwich,			grazing		
				normal			detonation ²		
				incidence					
Fictitious***	8.80	3.16	1.37	Open	0.333	0.815	Nonexistent material		
				sandwich,					
				normal					
				incidence					

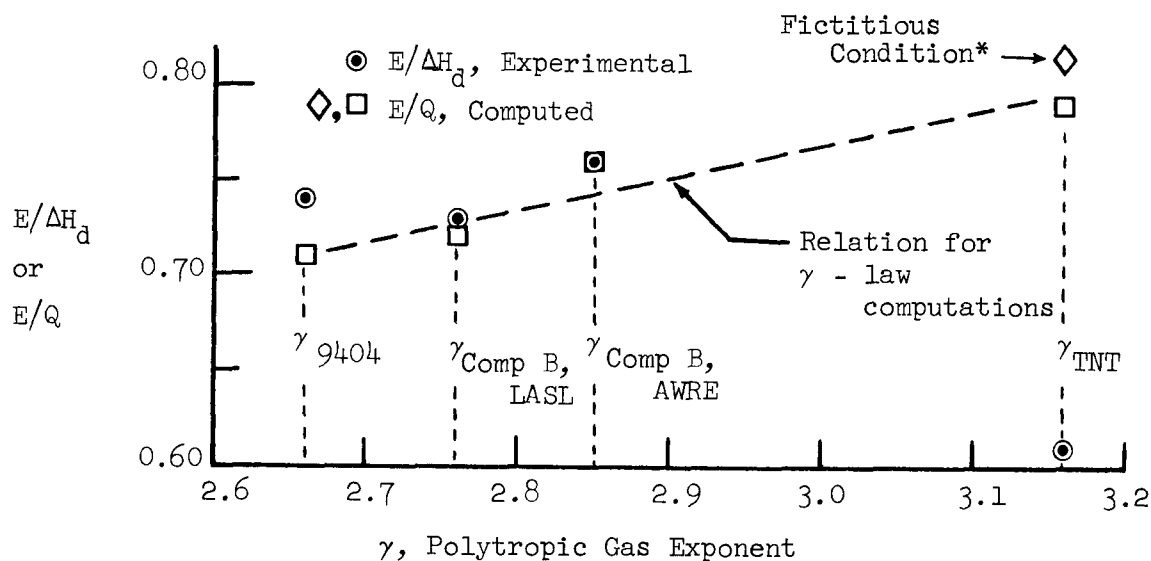
*From Ref. 10 and 11.

**Computed efficiency E/Q was matched to experimental result E/ ΔH_d at this value of M/C by use of computed metal velocity at $V/V_o = 2.7$. All computed results are reported at $V/V_o = 2.7$ accordingly.

***Fictitious set of properties: γ value of TNT, but detonation velocity of PEX-9404.

is, higher values of γ result in greater conversion of the gas cloud's internal energy into pV work at a given point in the expansion (i.e. a given V/V_0).

Perhaps the most obvious factor besides the γ value which might affect the efficiency of energy conversion is the speed of sound in the detonation products, which is the mechanism by which the various parts of the gas cloud communicate with one another and with the plate they are pushing. To see how significant "enhanced communication" might be in increasing energy conversion, we calculated a case for an explosive with the γ value of TNT but the detonation properties of PBX-9404, hence increased sound velocity in the detonation products. Only a slight increase in efficiency (2%) was indicated, showing that the γ value is the major factor contributing to calculated differences in efficiency.



*See Table 3.

FIG. 9

Chemical to Kinetic Energy Conversion Efficiency

The comparison in Table 3 of experimental results obtained for grazing incidence of detonation with calculated results for normal incidence requires justification. Lee and Pfeifer¹⁵ of LRL found in two-dimensional computer experiments that a tubular cylinder was driven to essentially the same final velocity whether it was axially initiated so as to provide normal incidence of detonation on the wall, or end-initiated so as to provide tangential incidence.

On an overall basis, the main point is that energy conversion efficiency does not change very greatly as a function of detonation product γ value. The calculated slight upward trend of E/Q with γ runs counter to a slight downward trend in the experimental data taken from Table 3 and also shown in Fig. 9. We conclude that the simple γ law equation of state for detonation products is not accurate enough to permit interpretation of the fine details of energy transfer, at least not in the manner of the interpretation attempted above.

Distribution:

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