EFFECT OF AN INERT MATERIAL'S THICKNESS AND PROPERTIES ON THE RATIO OF ENERGIES IMPARTED BY A DETONATION'S 1\textsuperscript{ST} AND 2\textsuperscript{ND} PROPULSION STAGES

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Abstract. Analysis of cylinder tests employing aluminum, steel, and copper cylinders of different thickness shows that Gurney Energy measurements have been affected by both the wall thickness and the material's dynamic properties. Experimental data for these tests and plate-push tests also show that the ratio of the initial free-surface velocity (1\textsuperscript{st} propulsion stage) to the final "steady-state" velocity obtained after the explosive gases have fully expanded (2\textsuperscript{nd} propulsion stage) can differ by a factor of two. The data show a clear dependence of this ratio upon the ratio of the inert material's thickness to the explosive's thickness. Phase transitions can also decrease propulsion efficiency by a significant margin.

INTRODUCTION

This paper presents observations gleaned from published experimental data while improving the BRIGS analytical package for explosive charges by separating explosive propulsion into a two step process: 1) initial motion imparted by a brisant process, and 2) subsequent acceleration by a gas-push process. As described in reference 1, the velocity imparted during the 1\textsuperscript{st} propulsion stage can be described by the Energy Transference Ratio (ETR) formulas. The 2\textsuperscript{nd} propulsion stage's gas-push process can be described by the familiar Gurney model wherein an explosive's gas volume expands from a "static" homogeneous "all-burned" high-pressure state into one wherein the velocities of the gases at the boundaries match those of inert boundary materials. Furthermore, due to its wide acceptance, the Gurney model also has been chosen to provide experimental data on conversion of an explosive's chemical energy to the final "steady-state" kinetic energy of the gases and inert materials. Unfortunately, when cylinder test data and plate-push data were collected and examined in order to characterize the energy that was converted during the total explosive-driven event, Gurney Energies were found to vary widely in the literature.

ANALYSIS AND DISCUSSION

Reference 2 was the first paper clearly identifying that there was a difference in the energy delivered by an explosive to different materials. This 1969 paper noted that the energy constant known as the "Gurney Energy" or the "Gurney Velocity" was significantly different when derived from US Navy, US Army, and Lawrence Livermore National Laboratory tests. For example US Navy sources found the Gurney Velocity for Composition B explosive to be 7610 or 7880 ft/sec (2320 or 2400 m/sec) while US Army sources used a value of 8800 ft/sec (2680 m/sec). Empirical data presented in refs. 3 and 4 revealed that early US Navy tests principally employed steel cylinders while US Army tests employed copper cylinders. Table 1 summarizes other examples of data found in published literature.
TABLE 1. Comparison of Gurney Velocities Derived from Experiments Using Steel Cylinders Versus Those Using Copper Cylinders

<table>
<thead>
<tr>
<th>Explosive</th>
<th>Steel in Ref. 3 (m/sec)</th>
<th>Copper in Ref. 5 (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp. A-3 (RDX)</td>
<td>2416</td>
<td>2630</td>
</tr>
<tr>
<td>Cyclotol (75/25 cast)</td>
<td>2320</td>
<td>2790</td>
</tr>
<tr>
<td>Comp. B</td>
<td>2310</td>
<td>2700</td>
</tr>
<tr>
<td>TNT (cast)</td>
<td>2040</td>
<td>2370</td>
</tr>
<tr>
<td>Tetryl</td>
<td>2209</td>
<td>2500</td>
</tr>
</tbody>
</table>

One of the problems with so-called "standard" tests, such as the copper cylinder tests, is that once a procedure is accepted as a "standard", very little other data is produced examining variations of materials or geometry. Fortunately, ref. 4 contains Gurney Velocity data, which were derived using final "steady-state" cylinder expansion velocities in the standard Gurney formula for cylinders and which show that the data were dependent upon the cylinder's material and wall thickness. Figure 1 presents a plot of these Gurney Velocities for Comp. B explosive clearly showing that experiments using steel cylinders of thickness equal to aluminum and copper cylinders yield lower Gurney Velocities.

![Figure 1](image)

FIGURE 1. Comparison of Gurney Velocities Versus Cylinder Wall Thickness Using Comp. B Explosive

Figure 2 presents a plot of the same Gurney Velocities data versus the areal density of the cylinder wall ($t_{cy} \times \rho_{cy}$) in units of g/cm². This representation of the data shows that a Gurney Velocity derived from the final "steady-state" velocity depends upon both the cylinder material and the areal density. However, it also shows that both aluminum and steel appear to absorb more energy during explosive-driven propulsion than does copper on an areal density basis.
Ref.1 presented a figure plotting the ratio of initial velocity ($V_i$) (from ETRi) to final velocity ($V_f$) (from ETRf) versus the ratio of plate thickness to explosive thickness ($t_p/T_e$). The data plotted in the figure also showed that the experimentally measured initial velocity of iron plates and cylinders was significantly lower than that found for other materials. Figure 3 presents a comparable plot using an expanded data set as well as plots of $V_i/V_f$ equations derived from ref.1's ETRi formula and Gurney equations for cylindrical and symmetric sandwich geometry modified into the same format.

According to ref.1, ETRi can be expressed as:

$$ETR_i = \frac{V_i}{D} \left( \frac{\rho_{cy} \rho_{ex}}{\rho_{cy} \rho_{ex}} \right)^{1/2} = 0.2085 \left( \frac{t_{cy} R_{cy}}{R_{cy}} \right)^{-3/40}$$

Where $D$ is the detonation velocity in km/sec, $\rho_{cy}$ and $\rho_{ex}$ are the cylinder and explosive densities in g/cm$^3$ respectively and $t_{cy}$ and $R_{cy}$ ($t_{pl}$ and $T_{ex}$ for plates) represent thickness and radius in mm.

The Gurney formulas for a cylinder and a symmetric sandwich as well as a relationship for approximating the Gurney Velocity using the detonation velocity and the adiabatic expansion constant ($\Gamma$) are found in ref. 6 to be:

$$V_{f_cyl} = (2Eg)^{1/2} \left[ \frac{M}{C + 1/2} \right]^{-1/2}$$

$$V_{f_{plate}} = (2Eg)^{1/2} \left[ \frac{M}{C + 1/3} \right]^{-1/2}$$

$$V_{f_{plate}} = (2Eg)^{1/2} \frac{0.605 D}{[\Gamma - 1]} \text{ (Roth's formula)}$$

Where $M$ and $C$ represent the masses of the inert material and the explosive.

Making the appropriate substitutions, the following formulas can be written:

$$\left( \frac{V_i}{V_f} \right)_{cyl} = \left( \frac{0.2085 / 0.3457}{(t_{cy} / R_{cy})^{-3/40}} \right)$$

$$\left( \frac{V_i}{V_f} \right)_{plate} = \left( \frac{0.2085 / 0.3457}{(t_{pl} / T_{ex})^{-3/40}} \right)$$

$$\left( \frac{V_{f_{plate}}}{V_{f_{cyl}}} \right)_{cyl} = \left[ \frac{(t_{pl} / T_{ex}) + 0.333 (\rho_{ex} / \rho_{pl})}{(t_{cy} / R_{cy}) + 0.5 (\rho_{ex} / \rho_{cy})} \right]^{1/2}$$

Data from cylinder tests used to construct Fig.1 were added to Fig.3 by using the ETRi formula to estimate the initial velocity. Since most of the data from which the ETRi formulas were derived represent experiments in which aluminum was used as the inert material, the ETRi formula calculated values were used to represent $V_{initial}$ for the aluminum cylinders. ETRi values calculated for the steel cylinders were simply divided by 2 to approximate the decreased initial velocities observed in currently available experimental data. As can be seen in Fig.3, this simple approximation for the energy lost to the iron $\alpha$ to $\epsilon$ phase transition produces "data" which nearly overlays some experimental data.
It appears that the propelled material’s thickness and phase stability under pressure can have profound effects during explosive propulsion. As shown in Fig. 3, the ratio of inert material thickness to the explosive radius during cylinder testing and of explosive thickness during plate-push testing can have a major effect on the partition of the energy transferred during the 1st and 2nd propulsion phases. Furthermore, the choice of material for use as a “standard” clearly affects the partitioning of energy transference as shown in Fig. 2 and 3.

CONCLUSIONS

This paper’s findings underscore the caution that must be exercised when using “standard” propulsion tests to derive parameters for models which are later applied to different materials or different geometry. Detonation-driven propulsion also clearly needs to be addressed by a two-step model rather than by a single gas-push cycle model. Furthermore, the effect of phase transitions occurring during the 1st propulsion stage needs to be considered both when deriving explosive “constants” from “standard” tests and when using the “constants” during the design of explosive devices.

REFERENCES