The effect of munition casings on reducing blast overpressures.

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Abstract

There exists a requirement to assess the maximum credible blast from an event in a magazine. This is particularly relevant to naval platforms where space is at a premium, and control measures may be applied to minimise the event to tolerable levels. Upper bounds based on the total net explosive quantity (NEQ) of the stored munitions are inherently pessimistic, so there is interest in obtaining more realistic estimates.

Energy conservation implies that the blast from a cased munition is less than the blast from a bare charge of the same NEQ. Indeed this is the basis of the familiar Gurney approach to metal acceleration by explosives. The paper reviews this formalism, and a number of existing formulae for effective NEQ, or equivalent bare charge, in terms of ratio of casing weight to charge weight, in the light of trials data from a number of sources. These include blast data from in-service munitions as well as from experimental configurations.

The evidence indicates that the nature of the casing material, as well as casing mass, is important in determining the equivalent bare charge. Potential explanations, and their implications, are discussed, and a correlation with casing material properties is developed.

Introduction

There exists a requirement (see other papers in this volume) to assess the maximum credible blast from an event in a magazine. This is particularly relevant to naval platforms where space is at a premium. Upper bounds based on the total net explosive quantity (NEQ) of the stored munitions are inherently pessimistic, so there is interest in obtaining more realistic estimates.

The usual approach is to relate the blast from a cased charge to that from a bare charge of the same explosive. The equivalent bare charge is defined as that quantity of the explosive which yields the same value of the airblast parameter of interest (usually peak overpressure or positive impulse) as the cased munition at the same distance from the detonation source. For assessing the hazard from a store containing mixed munitions these equivalent bare charges are then expressed in terms of TNT equivalents.

Energy conservation implies that the blast from a cased munition is less than the blast from a bare charge of the same NEQ, since casing fragments are projected. Indeed this is the basis of the familiar Gurney approach to metal acceleration by explosives. A number of formulae [1,2,3,4] for equivalent bare charge weight, or effective NEQ, in terms of the ratio of casing weight (M) to explosive charge weight (C) have been developed. These are briefly reviewed in the light of experimental and trials data from a number of sources.

There exists a considerable body of evidence that material properties of the casing are important in determining the equivalent bare charge weight, and hence that

these formulae are over-simplistic. Some improvements are suggested both in terms of M/C correlations derived from munition data, and improved estimates of Gurney energy related to casing material properties.

Equivalent bare charge formulae and concerns

Following the approach of Gurney [1] to metal acceleration, it is assumed that:

i) Each explosive has a characteristic specific energy, E_G, which is converted to the kinetic energy of the casing material and the product gases after detonation.

ii) Partitioning of the energy between the driven material (casing) and the product gases may be calculated on the basis of a uniform gas density, and a linear gas velocity profile.

iii) The explosive is ideal, or near ideal, so that all reactions are completed prior to casing rupture.

iv) The explosive's detonation energy continues to be converted into kinetic energy until the casing fragments attain a steady velocity.

If a long cylindrical cased charge of mass C, with a casing of mass M, is considered, this leads at rupture to the energy balance

$$C\,E_G = \tfrac{1}{2}\,M\,v^2 + \tfrac{1}{4}\,C\,v^2, \qquad (1)$$

where v denotes the fragment velocity. This derivation considers purely radial axisymmetric expansion: formulae for finite cylinders with endplates, and other geometries may also be derived (see eg. [5])

If the detonation energy of the explosive is denoted by E_0, then the total energy liberated into the gases is given as the sum of the gas kinetic energy and the internal energy:

$$\text{Gas energy} = C\left(E_0 - E_G\right) + \frac{CE_G}{1+2M/C}.$$

Let the Gurney energy E_G be a fraction f of the detonation energy E_0. The equivalent bare charge (C_b) is the uncased explosive charge which liberates the same amount of energy to the gas, hence

$$\frac{C_b}{C} = \left\{(1-f) + \frac{f}{1+2M/C}\right\} \qquad (2)$$

Using experimental fragment velocity data from TNT filled weapons, Gurney found that f was around 0.8. Using this value of f leads to what is usually referred to as Fano's formula, which first appears in [2]. A similar value was found for HBX-1 filled steel cased munitions [2].

An alternative assumption to (ii), above, is that at the time of rupture nearly all the product gas travels in a cylindrical shell with the same velocity as the fragments. This yields

$$C\,E_G = \tfrac{1}{2}\,M\,v^2 + \tfrac{1}{2}\,C\,v^2,$$

In place of (1), and following the procedure above, with f = 0.8, leads to

$$\frac{C_b}{C} = \left\{0.2 + \frac{0.8}{1+M/C}\right\}. \quad (3)$$

This formula is derived in [2] and appears in [3]. It is claimed that this formula gives an improved fit to the experimental data.

Some alternative fragmentation data for TNT filled cases considered in [2] yields the estimate f = 0.53, and a correspondingly modified bare charge formula. This value of f is significantly different, and does not support the hypothesis that the Gurney energy is a characteristic of the explosive.

An empirical formula which is claimed to fit experimental impulse data is given in [2] as

$$\frac{C_b}{C} = \frac{1+\frac{M}{C}\left(1-M'\right)}{1+\frac{M}{C}}, \quad (4)$$

where $M' = M/C$ if $M/C<1$, $M' = 1$ if $M/C \geq 1$.

In [2], these formulae (2,3,4) are correlated with experimental data for pressure histories from a number of steel cased TNT filled munitions, and it is found that they agree best with positive impulse data. If the equivalent bare charge for peak pressure is required, the right-hand side of any of the above formulae for C_b/C should be multiplied by 1.19. (4) including the factor 1.19 appears in a number of later publications (eg. [3,4]) as an accepted formula for the equivalent bare charge weight.

Thus it is seen that there exist some legitimate doubts concerning the accuracy of the available formulae. The first two, (2) and (3) above, depend on the assumption that the Gurney energy is a characteristic of the explosive. Further evidence against this, in addition to that mentioned above, is given in Backofen [6], and related publications, in the form of data assembled from cylinder tests using steel and copper cylinders, shown in Table 1 below.

Explosive	E_G from steel cylinder (kJ/kg)	E_G from copper cylinder (kJ/kg)
Comp. A-3 (RDX/Wax:91/9)	2918	3458
Cyclotol (75/25 cast)	2691	3892
Comp. B	2668	3645
TNT (cast)	2081	2808
Tetryl	2440	3125

Table 1. Comparison of Gurney energies derived from cylinder tests using steel and copper cylinders.

Clearly the concept that the Gurney energy is a characteristic of the explosive alone, and is independent the casing material, is not supported by experimental evidence.

Moreover the value of f varies significantly between compositions as shown in Table 2 below, particularly when explosives are non-ideal. Therefore the value of f employed in (2) or (3) should depend on the nature of the fill.

The formula (3) suggests that the bare charge equivalent is independent of the nature of the explosive fill, or at least that the factor 1.19 obtained through examination

Explosive	Detonation velocity (km/s)	Gurney energy (kJ/kg)	Heat of detonation (kJ/kg)	$f = E_G/E_0$
TNT	6.86	2977	4518.7	0.659
RDX	8.70	4004	5355.5	0.748
HMX	8.83	3920	5711	0.686
PETN	8.26	4292	4795	0.895
RDX/TNT 60/40	7.92	3672	5000	0.734
Tritonal (80/20)	6.70	2690	7406	0.363
Cyclotol (75/25)	8.25	3892	5125	0.759
Tetryl	7.57	3125	4602	0.679
Comp A-3	8.14	3458	5106	0.677

Table 2 : Values of E_G/E_0 for some common explosives (from [5])

of TNT filled munitions has wider applicability. However the variation in f demonstrated in Table 2 casts doubt on this. Moreover, as the factor 1.19 is dependent on the processing of the overpressure data to determine C_b from the measured results (free air data for cast TNT from Kirkwood and Brinkley [7] corrected for ground reflection using a coefficient of 1.8), it should be investigated further.

Munitions data

The concerns expressed above may be regarded as conceptual in nature. If the formulae give good agreement with the values of equivalent bare charge determined from blast overpressure measurements, their use, in practical hazard assessment at least, can be justified. Therefore the equivalent bare charges determined from blast overpressure for a range of munitions are compared with the values from the formulae (2,3,4) to determine their predictive ability.

First the underlying experimental data of [2], pressure measurements at various distances from a number of TNT filled steel cased charges, was re-examined. Current practice is to use Kingery curves [8], or their embodiment in tools such as Conwep [9], to relate measured peak overpressures or positive impulses to the equivalent bare charge of TNT. As the pressures were measured at considerable distances the hemispherical surface burst curves were used, assuming that the height of burst was small compared with the distance to the gauges.

The results are shown plotted and compared with the formulae above in figure 1 overleaf. It is seen that the overpressure data as processed using Kingery gives consistently higher equivalent bare charges than the previous approach. Fisher's formula (4) gives good agreement with the old processing approach, but requires modification of the pre-multiplying factor for pressure to 1.33 for the Kingery approach. The formulae (2,3) consistently yield lower values of the equivalent bare charge than the experimental data. As f is increased the equivalent bare charge is reduced.

It was found that exponential curves gave the best fit to the data: for the Kingery equivalent bare charge the recommended form is

$$\frac{C_b}{C} = 1.2691 \ \exp\left(-0.4355 \ M/C\right),$$

shown as the dotted line in figure 2 below. The solid curve gives the best fit to equivalent bare charges from Fisher's analysis of the recorded overpressure data.

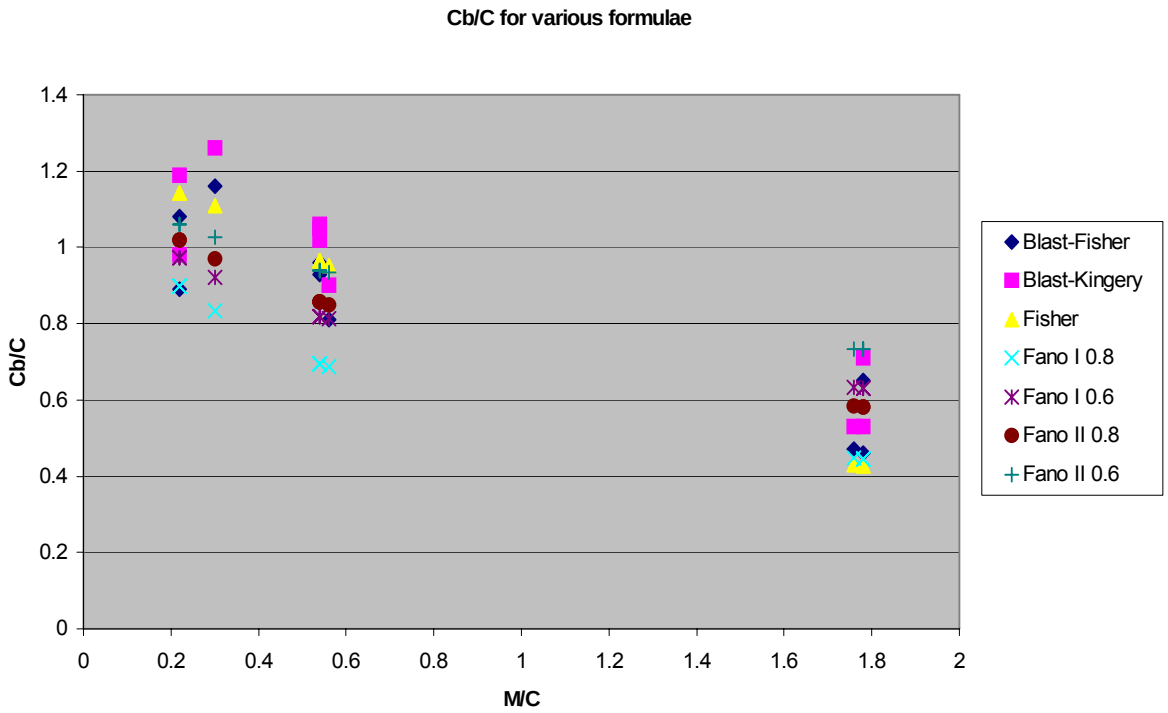

Figure 1: Ratio of equivalent bare charge for peak pressure to charge weight calculated by various methods for TNT filled steel cased munitions. The results from the experimental measurements are labelled as blast with the processing method: Fisher or Kingery. Fano I, II denotes results from (2), (3) respectively, with f = 0.6, 0.8.

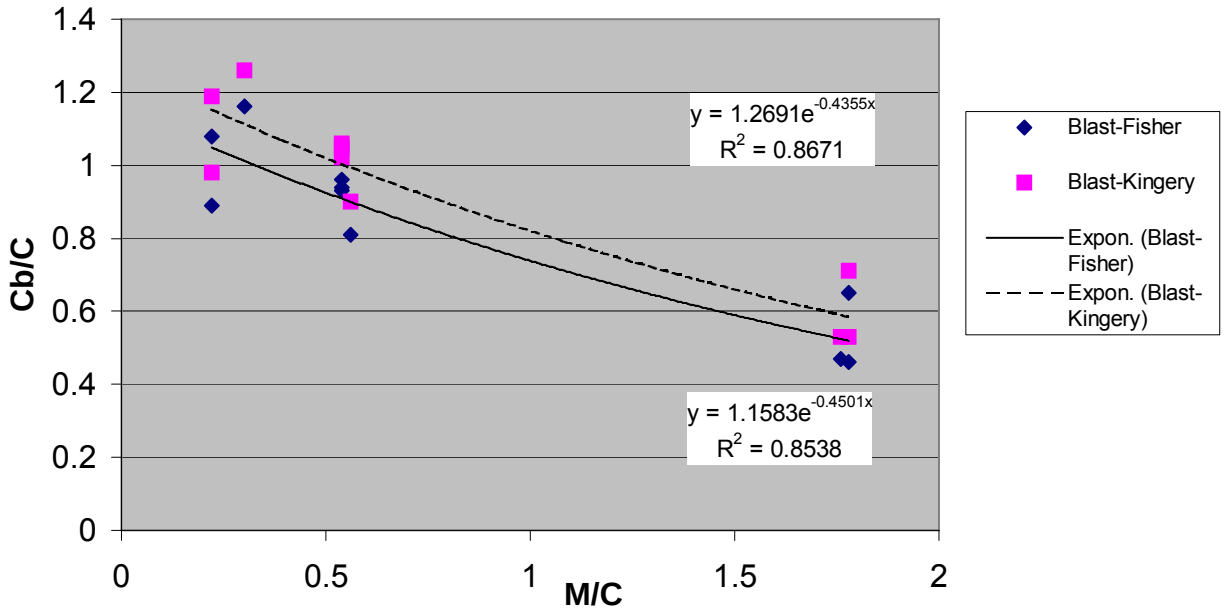

Figure 2: Showing best-fit exponential curves to the equivalent bare charges as estimated from blast overpressure data.

However, what if data obtained from trials on current UK munitions is added? Using the same Kingery approach to obtaining equivalent bare charges leads to Figure 3 below, which illustrates a potentially hazardous situation.

The data is widely scattered, giving equivalent bare charges up to 100% higher than the best-fit curve obtained previously. It is also clear that when higher M/C values are included the previous curve descends too steeply. The best fit to the combined data is

$$\frac{C_b}{C} = 1.0032 \ \exp\left(-0.1714 \ M/C\right), \qquad (5)$$

shown in Figure 4 overleaf, but the R^2 value is low due to the scatter of the data.

It is clear that if this approach is to be used for realistic hazard assessment, a better understanding of the important factors is required in order to reduce the scatter, which is still up to 50% above or below the suggested curve. We therefore return to a more detailed consideration of the overall energy balance for a detonating munition.

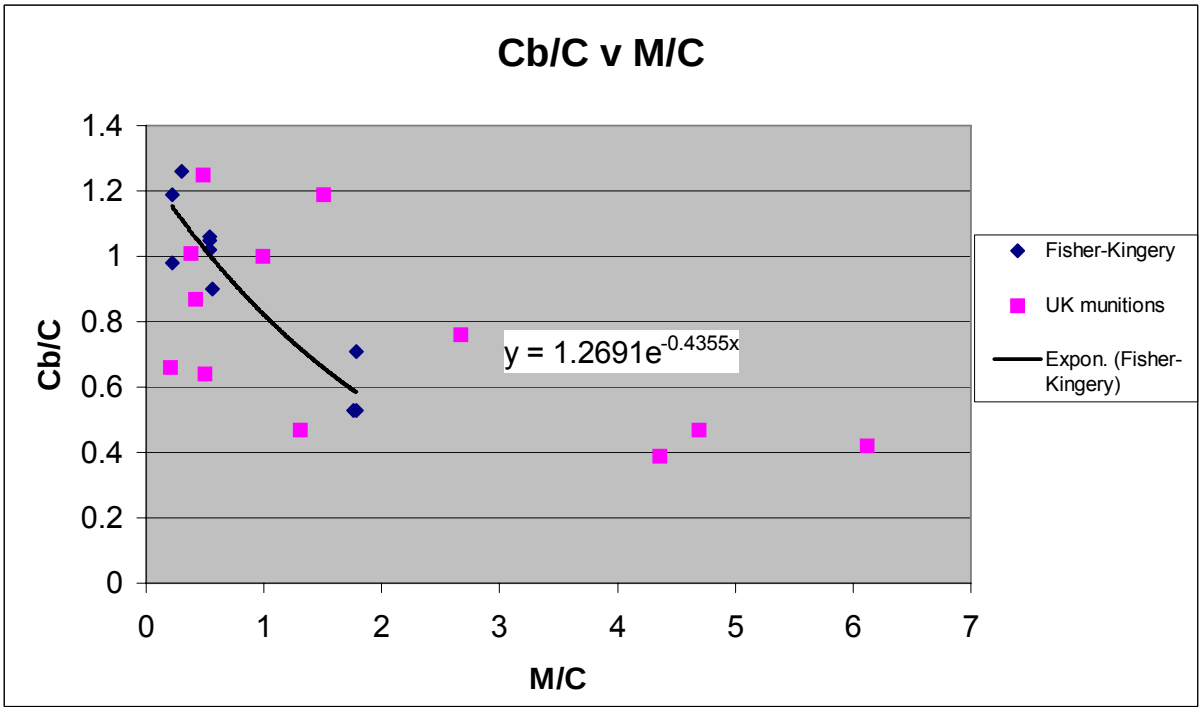

Figure 3: Ratio of equivalent bare charge for peak pressure to charge weight for UK munitions added to data from [2] analysed using Kingery, showing best fit curve to that data.

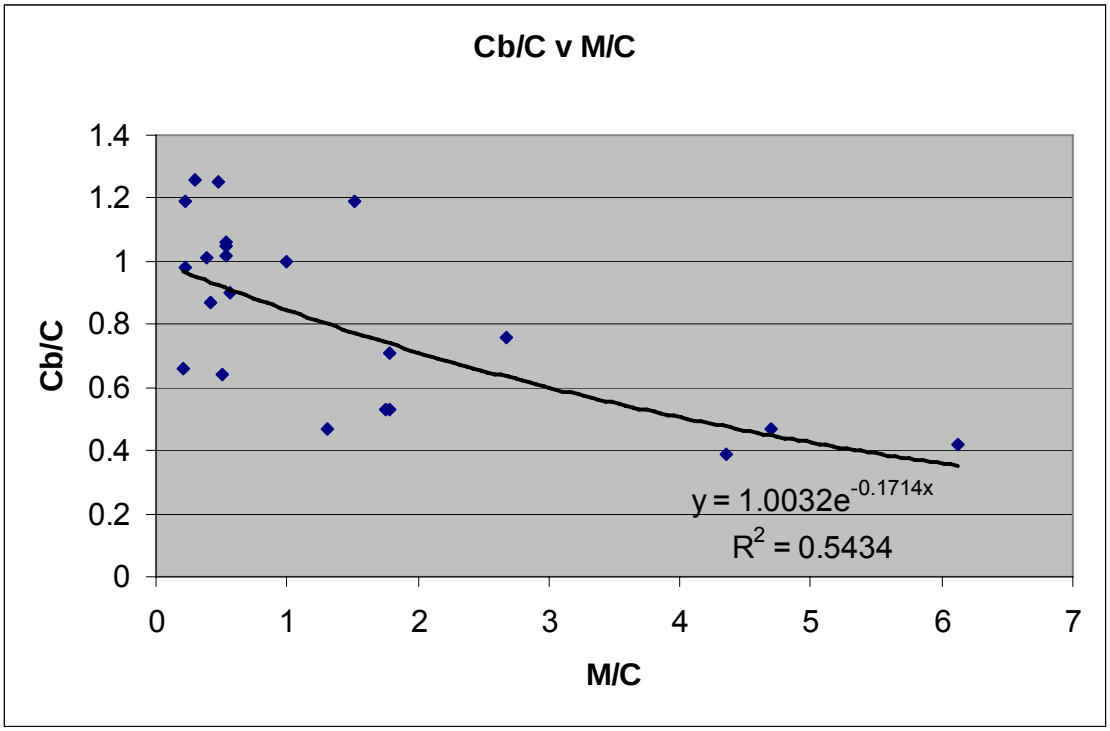

Figure 4: Best fit curve to the combined data of [2] and UK munitions.

Energy considerations

Conservation of energy applied to the detonation of a cased condensed phase explosive leads to the following energy balance at case rupture:

Energy released	=	internal energy of products	+	kinetic energy of products	+	kinetic energy of casing	+	energy absorbed by casing

From this it is deduced (see for example [10]) that

$$E_0 = E_G + E_{int}(\rho)$$

where E_0 is the specific internal energy of the undetonated explosive, and E_G is the Gurney energy, the specific energy converted to gas and casing kinetic energy, and $E_{int}(\rho)$ is the internal energy per unit mass of the detonation products of density ρ at the instant of expansion considered. This approach neglects both energy absorbed by the casing material in the form of strain/heat, E_s, and the kinetic energy imparted to the surrounding atmosphere by the expansion of the casing prior to rupture.

Assuming that the products expand adiabatically from the Chapman-Jouguet pressure, and that they behave as a perfect gas with a constant polytropic coefficient, γ, yields

$$E_{int}(\rho) = \frac{p}{(\gamma - 1)\rho}$$

where p denotes pressure. These assumptions effectively imply that the explosive is ideal, and that the origin of internal energies is the state of infinite expansion of the detonation products.

With this equation of state it is then well-known ([10,11]) that

$$D^2 = 2(\gamma^2 - 1)\, E_0 ,$$

$$p_{CJ} = \frac{\rho_0 D^2}{\gamma+1}, \text{ and } \rho_{CJ} = \frac{\gamma+1}{\gamma}\rho_0$$

where D denotes detonation velocity, p_{CJ} and ρ_{CJ} denote pressure and density of the detonation products in the Chapman-Jouguet state, and ρ_0 is the density of the undetonated explosive. Assuming adiabatic expansion of the detonation products it may then be shown [10] that

$$E_G = E_0 \left[1 - 2\left(\frac{\rho}{\rho_0}\right)^{\gamma-1}\left(\frac{\gamma}{\gamma+1}\right)^{\gamma} \right]. \quad (6)$$

The Gurney energy is therefore dependent on the degree of expansion considered. Once the casing ruptures the products gases will expand past the fragments, and the process of fragment acceleration effectively ceases shortly thereafter. The value of the Gurney energy is therefore dependent also on the tensile properties of the casing material, as this will determine the value of (ρ/ρ_0) at which rupture occurs. It should be noted that this result is independent of any assumptions about the form of the expression for the kinetic energy of the gas and casing in terms of fragment velocity, or the relative mass of metal and explosive. This demonstrates that E_G is dependent on casing material, and is not a characteristic of explosive alone.

It should be noted that if E_S is not neglected, (6) above becomes

$$E_G + E_S = E_0 \left[1 - 2\left(\frac{\rho}{\rho_0}\right)^{\gamma-1}\left(\frac{\gamma}{\gamma+1}\right)^{\gamma} \right]. \quad (7)$$

Rupture of the casing

Next the rupture process is considered in more detail. It is usually assumed that fragmentation occurs when the inner region of compressive hoop stress disappears and the pressure on the inner case surface is equal to the yield stress, σ_y, of the case material (see [12]). Assuming that the explosive products expand adiabatically yields at fracture, when $r = r_f$,

$$P = P_0 \left(r_f / r_0 \right)^{-2\gamma} = \sigma_y ,$$

where P_0 denotes the pressure on the inner case surface when the case radius $r = r_0$. For cylindrical geometry, mass conservation yields ρr^2 = constant. Thus, at fracture,

$$r_f / r_0 = \left(\sigma_y / P_0 \right)^{-1/2\gamma} \text{ and } \rho / \rho_0 = \left(\sigma_y / P_0 \right)^{1/\gamma}.$$

Substituting into the energy balance (7) yields

$$E_G + E_S = E_0 \left[1 - 2\left(\frac{\sigma_y}{P_0}\right)^{\gamma-1/\gamma}\left(\frac{\gamma}{\gamma+1}\right)^{\gamma} \right]. \quad (8)$$

If E_s is negligible we thus obtain

$$f = E_G / E_0 = \left[1 - 2\left(\frac{\sigma_y}{P_0}\right)^{\gamma-1/\gamma}\left(\frac{\gamma}{\gamma+1}\right)^{\gamma}\right]. \quad (9)$$

If E_s is not negligible, it may still be appropriate to expect that it is related to σ_y/P_0, and that an expression for f with the same dependence on σ_y/P_0 as (9) may be obtained.

Therefore the cylinder test data of Table 1 above, which showed that f or E_g is case material dependent, was re-examined to test this hypothesis. For each case the pressure P_0 was evaluated by assuming adiabatic expansion from the CJ state to density ρ_0,

$$P_0 = P_{CJ}\left(\rho_0 / \rho_{CJ}\right)^{\gamma}$$

using published data for the CJ parameters [5]. The values of yield stress were taken as 350 MPa for steel, and 175 MPa for copper. The data is shown in Table 3, and results plotted in Figure 4 below.

Explosive	Heat of detonation (kJ/kg)	Steel cylinder			Copper cylinder		
		E_G (kJ/kg)	$f = E_G/E_0$	σ_y/P_0	E_G (kJ/kg)	$f = E_G/E_0$	σ_y/P_0
Cyclotol	5125	2691	0.525	0.0254	3892	0.76	0.0127
Comp B	5015	2668	0.532	0.0312	3645	0.73	0.0156
TNT	4519	2081	0.46	0.0439	2808	0.62	0.0219

Table 4. Showing σ_y/P_0 for both steel and copper together with the Gurney energies evaluated from cylinder test data for various explosives.

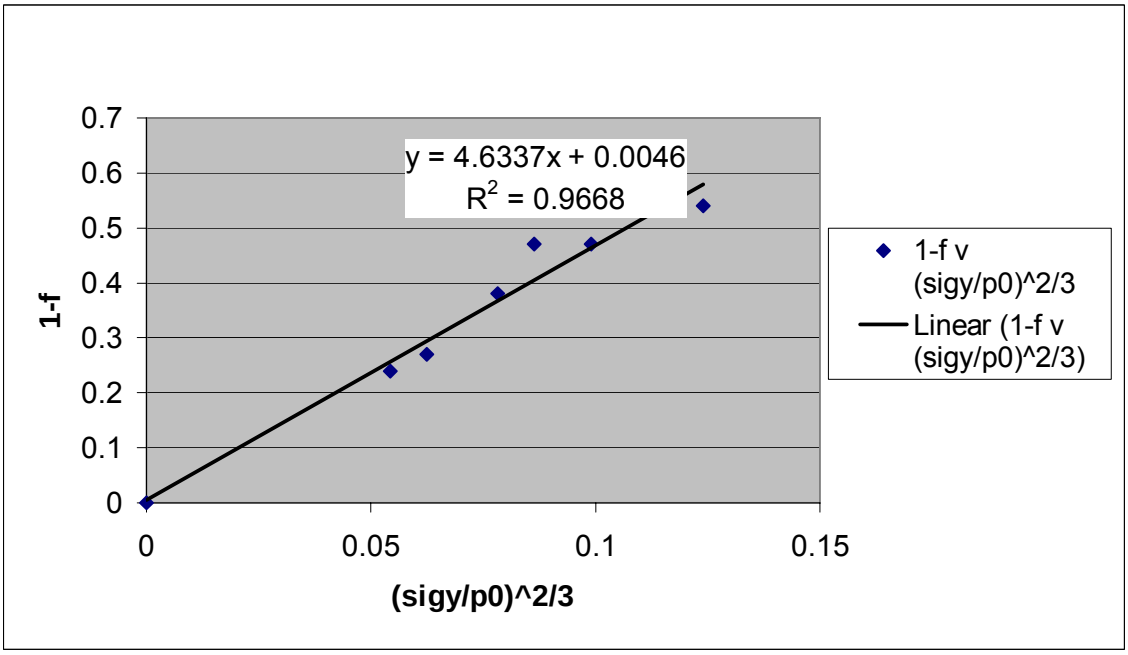

Figure 4: Showing the correlation of f (=E_G/E_0) with σ_y/P_0.

As can be seen from the graph there is a good correlation giving

$$f = 1 - 4.63\left(\sigma_y / P_0\right)^{2/3}, \qquad (10)$$

which is in the form suggested if γ is taken as 3, a commonly assumed approximate value. The fact that f is smaller than suggested by (9) with γ = 3 may be taken as an indication that E_S is not negligible in these cases. In the limit of weak casings, $f \rightarrow 1$ as would be expected at infinite expansion.

Conclusions

The limitations of current formulae for calculating equivalent bare charge have been demonstrated by comparison with munition data. From experimental data it is clear that the nature of the casing material affects the Gurney energy of the explosive, and a correlation with σ_y/P_0, the ratio of yield stress to initial pressure before case expansion, has been developed.

Further examination of munition data should now be undertaken, to evaluate the improvements in the predictions of the formulae when f is given by (10). In the mean time, the correlation (5) provides better estimates of equivalent bare charge in terms of M/C than (4), particularly at higher values of M/C.

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