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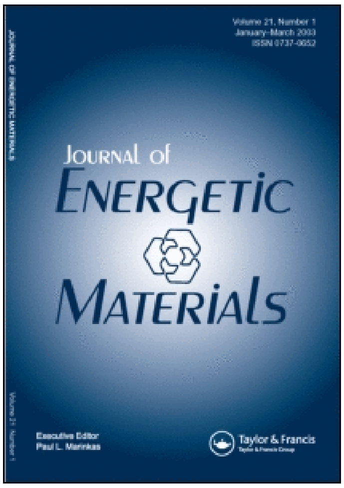

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H. R. James[a]
[a] Atomic Weapons Establishment Foulness Island, Essex, UK

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PREDICTING THE RESPONSE OF EXPLOSIVES TO ATTACK BY HIGH-DENSITY SHAPED-CHARGE JETS

H R James

Atomic Weapons Establishment
Foulness Island, Essex, UK

ABSTRACT

Predicting an explosive's response to jet attack would appear to be difficult due to the complex nature of the projectile. Consequently it is surprising that such a simple criterion as that obtained by Held (v^2D = constant) seems to be adequate in describing the initiation boundary of a given explosive under such circumstances. This paper discusses the complexity of jet impacts and compares experimental data with initiation boundaries formed by more regular projectiles. It appears that round-nosed rods, spheres and some jets form one class of projectile while flat-nosed rods form another. Both classes of projectile obey the v^2D criterion, which is shown to approximate to the critical energy criterion. Such an approximation enables predictions to be made about the effect of jet density on the initiation boundary and gives estimated values of such boundaries for explosives tested only by plate or rod impacts. Some suggestions are made as to why such simple initiation criteria work, but the nature of jet formation also leads to a warning about placing too much reliance on such predictions for charge demolition, since small changes in tip geometry may precipitate drastic changes in apparent charge sensitivity.

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INTRODUCTION

This paper is concerned with predicting the initiation boundaries of bare explosives impacted by high-density jets. Bare explosives in this context mean those which are decoupled from a barrier by an air gap, the barrier being necessary to establish the initiation boundary by attentuating the jet velocity to a point where no initiation occurs.

The general principles behind jet initiation of explosives are, to some extent, understood. Chick and Hatt[1] have shown that there are differences in the detailed mechanisms between initiation of explosives in contact with the barrier and those decoupled from it. However, both mechanisms depend on shock initiation. Where the explosive is in contact with a covering plate or case, the initial shock caused by the impact of the jet on this protective layer must be strong enough to run through the casing and trigger sufficient reaction in the explosive to eventually cause detonation. If the shock is too weak to start detonation, Chick and Hatt postulated that it acted to desensitize the explosive, inhibiting subsequent initiation by the direct contact of the jet after it had penetrated the case. Although this latter view has recently been challenged by Held[2,3], the evidence does show that the decoupling of the explosive from the case enables a less energetic jet to start detonation than that needed when charge and case are in contact.

For bare explosives, detonation occurs soon after impact and close to the jet tip. Hence initiation is caused by the initial shock generated by the impact of the jet in a similar manner to that which operates for the high speed impact of more conventional projectiles, such as spheres and rods. The main differences between such projectiles and jets lie in the possible variations in shock formation caused by the potentially more complex nature of the geometry, homogeneity and velocity gradient of the jet tip.

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The quantitative description of the initiation boundary has been found by Held[4] to be suprisingly simple for copper jets impacting bare 65/35 RDX/TNT. The criterion v^2D = constant appears to fit the boundary, where v is jet impact velocity and D is the jet tip diameter. This criterion was already known to apply to the impact of right circular cylinders[5], and will be shown in the present paper to also apply to spheres and round-nosed rods. The commonality of the criterion allows comparisons to be made between jet and more regular projectile impacts, and a correspondence to spheres and round-nosed rods will be demonstrated. This correspondence indicates possible reasons as to why such a simple criterion should apply to such a potentially complex projectile, and suggest probable limitations to its use.

The v^2D criterion will be shown to be an approximation to the critical energy (E_C) criterion, which was originally formulated by Walker and Wasley[6] for 1D impacts and developed by James[7,8] for more complex projectiles. This link allows predictions to be made for a wider range of jet materials since the E_C criterion accounts for the effect of projectile material when calculating the initiation boundary. It also allows predictions to be made for jet impacts into a wider range of explosives, providing the value of E_C for the explosive has already been obtained. As well as extending the applicability of the v^2D criterion, the known limitations of the E_C criterion indicate the limits to which predicting jet impacts can be taken.

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THE LINK BETWEEN JETS AND REGULAR PROJECTILES

Initially there appears to be no obvious connection between a jet tip and more regular projectiles such as spheres or rods. While a regular projectile has uniform shape, velocity and density, a jet tip can have:-

a. A velocity gradient.

b. An irregular or complex shape, eg the tip could be hollow or there could be irregular changes in jet diameter.

c. Variation in density.

d. Non-homogeneity of tip, ie the jet could be particulate rather than consisting of a coherent mass.

Despite these possible complexities, Figures 1 and 2 show that Campbell's experimental results[9] for jets are comparable to results from regular projectiles impacting the same explosive. Figure 1 compares copper jets impacting PBX9404 with steel flat- and round-nosed cylinders[10] (the Hugoniots for steel and copper are very similar). Campbell derived a v^2D value from the jet impacts of 16 ± 2 $mm^3/\mu s^2$, which is seen to provide a good fit to the round-nosed rod data as well. In contrast the flat-nosed rod data lies on an entirely different line with $v^2D = 4\ mm^3/\mu s^2$. Figure 2 shows a similar result for cast 60/40 RDX/TNT. Campbell's value of 29 $mm^3/\mu s^2$ for jet impacts, provides a good fit to the sphere data[11,12] (spheres and round-nosed rods are assumed to be equivalent for shock initiation of bare explosive[8]). Again the flat-nosed rod data[11,13] has a much lower value of v^2D.

One possible reason for this equivalence lies in the use of a barrier to attenuate the jet. As the jet penetrates the barrier its tip will become rounded. This process is illustrated in Figure 3, albeit with a rod of constant velocity, where a copper cylinder (originally flat-nosed) has been radiographed penetrating a stack of aluminium plates[14]. After the jet has emerged from the barrier, the rounded tip will presumably survive to provide the striking surface when impacting the explosive.

A further reason is that the high velocity and small diameter of the jet tip ensures an intense, but brief, initial shock generated in the explosive by the jet impact. Consequently only a very localised region of the jet tip will be involved in the formation of this shock and hence, since it is this shock which

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determines whether detonation will occur, only a small region of the jet tip is involved when determining the response of the explosive. This minimises the effects of variable conditions behind the jet tip, such as velocity and density gradients, and enables the tip to approximate to a regular projectile which has constant conditions behind the striking surface.

The equivalence of Campbell's jet data to sphere (or round-nosed rod) impact calls into question the modelling of this data by Mader and Pimbley[15] where a flat-nosed rod was used to simulate the jet. Indeed where PBX9404 was modelled, the results should have been close to the experimental data of Bahl et al[10], in which steel flat-nosed rods of similar diameter were used (see Figure 1), instead of corresponding to the v^2D value of the jet and round-nosed rod data.

Not all jet data can be so conveniently linked to regular projectiles. Held[4], impacting copper jets into cast 65/35 RDX/TNT (density 1.72-1.73 Mg/m^3), obtained a value for v^2D of 5.81 $mm^3/\mu s^2$. This is compared in Figure 4 with Moulard's experimental results[16] for steel flat-nosed rods impacting cast 65/35 RDX/TNT (density 1.73 Mg/m^3). As can be seen, Held's jet data has a smaller value of v^2D than even the flat-nosed rod data, and so does not agree with either of the two main types of regular projectile identified so far.

The reason for this discrepancy is not obvious since on the one hand it seems unlikely that Held's batch of explosive would be so much more sensitive compared to Moulard's. Alternatively, for shock initiation, a flat-nosed cylinder should be the most efficient form of projectile for causing detonation, ie it should give the lowest value of v^2D for a given explosive. This sort of result should warn against over-confidence when attempting to predict initiation by jet impact.

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THE LINK BETWEEN V^2D AND THE CRITICAL ENERGY CRITERION

The value of v^2D for a particular explosive depends on the jet material as well as on the sensitivity of the explosive under test. Since most of the published experimental data on high-density jets use copper as the jet material, attempts to extend the applicability of v^2D to any jet have to be centred on finding a more general criterion which can account for the material properties of the projectile.

A criterion which can satisfy this requirement is the critical energy criterion, originally developed by Walker and Wasley for 1D impacts and recently modified by James to account for other types of projectile. This criterion states that there is a critical energy per unit area (E_C) for a given explosive which, if exceeded by the initial shock generated upon impact, will cause detonation. James[7] has shown that for flat-nosed cylinders of circular cross-section:-

$$E_C = PuD/6c \qquad (1)$$

and for spheres or round-nosed rods

$$E_C = PuD/18c \qquad (2)$$

The values of pressure (P), particle velocity (u) and sound velocity (c) all relate to conditions behind the initial shock generated in the explosive, and can be calculated knowing the impact velocity and the Hugoniots of the projectile and solid explosive. The value of E_C is constant for a given explosive and is of the order of 0.5 - 2.0 MJ/m^2 for a number of commonly used secondary explosives[8].

Hence the E_C criterion links material properties (needed to calculate P, u and c) to impact velocity and projectile diameter for a given explosive. It is also shown by Figures 5 and 6 that for a given projectile material (or two materials such as steel

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and copper with similar Hugoniots) the v^2D criterion approximates to the initiation boundary obtained from a constant value of E_C. Figure 5 shows the experimental data given by Slade and Dewey[5] for steel flat-nosed rod impacts into Comp B and tetryl. Figure 6 shows round-nosed rod and jet impacts into PBX9404[9,10]. A comparison between the v^2D values fitted by Slade and Dewey to their experimental data, and the relationship of v to D obtained by the E_C criterion shows good agreement. A similar agreement is shown in Figure 6.

Data used to calculate the Hugoniots of materials discussed in this paper are given in Table 1, while the values of E_C needed to give the best fit to the experimental jet data are listed in Table 2 together with published values of E_C obtained from 1D impacts into the same explosive. The agreement between the E_C relationship for v and D, and the v^2D = constant criterion, enables predictions to be made as to the effect of jet material on v^2D. Also the agreement in the values of E_C obtained both from 1D data, and from fitting the E_C criterion to jet experiments for the same explosive, gives some confidence in predicting v^2D for an explosive which only has a value of E_C based on plate or regular projectile impact data, and has not been subjected to shaped charge attack.

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TABLE 1

Constants for the Linear Shock/Particle Velocity Relationship Needed to Calculate a Material's Hugoniot.

Material	Density Mg/m^3	a km/s	b	Reference
PBX9404	1.844	2.43	2.57	17
Comp B	1.713	2.71	1.86	18
Cyclotol 75/25	1.76	2.02	2.36	19
Tetryl	1.54	2.17	2.76	8
Pressed TNT	1.52	2.08	2.33	17
Aluminium	2.7	5.27	1.37	20
Magnesium	1.776	4.57	1.21	21
Platinum	21.449	3.68	1.46	21
Gold	19.24	3.07	1.54	21
Tungsten Alloy	17.0	3.94	1.44	14
Lead	11.346	2.03	1.47	21
Copper	8.9	3.958	1.497	22
Brass	8.517	3.78	1.431	22
Mild Steel	7.84	3.596	1.6863	23
Plastic	1.41	1.66	1.48	21
Paraffin	0.917	3.12	1.47	21

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TABLE 2

Comparison Between Values of E_C Obtained from Plate and Jet Data.

Explosive	Plate Data			Jet Data	
	Density Mg/m^3	E_C MJ/m^2	Reference	Density Mg/m^3	E_C MJ/m^2
PBX9404	1.842	0.64	24	1.844	0.70
60/40 RDX/TNT	1.73	1.20-1.47	25	1.713	1.50

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THE EXTENSION OF v^2D TO DIFFERENT JET MATERIALS

Figure 7 shows the dependence of the value of v^2D for a given explosive (PBX9404) upon the jet material. The value of v^2D for the various materials shown have been calculated by assuming the jet is equivalent to a round-nosed rod impact and E_C has a constant value of 0.70 MJ/m^2. The results are compared with attempts by Mader and Pimbley[15], and Chick et al[26] to introduce material effects into the v^2D criterion.

Mader and Pimbley numerically simulated the effect of different jet materials by using a 2D Eulerian hydrocode which incorporated an explosive burn model called 'Forest Fire'[27]. The results led them to amend the criterion to ρv^2D = constant, where ρ is the initial density of the jet material. Chick et al performed a limited series of experiments on covered explosives and came to the conclusion that $\rho^{0.5}v^2D$ = constant. As can be seen in Figure 7, this latter result is closer to the E_C calculations, despite being obtained for covered rather than bare explosives.

The scatter in the E_C calculations is primarily due to the variation in sound speed between the different materials, a factor not included in the above amendments to the v^2D criterion. However, for the high-density jets, Chick et al's relationship of $\rho^{0.5}v^2D$ = constant is a reasonable approximation.

The preceding discussion assumes that the jet tip will always remain a homogeneous mass. However, one effect of changing the liner material in a shaped charge is to introduce the possibility of obtaining a non-homogeneous jet. This is certainly true of low-density liners, but also applies to materials such as lead. The effect this would have on the value of v^2D (assuming D to be the diameter of an envelope containing the main mass of the jet tip) is difficult to predict.

PREDICTING v^2D FOR EXPLOSIVES NOT TESTED BY JET IMPACT

To predict a value of v^2D for an explosive which has not yet been subjected to jet attack, the following are required:-

a. The Hugoniots for both the proposed jet material and the solid explosive.

b. A value of E_C for the explosive at the required density and specification. It should be noted that small changes in either the density or detailed specification of the explosive can lead to relatively large changes in E_C[8].

c. The assurance that the E_C criterion is applicable for the particular explosive and over the range of impact velocities required. Limitations in both these areas have been observed[25].

Given the above, it is then assumed that the jet will behave as a round-nosed rod upon impact, and the jet material will form a coherent tip. Equation (2) is then used to find the value of v^2D.

This process has been carried out on two explosives for which jet data is available in order to compare the final result with reality. Table 3 compares values of v^2D derived from E_C data with that obtained from copper shaped charge jets.

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TABLE 3

Values of v^2D Predicted from E_C Data.

Explosive	E_C Data				Jet Data		
	Density Mg/m^3	E_C MJ/m^2	Ref	Predicted v^2D mm^3/μs^2	Density Mg/m^3	v^2D mm^3/μs^2	Ref
Pressed TNT	1.55	0.63-0.67	28	15	1.52	13	29
Cast 75/25 Cyclotol	1.76	1.98	13	41	1.743	37	9

As can be seen, a good agreement is achieved between predicted and actual values of v^2D.

CONCLUSIONS

The majority of published data on high-density jet impacts into bare explosives support the view that such projectiles behave as round-nosed rods rather than as flat-nosed cylinders. The reason for this probably lies in the penetration of the barrier used to attenuate the jet. Such penetration tends to round the nose of the projectile. Problems still exist for some data where links between regular projectiles and jets to not appear to exist. A convincing explanation for these results has yet to be found.

The link between jets and round-nosed rods gives rise to a problem when attempting to predict the response of an explosive to shaped charge attack. Round-nosed rods are less efficient at causing detonation than their flat-nosed counterparts. Consequently it is possible in a few cases, for jets that have broken into discrete elements, to have one element of the jet being completely used up as it breaks through the barrier, leaving the following element, which may have a flat face, to strike the explosive. Although the two elements may have the same diameter,

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the velocity needed to cause initiation will differ by a factor of about two.

By showing v^2D approximates to the E_C criterion, the effect that changing the jet material has on v^2D for a given explosive can be calculated. It appears that the $\rho^{0.5}v^2D$ = constant, found by Chick et al[26] for covered explosives, provides a reasonable approximation for high-density jets attacking bare explosives. However, such a criterion does assume a coherent jet tip, which may not always be produced when the shaped charge liner material is changed. The effect of a non-homogeneous tip is difficult to predict.

The link between jets and round-nosed rods can be used in conjunction with the E_C criterion to predict values of v^2D for explosives not yet subjected to jet attack. This method depends on the explosive being suitable for the application of the E_C criterion (see work by de Longueville et al[25]), and on a value of E_C being available. It should be noted that both the v^2D and E_C criteria are empirical. Consequently, although this paper has shown that they can be applied to a wide range of situations, it must be stressed that in areas where no experimental evidence exists they should only be used with extreme caution. Hence, any attempt at predicting explosive behaviour under jet attack must take note of the caveats expressed in this paper.

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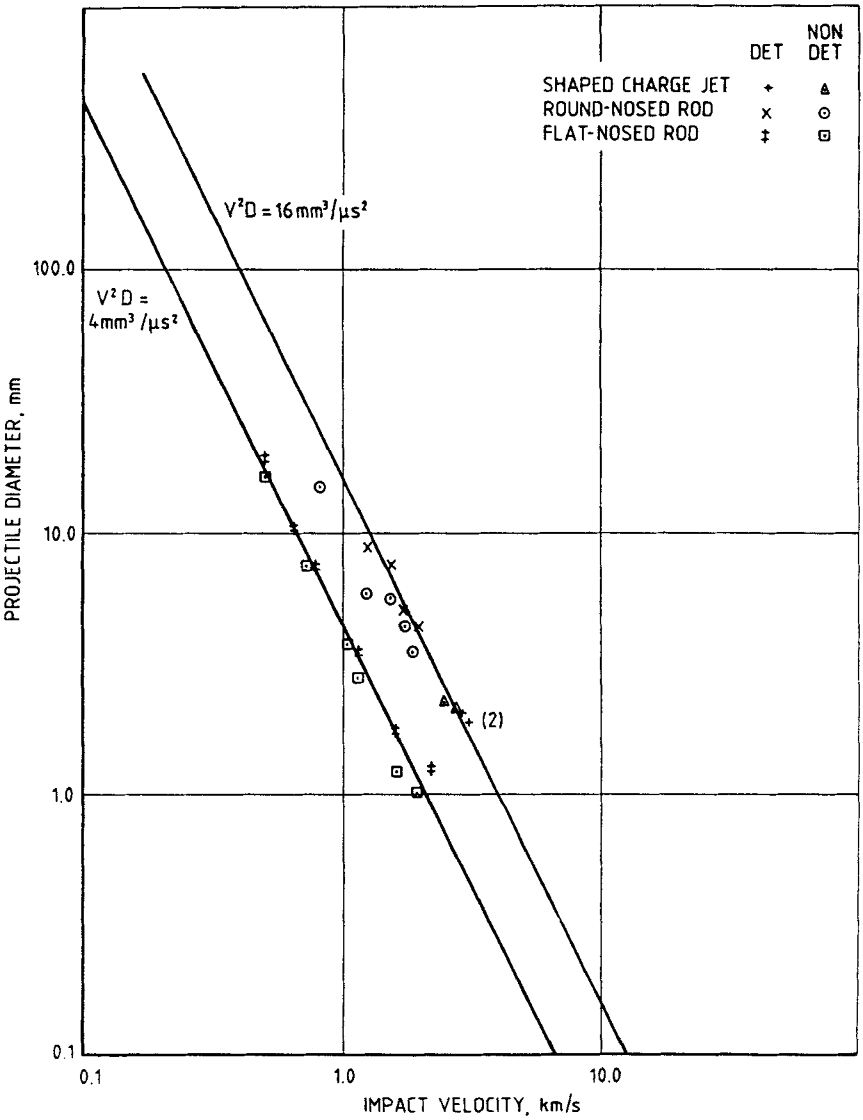

FIGURE 1

Initiation Boundaries Formed by the Impact of both Regular Projectiles and Shaped Charge Jets into PBX9404.

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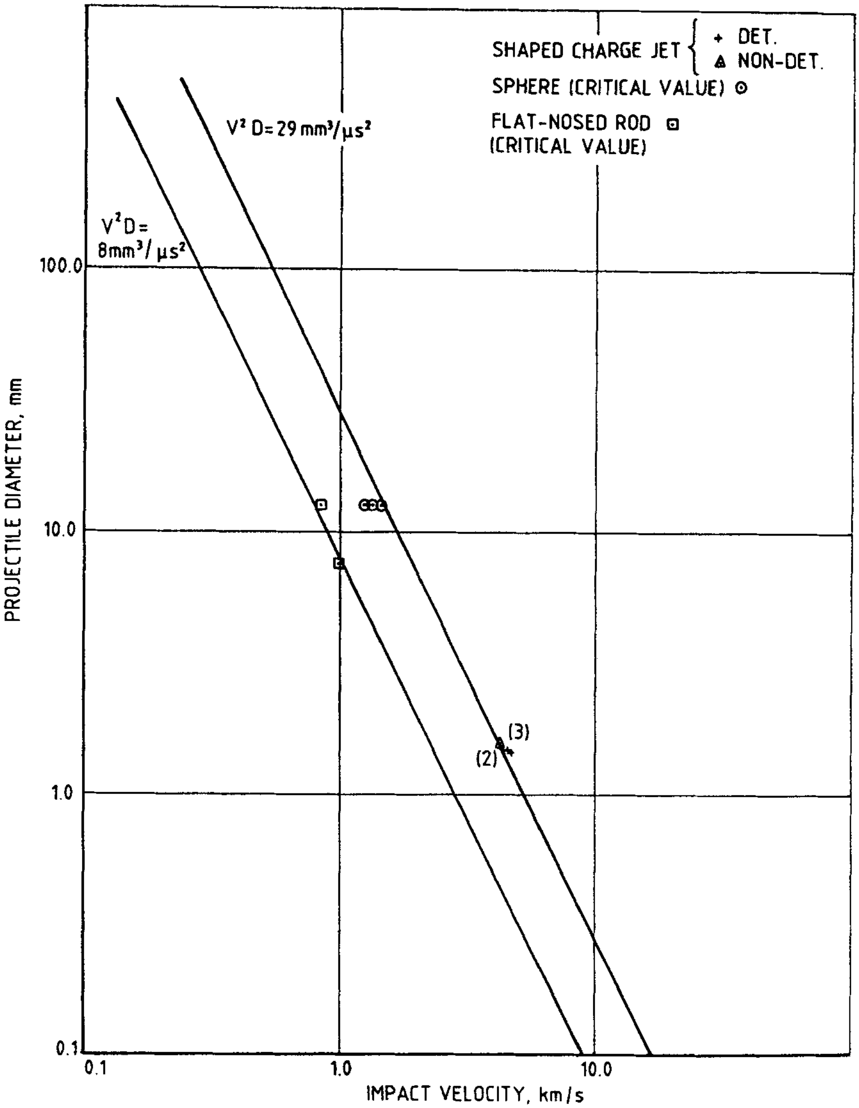

FIGURE 2

Initiation Boundaries Formed by the Impact of both Regular Projectiles and Shaped Charge Jets into 60/40 RDX/TNT.

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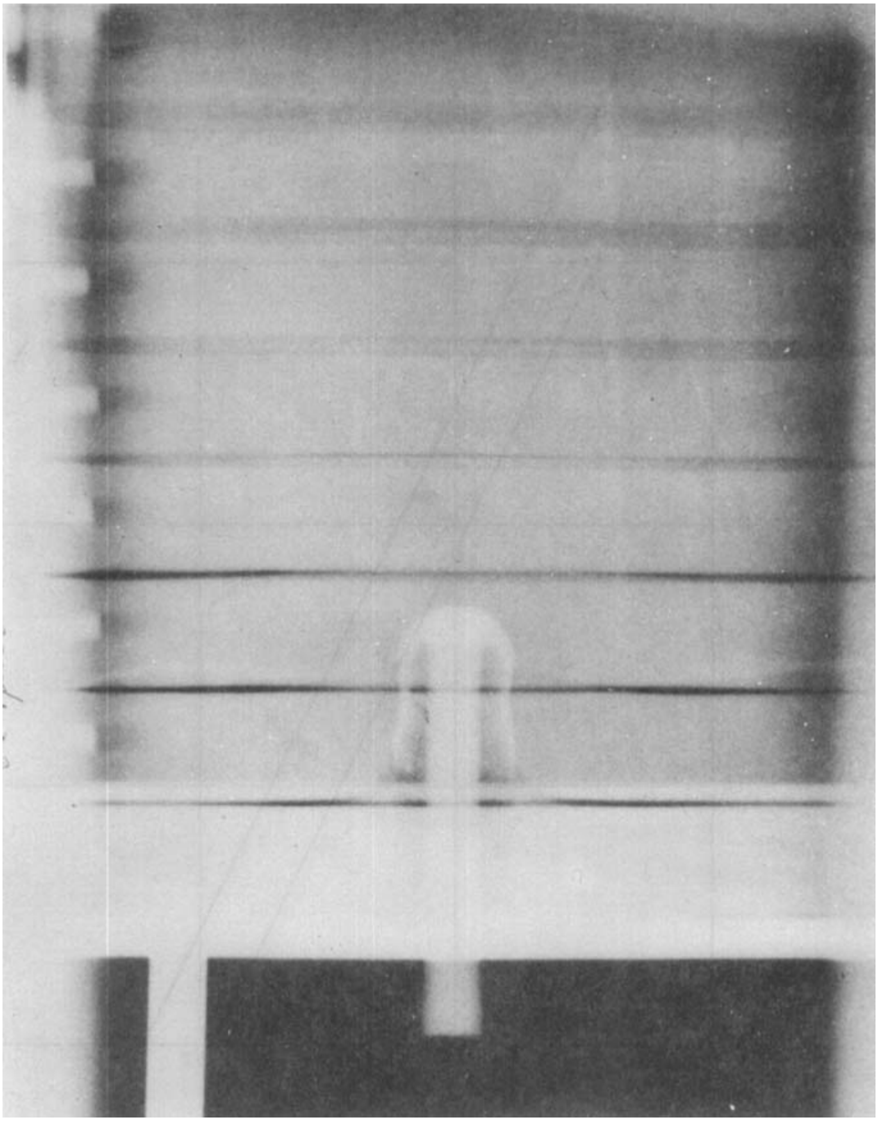

FIGURE 3

Radiograph of a Copper Flat-Nosed Rod Penetrating a Stack of Aluminium Plates.

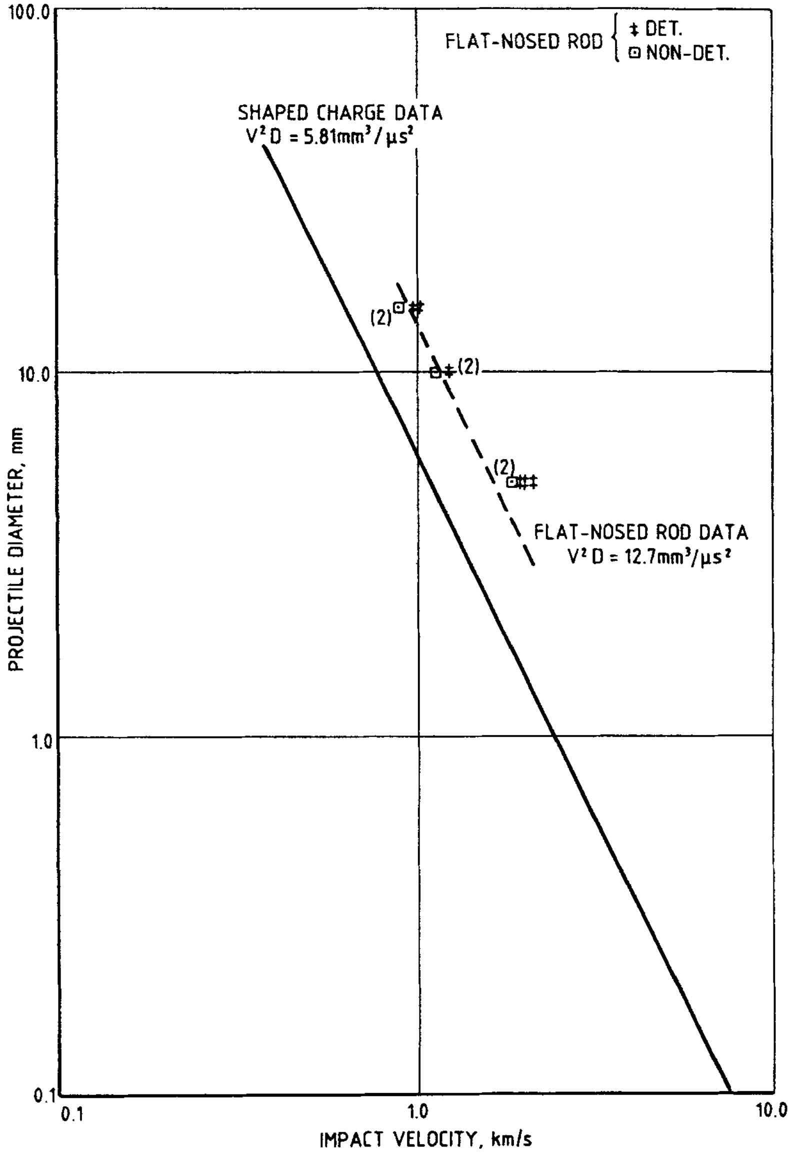

FIGURE 4

Comparison of Held's Jet Data with Moulard's Flat-Nosed Rod Data for 65/35 RDX/TNT.

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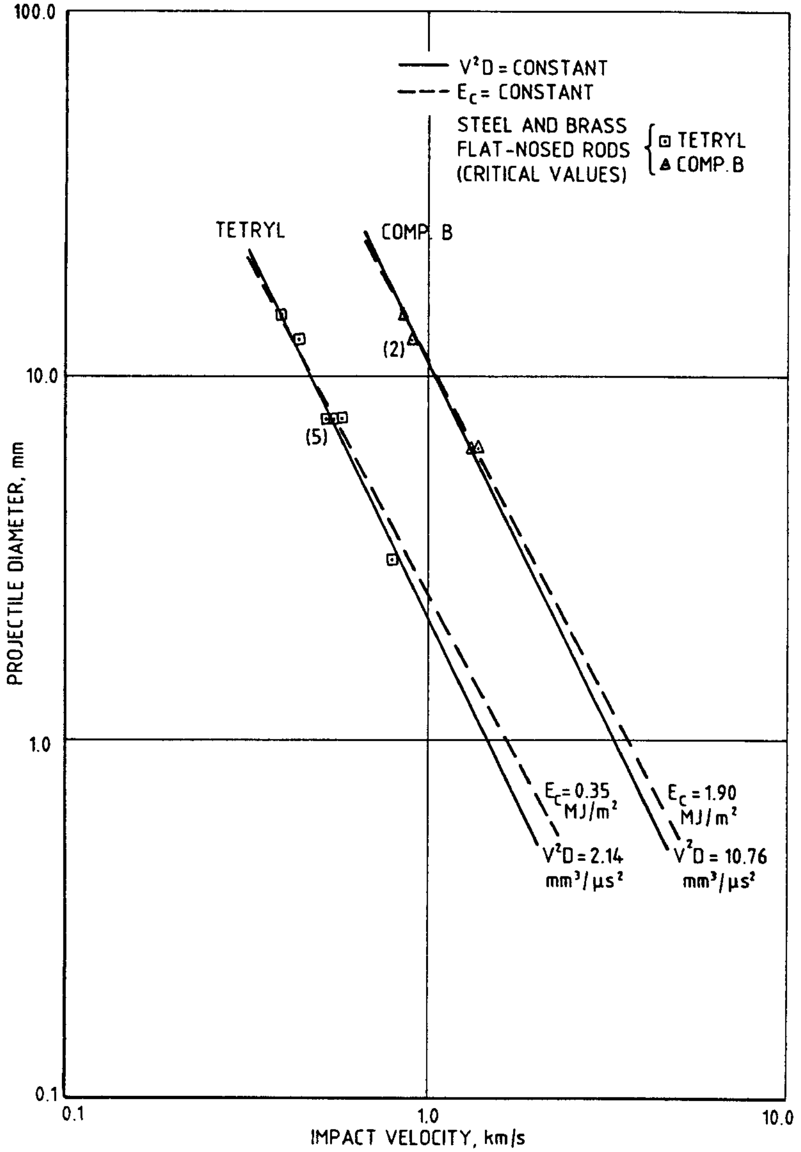

FIGURE 5

Comparison of Initiation Boundaries Obtained from v^2D and Ec Criteria for Two Explosives Impacted by Flat-Nosed Rods.

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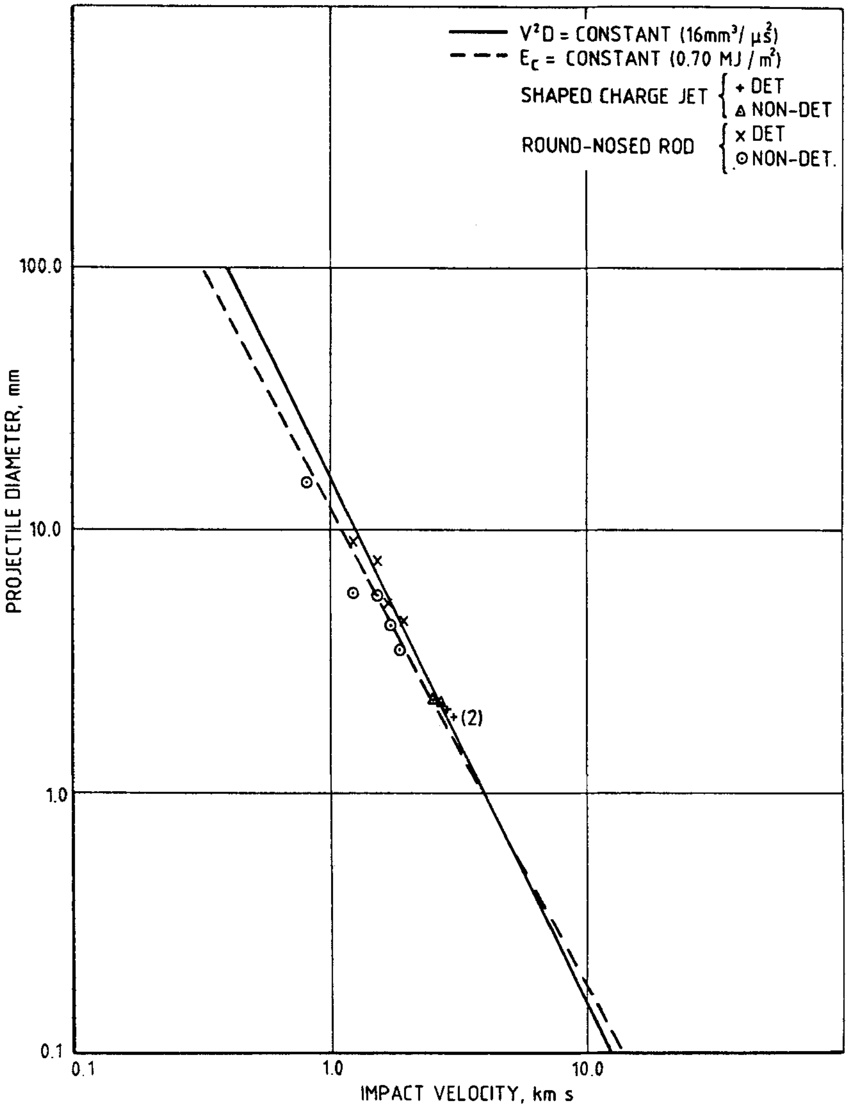

FIGURE 6

Comparison of Initiation Boundaries Obtained from v^2D and Critical Energy (Ec) Criteria for PBX9404.

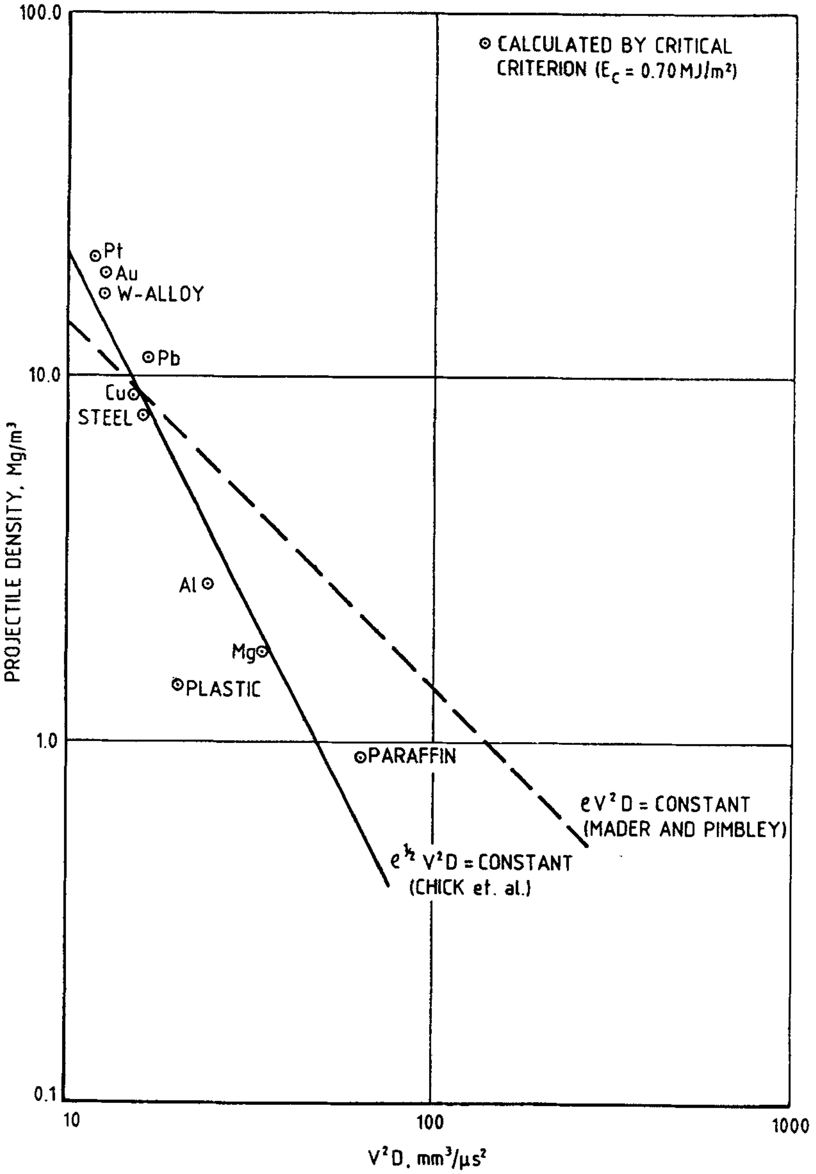

FIGURE 7

The Dependence of the v^2D Criterion Upon Projectile Material : Jet Impacts into PBX9404.

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