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CRITICAL ENERGY FOR SHOCK INITIATION

OF

FUZE TRAIN EXPLOSIVES

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A B S T R A C T

Results of shock initiation experiments conducted for tetryl and A-5 are presented, along with some data on the shock initiation of other explosives. The experiments were conducted using a gun system. An equation which has been useful in correlating these shock data is given. Some applications of the critical energy concept (represented by the above equation), to explosive train designs for NASA space systems are included. The concept's usefulness to DOD ordnance agencies now replacing tetryl in fuze trains with A-5 is also indicated.

INTRODUCTION

One of the more demanding requirements placed upon the designer of fuze trains is the demonstration of the reliability and the safety of the device he has designed. Historically, the design of fuzes using explosive and pyrotechnic trains was more an art than a science, and the successful designer required much experience. A statement from a recent publication[1] emphasizes this point: "The only positive method to determine whether a pyrotechnic device will function satisfactorily is to test fire it. The high reliability and confidence level customarily imposed would require very large numbers of devices to be fired in order to fulfill the

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requirements. For example, a 0.999 reliability at a 95% confidence level requires the test firing of 2996 devices without a failure. The cost of this demonstrated reliability generally proves to be prohibitive."

In the past, the "margins of safety" for the inadvertent firing of a fuze train and also for the performance reliability could only be crudely estimated. There has been a large body of data published on explosives which seemed to indicate that the shock initiation of an acceptor charge by an explosive donor was a function of only the peak shock pressure attained by the donor. Such data are still being generated. However, a number of workers in the field of high explosives have accepted the idea of a "critical energy fluence" or a "P^2t" requirement for shock initiation which appears to be more useful.[2,3] This idea has been tested for application to fuze explosive trains in a study[4] for NASA, and some information from this work will be presented in the discussion which follows.

This critical energy concept is based on a number of experimental observations showing that a strong correlation exists between the shock initiation of an explosive and a specific quantity of energy transmitted to the explosive by a shock wave. For example, pressed TNT with a density of 1.65 g cm^{-3} requires $\sim$34 cal cm^{-2} for initiation.[2] This quantity of energy could be obtained from a 45 kbar shock maintained for 0.5 μsec, a 20 kbar shock for 1.0 μsec, or a 12 kbar shock for 1.5 μsec.

The utility of this concept to the fuze train designer is that he can select explosives for his donor or acceptor charge designs with previously determined critical energy values to satisfy the safety requirements of his system. The energy output of the donors can be determined from their

pressure-time histories when fired in the appropriate design geometry. Since the acceptor charges can then be selected by their previously determined critical energy values, the "safety margins" for both performance and operational safety can be evaluated.

As DOD ordnance agencies are now replacing tetryl in fuze trains and in other applications with an RDX-based explosive designated as A-5, it would be very helpful to the ordnance designers involved in this replacement process if they were given an equation and critical initiation energy values for these two explosives that could be used to compare and predict the performance of these (and other) explosives in fuze trains.

RESULTS AND DISCUSSION

The critical energy concept evolved from the correlation of flyer plate energy with initiation or non-initiation of the acceptor explosive in a large number of experiments on pressed TNT and two plastic-bonded explosives, PBX-9404 and LX-04 (see Figure 1).[2] The equation by which the critical energy of a specific explosive can be calculated is derived from conservation of momentum principles.[2] This equation is

$$E_c = \frac{tP^2}{\rho U_s (41.84)} \qquad \text{Eq. 1}$$

where t is the shock width in μsec, P is the average shock pressure in kbar, ρ is the initial density of the test explosive in g cm^{-3}, U_s is the shock velocity in the test explosive at the pressure P in cm μsec^{-1}, and 41.84 is the constant that gives the critical energy E_c in cal cm^{-2}.

The values needed for the equation can be obtained with flying plate experiments in a gun. A rough estimate of the critical energy of a new

explosive can be made from data obtained in a gap test or a wedge test. The gun experiments are then designed to give flyer plate energies in the range of the estimate. The shock width is determined by the plate thickness, and the pressure in the test explosive is determined by the material and velocity of the flyer. The Hugoniot data for the U_s values can also be obtained from the gun experiments. The density, which is the only other independent variable, can be measured.

In the gun experiments discussed below, the brass flyer plate is very thin, compared with the thickness of the explosive sample; it is also considerably more dense. When these conditions exist, the shock pulse that acts on the sample unloads in a step-wise fashion; it does not possess precisely the assumed rectangular form. Although this pulse is somewhat less efficient in initiating the reaction in the explosive than a rectangularly-shaped pulse of the same energy, this effect is relatively small in the geometry of this experiment.[5] In Table 1 we show the total calculated kinetic energy of the flyers in each experiment, but consistent with the previous statement, we have assumed that the critical energy of initiation to be about 90 percent of the flyer plate energy. When a pressure transducer is used in future experiments which will show the actual pulse shape, a more precise value for the energy delivered to the explosive in each experiment can be obtained. In addition, a more precise value for the critical energy can then be determined.

We have used the gun method to determine the critical energy of tetryl and its new replacement for DoD fuze train designs, A-5 (RDX:Stearic Acid; 98.5:1.5). Table 1 contains a summary of data from gun experiments with tetryl and A-5. We had estimated that the critical energy for each of

these explosives should be about 10 cal cm^{-2}, and the gun experiments were designed accordingly. A brass flyer plate 0.0273 cm thick was used in each of the experiments summarized in Table 1.

Table 1. Data From Gun Initiation Experiments With Tetryl and A-5

Explosive	Flyer Plate Velocity (cm μsec^{-1}	Pressure (kbar)	Flyer Plate Energy (cal cm^{-2})	Initiation (yes/no)	Estimated Critical Energy (cal cm^{-2})
Tetryl	.063	29.2	10.9	Marginal	9.8
Tetryl	.067	29.8	12.5	Yes	11.2
Tetryl	.071	33.8	13.9	Yes	12.5
A-5	.054	23.5	8.1	No	>8.1
A-5	.072-	33.9	14.4	Marginal	13.0
A-5	.072+	34.1	14.5	Yes	13.0
A-5	.072+	34.4	14.6	Yes	13.1

As shown in Table 1, the critical energy for the initiation of tetryl is approximately 11 cal cm^{-2}, and the value for A-5 is approximately 13 cal cm^{-2}. Therefore, the initiating forces for A-5 in the new fuze train and other designs must be a little stronger or be held for a little longer duration to give the same margin of reliability. On the other hand, A-5 should provide about a 20% improvement in safety margin with relation to its shock sensitivity as compared to tetryl.

A schematic representation of the experimental design of the acceptor explosive target for the gun studies is given in Figure 2. This tiered disk is instrumented with velocity pins so as to provide the time of travel of the incident shock front across each of the three 0.635 cm tiers and the

final 0.318 cm tier. This time of travel is compared with the time that would have been required for the shock to transit the same distance at the nominal detonation velocity, and the difference (designated as the excess transit time) is obtained.

The patterns of these excess transit times (xstt) in the gun shots provide some understanding of the initiation process in tetryl at relatively low initiating pressures. In these experiments, the initial shock velocity, as determined by the Hugoniot relationships of the flyer plate and the explosive, is low compared to the steady-state detonation velocity. If there were no reaction in the acceptor explosive, the incident shock would gradually degrade in velocity and the xstt (as defined above) increase continuously with sample thickness. If, instead, the shock pressure is relatively high, chemical reaction would begin at or near the shock front, causing the shock to accelerate and the xstt to decrease. The xstt would become constant if full detonation velocity were achieved. Now consider Table 2, where total xstt's at various thicknesses of tetryl from the experiments in Table 1 are given. The 29.2 kbar experiment shows an increase in xstt between the 6.35 mm,12.70 mm, and 19.05 mm stations but a decrease between the 19.05 mm and the 22.225 mm stations. This implies that a "super detonation", possibly analagous to that reported for liquid explosives by Campbell, et al[6], occurs in the buildup to detonation of tetryl under these conditions. However, a simple calculation yields a value for this "super detonation" that is unbelievable (95 mm μsec^{-1}). It seems more reasonable to explain the data from this experiment in another way. For example, at 29.2 kbar, the energy of the initiating pulse

was very near to the critical energy. Thus, very small differences in the explosive density could cause a relatively large effect in the time of detonation buildup. It is possible that the center 20 mm of the sample detonated a little sooner than the rest, resulting in apparent "super detonation".

The higher pressure shots also exhibit decreases in xstt's that could be interpreted as "super detonation", but now the magnitudes are within the range of possibility for true "super detonation". This pattern has been seen in other tetryl initiation experiments of the same kind not reported here. Lindstrom[7] reported apparent "super detonation" in wedge experiments on tetryl that were due to the reflective covering he used on the wedge. In the absence of a covering, he could see no "super detonation". Thus, it is not clear at this time whether or not the "super detonation" observed in tetryl is real. Density gradient arguments could be used to say that it is not, since samples were pressed to size and possibly could have axial density gradients. However, Stirpe et al[8] have observed overshoot in the buildup to detonation in 1.72 gm cm^{-3} density PETN from initiating shocks in the 10 to 39 kbar range, so the possibility exists, at least, for the same phenomena to be occuring in tetryl. A more detailed analysis of the tetryl overshoot will be presented at a later date.

Table 2. Excess Transit Times in the Tetryl Experiments

Pressure Transmitted into Tetryl (kbar)	Flyer Plate Thickness (cm)	Total Excess Transit Time at Various Thicknesses 6.350 mm (μsec)	12.700 mm (μsec)	19.050 mm (μsec)	22.225 mm (μsec)
29.2	.0273	1.12	3.08	3.74	3.35
29.8	.0273	1.08	1.50	1.25	1.14
33.8	.0273	1.07	0.89	0.85	0.84

As previously mentioned, a study was made[4] under a NASA contract to test the application of the critical energy concept to fuze train design. The variables considered in this work for the donor were the explosive diameter and quantity, the closure material, and the gaseous and closure fragment energies. For the acceptor unit, the variables were the explosive sensitivity and particle size (as related to the critical energy), the closure material and thickness, the explosive confinement, and the air gap from the donor (see Fig. 3). A large number of donor-acceptor systems were examined in this study, and two of the general conclusions obtained are as follows:

1. Variability in detonation transfer was caused by differences in donor output; acceptor sensitivity may be considered essentially constant.
2. The principle of detonation transfer based on critical energy proved valid for miniature donors and various closure materials.

One other observation made by the investigator in the NASA study is that the pressure in kbar for initiation obtained in the Naval Ordnance Laboratory (NOL) Small Scale Gap Test (SSGT) roughly approximates the critical energy in cal cm^{-2} for a number of explosives. This is a fortuitous and possibly misleading observation, but it may be useful to the designer. Nominal critical energy values and the results from the NOL SSGT for some selected explosives are given in Table 3.

Table 3. Critical Energy Values and Results From NOL SSGT For Some Selected Explosives

Explosive	Density ($g\ cm^{-3}$)	Critical Energy ($cal\ cm^{-2}$)	NOL SSGT (kbar)
Lead Azide	4.93	3×10^{-2} [d]	
PETN	1.00	3 [d]	
Tetryl		∿11	
RDX			11
PBX-9404	1.840	12 [a]	13
A-5		∿13	
HNS-II		--	15
LX-04	1.860	26 [a]	25
HNS-I	1.555	<34 [c]	25
TNT	1.620	32 [b]	29
TNT	1.645	34 [a]	--
DATB	1.676	39 [c]	39-45
TATB	1.762	72-88 [c]	74

[a] Reference 2

[b] Reference 4

[c] Reference 9

[d] The value given is based on a minimal amount of data, and it should be considered as tentative.

Note:

HNS - Hexanitrostilbene
DATB - Diaminotrinitrobenzene
TATB - Triaminotrinitrobenzene

CONCLUSIONS

The critical energy evaluation idea appears to provide a useful concept for the designer of fuze explosive trains. This concept has been tested with satisfactory results for a number of fuze or detonation-transfer systems. The critical energy for the initiation of tetryl is $\sim$11 cal cm^{-2} and for A-5 is $\sim$13 cal cm^{2}. Thus, on the basis of the critical energy concept, the A-5 should be an acceptable alternate fuze train explosive.

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FIGURES

1. PBX 9404, LX-04, TNT Critical Energy Graph
2. Acceptor Explosive Target Schematic for Gun Studies
3. Variables Studied by MDAC for NASA

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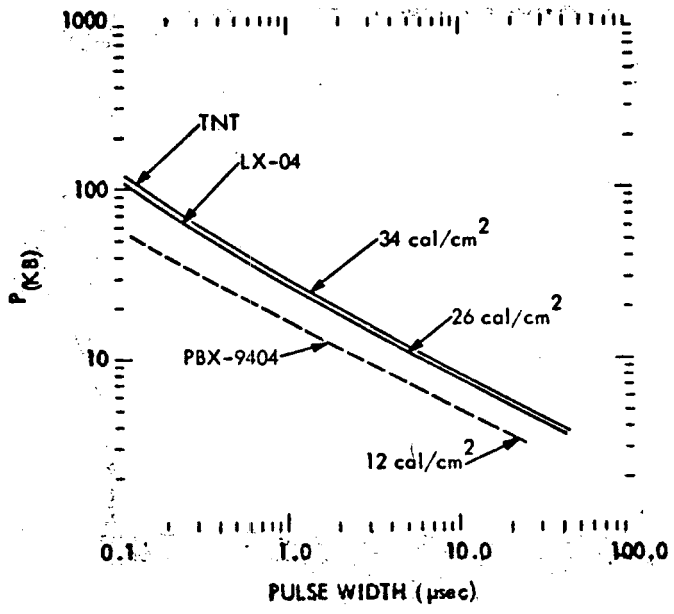

Fig. 1. Critical Energy Plots for PBX-9404, LX-04 and TNT.

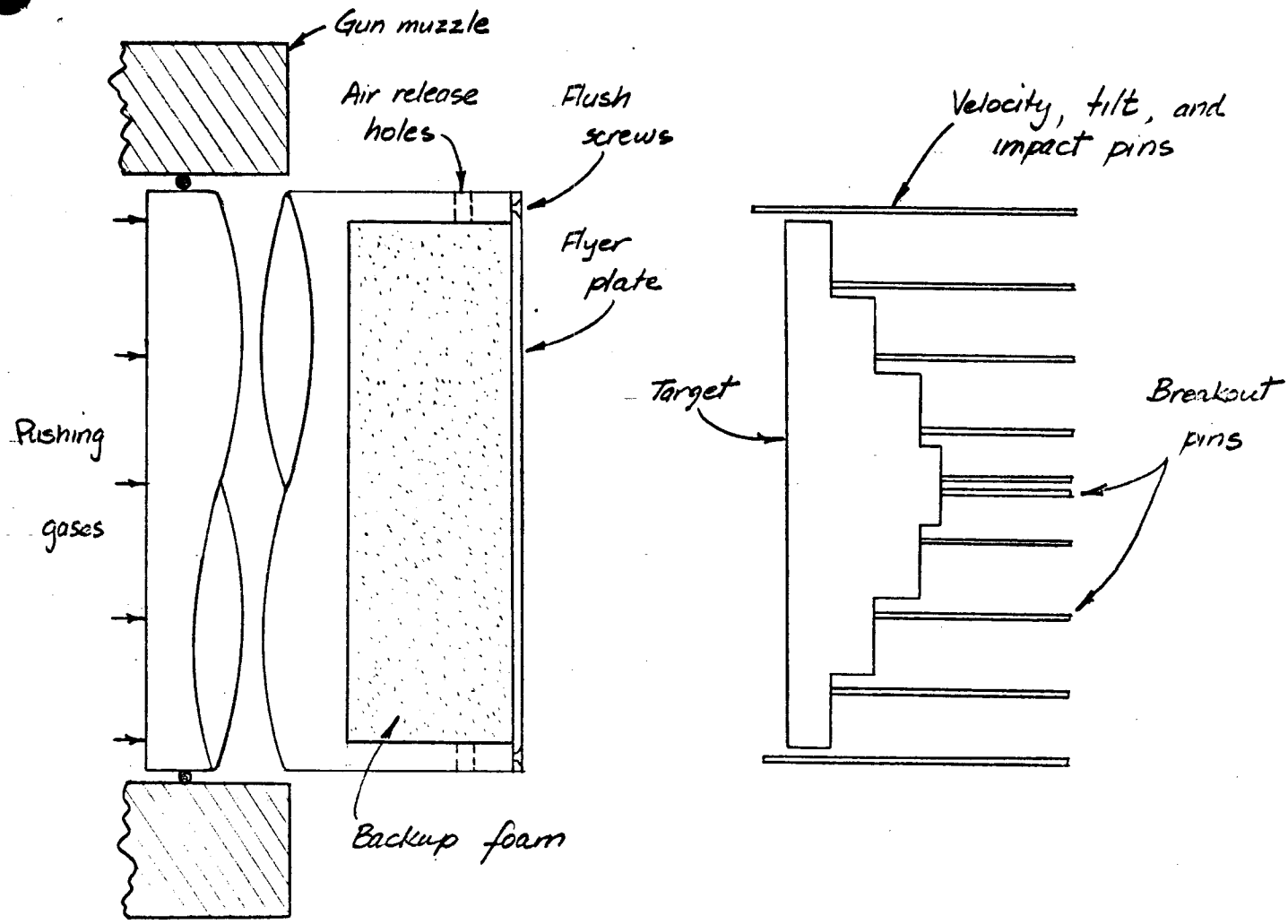

Fig. 2. Acceptor Explosive Target Schematic for Gun Studies.

VARIABLES STUDIED

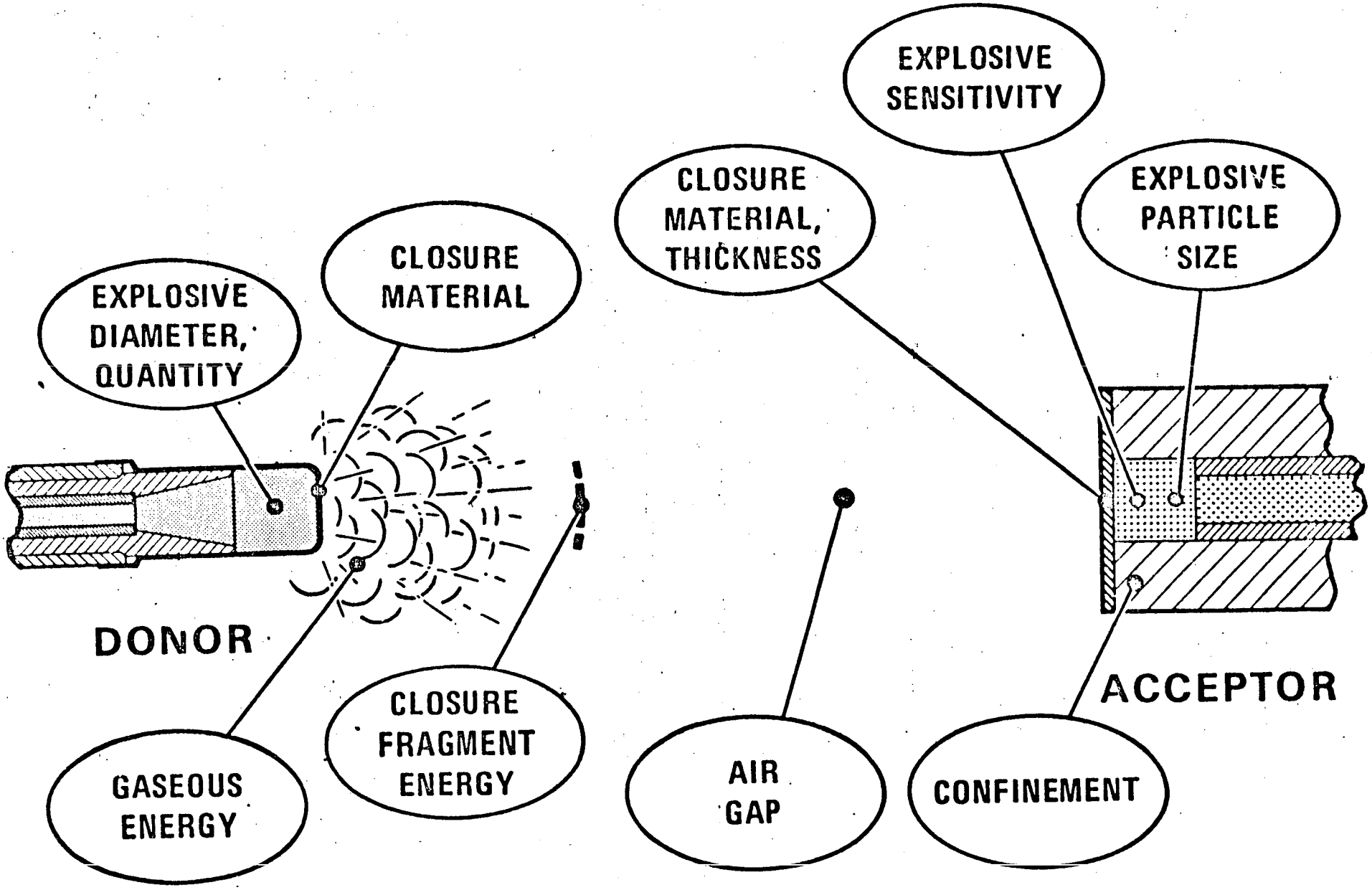

Fig. 3. Variables Studied by MDAC for NASA.

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