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PROJECTILE IMPACT IGNITION CHARACTERISTICS OF PROPELLANTS

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FINAL REPORT

W. H. ANDERSEN

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U. S. ARMY RESEARCH OFFICE

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The results of an investigation of the projectile impact ignition characteristics of propellants are described. Impact tests were conducted on a single, double and triple base propellant, and a deflagratable composite explosive. The tests were conducted by firing different diameter, flat-nosed brass projectiles into small cylinders of the propellant at various velocities and observing the impact reaction by various sensors.

The general behavior of the four materials to impact was the same. The

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The critical impact velocity necessary to induce a sustained reaction in a propellant decreased with increasing projectile diameter. The nature of the reaction depended on the diameter. At small diameters, the induced reaction was always detonation; whereas at the largest diameter the reaction was deflagration, whose intensity increased with increasing impact velocity. A higher critical velocity then again resulted in detonation. A model based on the view that the ignition and reaction in an impacted (shocked) propellant are independent processes was postulated to explain the results. The critical velocity for inducing ignition was consistent with the critical energy concept.

The impact characteristics are discussed in terms of the fundamental processes that may control the overall ignition event, and semiquantitative models are developed that describe several of the processes.

Accession For

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1. INTRODUCTION

An understanding of the response of propellants and explosives to projectile impact is of great practical importance, since the response determines the hazard consequences of the impact. However, impact ignition is a complex phenomenon, whose present understanding is limited.

For the past three years Shock Hydrodynamics has been conducting studies toward obtaining a more basic and improved understanding of impact ignition, and the factors that control the impact sensitivity of propellants. Significant findings of a fundamental nature have been obtained. These findings have resulted in the development of a qualitative model that more adequately describes the processes that control the ignition event, and the overall response of the material to impact. In addition, certain aspects of impact ignition were examined in more quantitative detail, and impact sensitivity data were obtained on four real propellants.

This report summarizes the results of the studies. This summary is relatively brief however, since most to the work has been published (or is in press). Details of the work are available in the original papers.

2. NATURE OF THE PROBLEM

The conventional method of determining the projectile impact sensitivity of an explosive consists in measuring the impact velocity required for 50% probability of initiating a detonation reaction in the explosive, i.e., the V_{50} of the reaction. This velocity is often called the critical impact velocity. The method thus merely demonstrates the existence or absence (Go or No Go) of a propagating detonation reaction being induced in the explosive by the impact. Experimental data on the projectile impact sensitivity of explosives under various conditions are available in the literature (for a summary on bare explosives, see ref. 1). Figure 1 (taken from ref. 1) shows the critical impact velocity of several bare explosives as a function of projectile diameter. The critical velocity decreases with an increase in projectile diameter and then appears to level out. This means that an explosive is more sensitive to initiation at larger projectile diameters. However, the data does not provide information on ignition under conditions that the reaction does not build up into detonation.

On the other hand, in the case of propellant-type materials (as was of interest to this program) the impact response can be more complex. Depending on various factors, the material may exhibit a range of reaction behavior that may or may not include propagating detonation. These factors include the size (dimensions), composition, and physical form of the material sample, and the geometry, composition and velocity of the projectile. The measurement of the impact sensitivity of this type of material is more difficult than for conventional explosives, and relatively little is known regarding the proper evaluation and interpretation of the measurements. A fundamental understanding of the impact ignition event (including knowledge of the controlling molecular processes and material properties) is thus necessary in order to assess the impact sensitivity of propellants.

3. EXPERIMENTAL IMPACT STUDIES

The approach of the experimental studies was to determine the impact

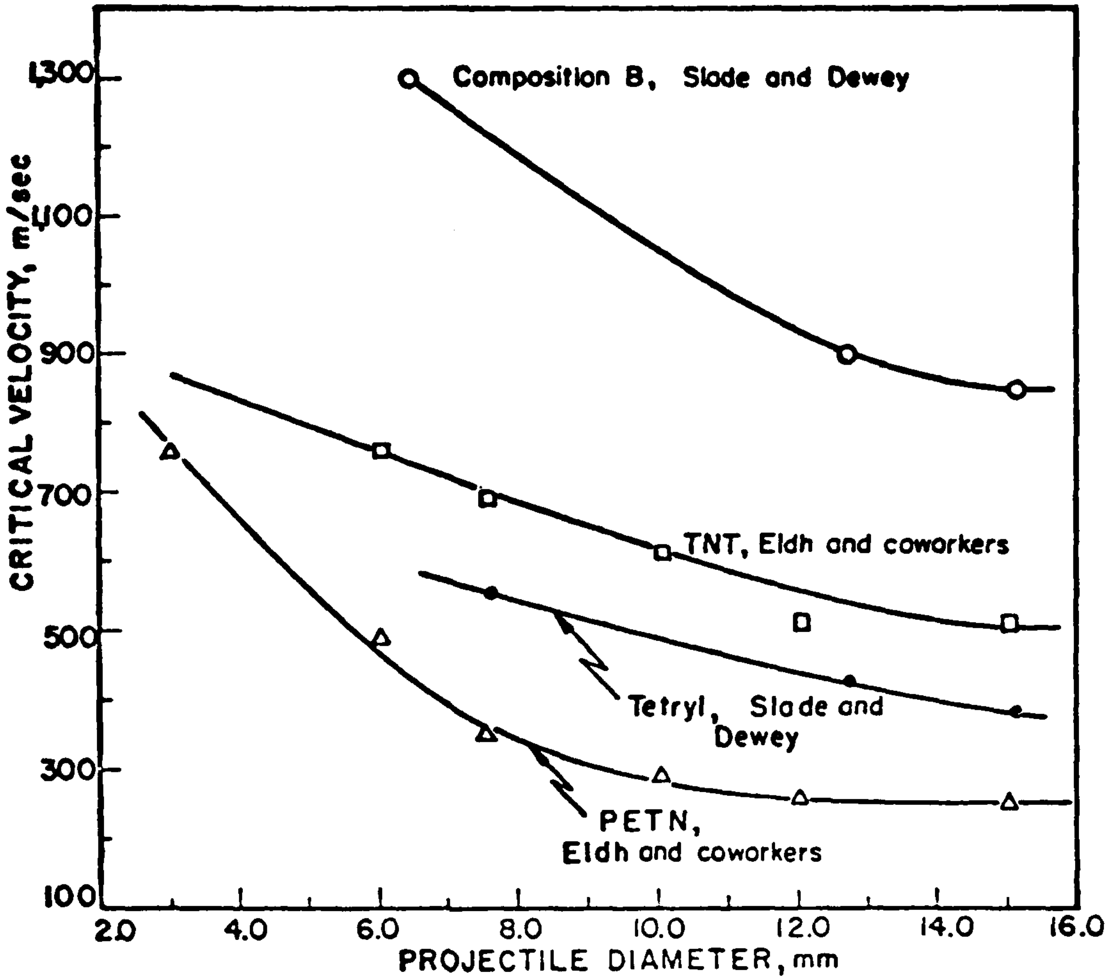

Figure 1. Critical Impact Velocity Necessary to Initiate Bare Explosives to Detonation (from ref.1).

ignition characteristics of various classes of propellant-type materials as a function of projectile diameter. The projectile diameter is of special importance since (for normal projectiles) it controls the time duration that a portion of the impacted material is subjected to the full shock compression and heating before rarefaction release. The tests consisted of impacting small cylinders (1.5 in. diam. x 0.75 in. thick) of the bulk propellant with flat-ended brass projectiles of different diameters (.22, .257 and .50 caliber) fired from guns at various velocities, and observing the impact reaction by an open shutter camera, photocell, post inspection and weighing of the propellant fragments.

The test apparatus and sensors were patterned after those described in ref. 2, with some modifications that are described in ref. 3 and 4 (which summarize the impact ignition studies). The light emitted by the impact reaction was detected by the open shutter camera and photocell. Minor reaction showed up on the camera film in the form of flash and luminous streamers, whose intensity and concentration increased with the degree of reaction. For extensive burning or detonation, however, the film was overexposed (white). A novel feature of the apparatus was the use of a photocell, which was of especial value in distinguishing a transient ignition event from a self-sustained burning reaction. In a non-sustained event the signal from the initial impact reaction quickly decayed; whereas in sustained burning (or detonation) it remained relatively constant or increased. The overall extent of reaction was also determined by the weight loss of the material caused by the impact. Another modification of the apparatus was the use of a non-contact velocimeter developed on the program (ref. 5) to measure the projectile velocity. The conventional metal foil shorting technique used previously proved undesirable for the larger caliber projectiles, since their flat nosed shape caused foil debris to be pushed ahead of the projectile. Figure 2 shows the instrumented target box used in the studies.

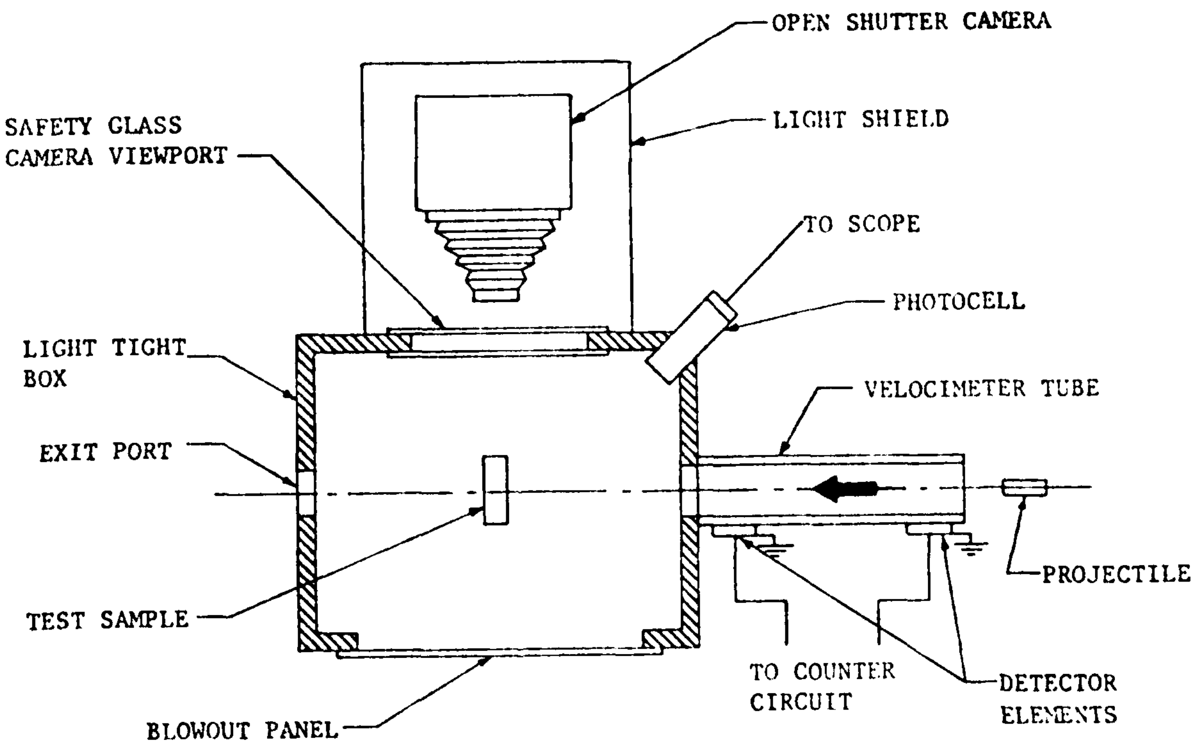

Figure 2. Instrumented Target Box (top view).

3.1 EXPERIMENTAL RESULTS

In order to encompass a wide degree of propellant properties, the impact tests were made on a single base (M1), double base (SHF-1), triple base (M30), and a deflagratable composite explosive (LOVA-X1A). This latter propellant was made up of 75 wt% small grain HMX explosive embedded in a polyurethane binder. The composition of these propellants was seclected on the basis of discussion with Dr. J. J. Rocchio of the Ballistic Research Laboratory in order that they be of practical value (to the Army) as well as of fundamental importance. The propellant samples used in the studies were provided by Dr. Rocchio.

Figure 3 (from ref. 3) summarizes the test data obtained for the composite explosive propellant, and Fig. 4 (from ref. 4) for the single, double and triple base propellants. The general behavior of the four materials to projectile impact was the same. The critical (minimum) impact velocity required to produce a sustained reaction in a sample decreased with increasing projectile diameter. This means that a propellant is more sensitive when struck by a larger diameter projectile. Below this critical velocity only breakup (no sustained reaction) of the sample occurred. The nature of the induced reaction depended strongly on projectile diameter. At the smaller diameters the impact induced detonation in the sample at the critical and higher impact velocities. A very high impact velocity was required (for the single and double base propellants no detonation was obtained in the velocity range studied). However, at the large (0.5 in.) diameter the critical velocity induced a sustained burning in all the propellants, and the initial intensity of the burning generally increased with increasing impact velocity. At a sufficiently high velocity and above (for the composite and double base formulations), the impact then again induced a detonation in the propellant.

3.2 IMPACT IGNITION MODEL

The general behavior of the impacted propellants just described does not seem to have been observed before, and is considered to be of some significance. Thus the observation that the impact at large projectile diameter induces burning at a lower velocity threshold than for detonation implies that the ignition and reaction buildup to detonation are independent processes. This hypothesis is consistent with certain recent studies on the shock wave initiation of explosives (ref. 6, 7). The following model was postulated (ref. 3) to explain the experimental findings.

The passage of the impact-induced shock wave in the propellant was assumed to initiate an exothermic ignition reaction at hot spots formed by the interaction of the shock wave with pores or other defects initially present in the unshocked material. The ignition incurs a small time delay that decreases with increased pressure. This causes the critical (minimum) impact velocity for ignition to decrease with increasing projectile diameter (since the shock pressure is maintained for a longer time period with a larger diameter projectile, the initiation stimuli can be less intense).

After ignition, reaction and pressure buildup occur. It was postulated that the concentration of effective (ignited) hot spot sites controls the buildup rate, and that the concentration of effective sites increases significantly with increased pressure. The general impact behavior of a propellant

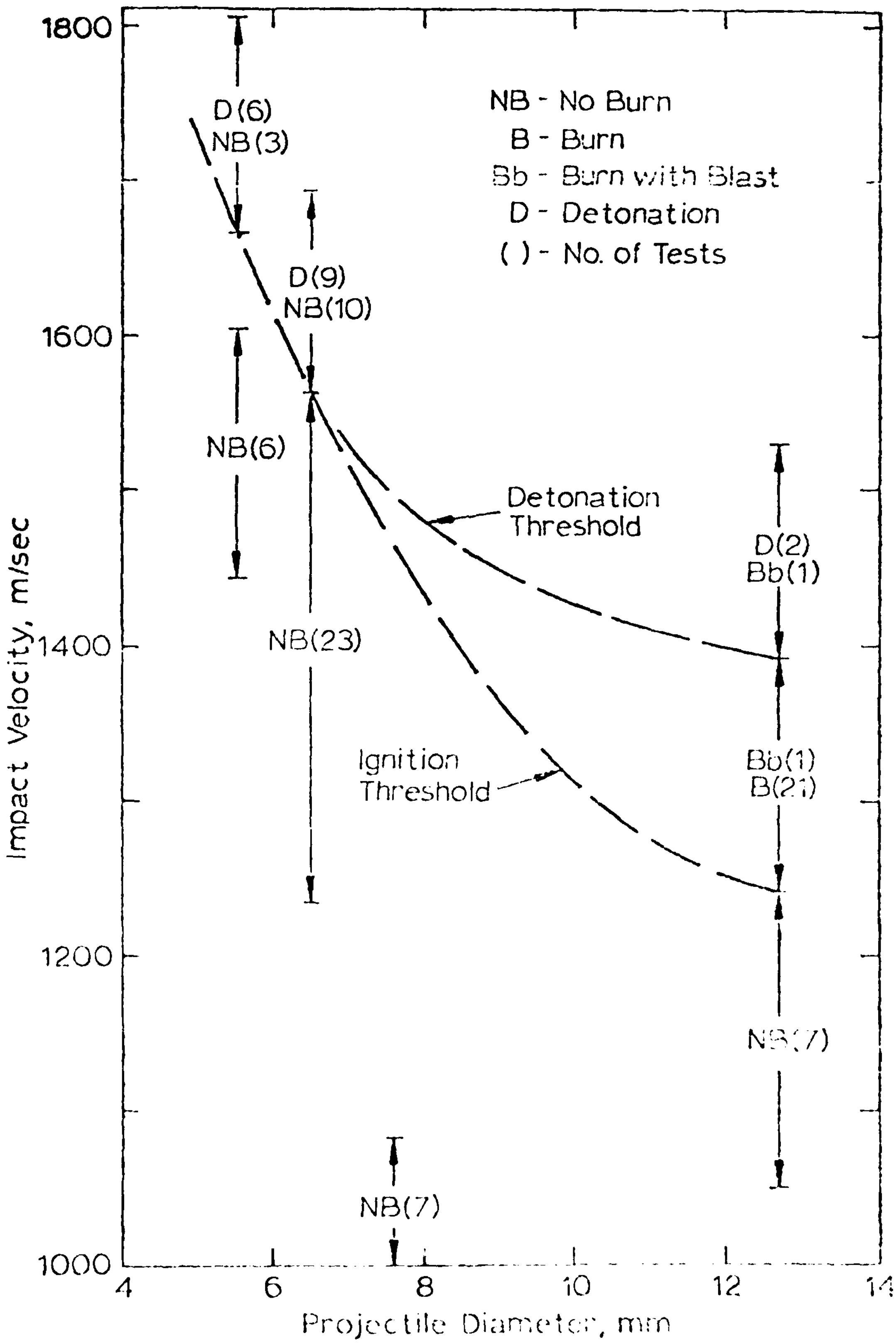

Figure 3. Impact Ignition Behavior of the Composite Explosive Propellant (LOVA).

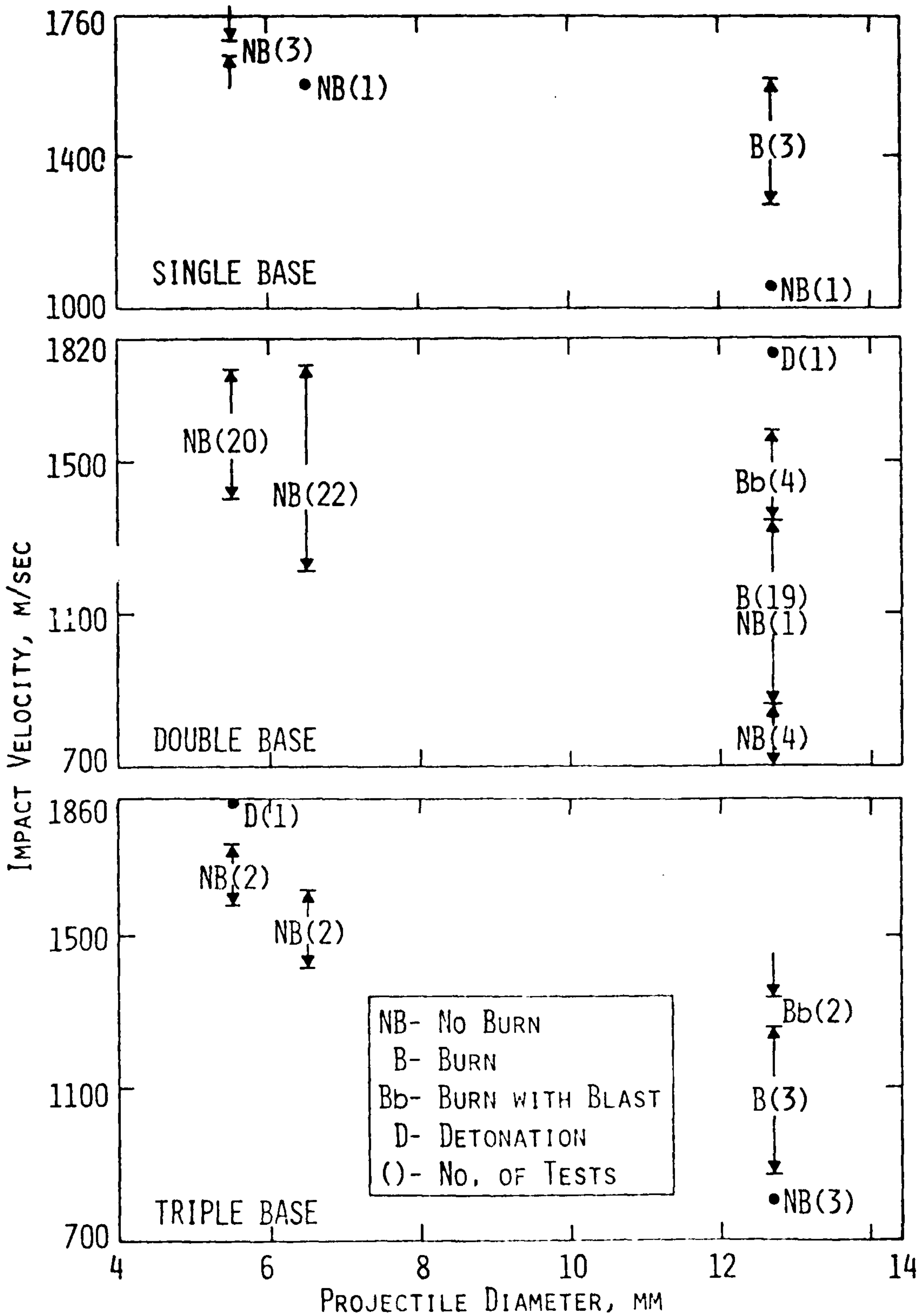

Figure 4. Impact Ignition Behavior of the Single, Double and Triple Base Propellants.

with specified composition (decomposition kinetics) and void concentration then depends in part on the pressure level required to produce the ignition reaction. A large concentration of ignition sites leads to rapid pressure buildup and detonation of the material. However, the reaction rate for a low concentration of sites is relatively small, which allows time for rarefaction loss and quenching to prevent the buildup. In this case only some manner of deflagration occurs. The expansion loss can arise in a number of ways including end rarefaction after pressure release to stagnation conditions in the projectile, lateral rarefaction in small size propellants, and end and side rarefaction from the shock front reflecting from free surfaces in the fracturing material (sample length can be of special importance here).

For the propellants studied on this program the porosity content was small and the thermal decomposition kinetics relatively slow. Consequently at small projectile diameters a very large impact velocity was required to ignite the propellants. The ignition resulted in a detonation since the concentration of effective ignition sites was large because of the high pressure. However, at the large projectile diameter the critical velocity was significantly smaller. The impact ignition therefore resulted in a deflagration since the lower reaction rate caused by the small concentration of ignition sites allowed rarefaction loss to prevent reaction buildup. A higher impact velocity (at the same diameter) increased the concentration of sites, which increased the intensity of the deflagration. Finally, at a sufficiently large impact velocity detonation was produced here also as the result of a sufficiently high concentration of ignition sites.

3.2.1 Critical Energy for Initiation

It has been shown by Walker and Wasley (ref. 8) and others that the shock initiation to detonation of an explosive charge appears to often require that a certain critical energy per unit area, E_c, be delivered to the charge, where

$$E_c = Put = P^2 t/\rho_o U = K \qquad (1)$$

P, u and U are the pressure, particle velocity and propagation velocity of the shock, t is the duration of the shock pressure, ρ_o is charge density and K is an experimental constant for a particular charge. For a normal projectile (length greater than about 0.5 diameter), t is given approximately by (ref. 9).

$$t = d/2C_p \qquad (2)$$

where d is projectile diameter, C_p is the lateral rarefaction wave velocity in the projectile

$$C_p^2 = (K' + G/3)/\rho_p \qquad (3)$$

and K', G and ρ_p are bulk modulus, shear modulus and density of the projectile. The evaluation of Eq. (1) requires the shock Hugoniot of the propellant. This was not available, but was estimated (ref. 3) for the composite propellant (Fig. 5) using a density interpolation method, and essentially the same results were obtained also by another independent method. The properties of the shock wave induced in the propellant by the brass projectiles were than estimated using the standard reflection method (Fig. 5 and Table 1).

It was found that the critical energy criterion is obeyed for the ignition but not the detonation threshold curve in Fig. 3. This is of some significance, and provides quantitative support for the postulated model. Thus Eq. (2), which relates the impact pressure duration to projectile diameter, was assumed in the model to define the ignition time and not the detonation time of the impact reaction. That this is indeed true is shown directly by the fact that an ignition threshold curve exists (Fig. 3), which under suitable conditions (large projectile diameters), is a threshold for deflagration rather than detonation. That it is also a threshold for detonation under suitable conditions (small projectile diameter) indicates that conditions were then favorable for the ignition reaction to buildup into detonation. The thermal decomposition kinetics, grain size, and initial porosity content of a material are other factors that affect the rate of reaction buildup (as well as ignition).

3.2.2 Effect of Projectile Diameter

Experimental studies by Slade and Dewey (ref. 9) and others have shown that the critical impact velocity, V_i, for the detonation of secondary solid explosives is usually related to the projectile diameter by

$$V_i = A/d^{1/2} + B \tag{4}$$

where A and B are constants. This empirical equation gives a reasonable fit to the detonation threshold data in Fig. 3, and also to the ignition threshold data (the threshold curves shown in Fig. 3 are not fits of this equation). However, it was shown on the program (ref. 10) that Eq. (4) can be derived from Eq. (1), and that in this case a unique relation exists between A and B; i.e., they are not arbitrary. Evaluating these parameters shows the unique relationship to be consistent with the ignition threshold curve but not with the detonation curve, as might be expected since the value of K enters in the calculations. These results again support the view that the ignition and reaction buildup are separate processes, and that the critical energy criterion relates to the ignition threshold when it is evaluated using Eq. (2). For many materials (and under many conditions) this also corresponds to the detonation threshold. When it does not, however, Eq. (4) can still be used to empirically fit the results, and it is likely that the parameters A and B can be derived for this case also if the effect of the reaction buildup time is included in Eq. (2).

3.3 VULNERABILITY CONSIDERATIONS

The analysis given in section 3.2.2 gives quantitative information regarding the impact sensitivity of the propellants. For example, Fig. 3

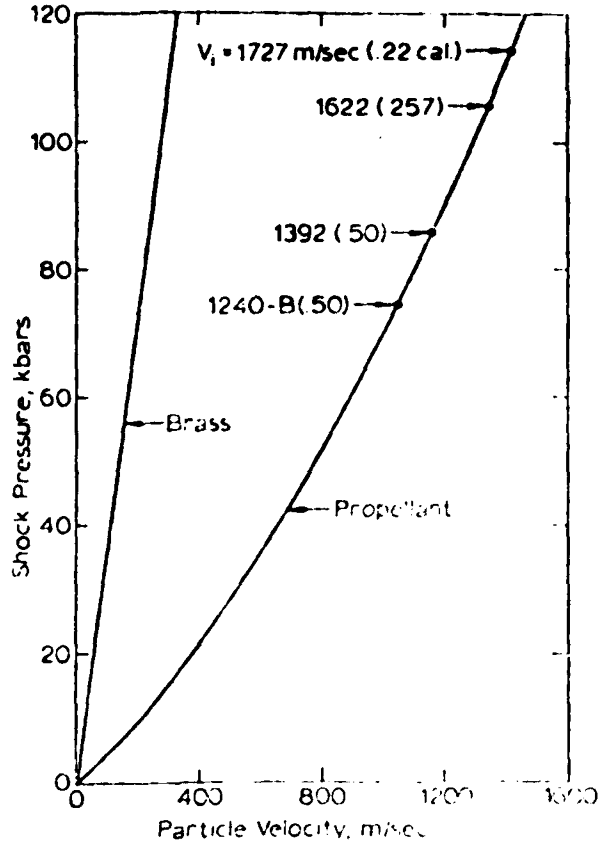

Figure 5. Shock Hugoniots, and Impact Properties of the Composite Propellant.

TABLE 1. Critical Initiation Energies of the Propellant.

Projectile Diameter (cm)	V_i (m/sec)	P (kbar)	Put=K E_c (cal/cm^2)	$P^2t=K_1$ E_c (cal/cm^2)
0.556	1665*	110	341	355
	(1727)**	114.8	370	387
0.65	1563	102.5	352	360
	(1622)	106	374	385
1.27	1392	86	511	496
	1240B***	74.8	398	375

* Lowest (Threshold) Impact Velocity for Detonation.

** Averaged Impact Velocities.

*** Threshold Impact Velocity for Burning.

shows the critical impact velocity necessary to ignite and detonate the LOVA-X1A propellant. The curves may be compared with the critical impact velocity of other materials, such as the explosives given in Fig. 1. The critical impact velocity (at a specified projectile diameter) is much larger than for conventional pressed explosives, which mean that the composite explosive is relatively insensitive.

The materials can also be compared on the basis of pressure. Figure 5 and Table 1 show the necessary shock pressures at the various projectile diameters for the composite propellant. The initiating shock pressure decreases with an increase in projectile diameter because the pressure duration increases. The pressure is larger than for most conventional solid explosives because the propellant is relatively insensitive. The sensitivity can also be compared with other explosives on the basis of critical energy, and the value of the composite explosive propellant ($\sim$ 375 cal/cm^2) is significantly larger than values given by Walker and Wasley (ref. 11) for conventional explosives, e. g., pressed TNT = 34, Comp. B = 36 and cast TNT = 100 cal/cm^2.

Most real munitions are cased, and the propellant is used in the form of relatively small grains. A general comparison of the projectile impact behavior of the preceding bare propellants with the ignition characteristics of their cased grains has certain implications regarding the mechanism of impact ignition of cased vs bare propellant; and the general relative vulnerability of the cased composite explosive propellant vs conventional cased formulations. Some of these implications were discussed at a symposium on the subject (ref. 12), but will not be considered further here. The experimental impact data obtained on this program has also been useful for correlation with experimental detonation, card gap sensitivity and stacked grain sensitivity data obtained on another program (ref. 13).

4. ANALYSIS OF IGNITION MECHANISM

Analytical studies were conducted on various processes that may be involved in the ignition and reaction buildup of an impacted propellant in an effort to describe the ignition event on a more quantitative basis. Some of these studies will now be summarized.

4.1 GENERAL CONSIDERATIONS

The impact ignition of solid explosive materials results from the heating of the material at certain sites (hot spots) that are created in the material by the impact shock. The passage of the shock wave through the material produces the hot spots at various defects (such as pores, cracks or other density discontinuities) that are initially present in the material. According to the preceding impact model, the concentration of the effective (initiating) hot spots increases with an increase of impact pressure. At sufficiently high pressure the heterogeneity of the ignition event may thus become essentially homogeneous in nature.

4.1.1 Solid vs Gaseous Hot Spots

Little is known regarding the nature of the hot spots that control the ignition event. Hot spots can be formed in the solid material by various means including shock compression and interaction (ref. 14, 15), and friction (ref. 16, 17). However, if the material at various sites is heated essentially instantaneously to some particular hot spot temperature and then undergoes adiabatic reaction, it can be shown (ref. 3) that the induction time for reaction will not explain the strong dependence of projectile diameter on critical impact velocity shown in Fig. 1, 3, 4. Thus if solid hot spots cause the ignition, other processes (besides adiabatic reaction) must also be involved. It can also be shown that this general mechanism is greatly in variance with the critical energy relation (Eq. 1).

Hot spots can also be formed by the adiabatic (or shock) compression of gas (or air) pockets that may exist (as pores) within the material. This mechanism was early postulated (ref. 16) to be involved in shock ignition. However, most later studies do not seem to support the concept of shock wave ignition by gaseous hot spots (ref. 18).

4.1.2 Meaning of Critical Shock Initiation Energy

Although Eq. (1) has been found to describe the shock initiation of several explosives to detonation under a wide variety of conditions, the equation has also been found to be inapplicable in many instances (ref. 6, 7, 19). Walker and Wasley derived Eq. (1) on the basis of the energy transferred to an explosive by an impacting plate (ref. 8). They ascribed a special energy fluence of the critical impact that results in initiation, i. e., they believe that a critical energy (given by Eq. 1) must be delivered to the explosive to cause its initiation.

However, it was shown on this program (ref. 20) that Eq. (1) is merely the Hugoniot energy of the explosive delivered for the time duration of the impact. Since the energy corresponds to that of an inert shock wave in the material, it was postulated that the time duration contained in Eq. (1) is actually the self-sustained ignition time of the material under the prescribed conditions. Thus the critical energy merely represents the Hugoniot energy delivered during the shock ignition of the material, and has no special relevance to the initiation process other than that a particular pressure is required to cause the self-sustained ignition of the material in a particular time. If conditions are suitable, the ignition will build up into a detonation, and the initiation to detonation of the material will then also obey the critical energy relation.

If the preceding view is valid, then the ignition can be described in terms of an ignition time that contains the effects of the various processes involved. Under conditions that the ignition time reflects the validity of Eq. (1), the ignition (and possibly also the detonation) will obey an apparent critical energy fluence. However, in principle self-sustained ignition can also occur under other conditions, depending on the processes involved and the form of the equations that describe the processes.

The preceding view is supported by the data in Fig. 3, which show that the critical energy relation is essentially obeyed for the ignition of the material, but not for its detonation under the experimental conditions. However, if the length of the relatively short propellant sample (0.75 in.) used in the studies had been longer, allowing more time for the buildup of the reaction after ignition, detonation would probably have resulted from the critical impact ignition at the larger projectile diameters. The critical energy relation thus pertains fundamentally to the ignition rather than the detonation process.

4.2 IGNITION BY A HOT, STAGNANT GAS POCKET

In order to further elucidate the role of gaseous hot spots, a detailed analysis was made of the ignition of an explosive by a hot stagnant gas pocket (ref. 21), such as may be produced in a porous material by impact or shock. The effect of the various factors that control the surface heating and ignition event over a wide range of conditions were discussed. Figure 6 shows the computed ignition time of several explosives as a function of heat flux. The corresponding ignition energies were also calculated, and it was shown that the computed energies at 3 msec ignition time are in general agreemen with experimental measurements made at low gas pressures by Bryan and Noonan (ref. 22). At low pressures the heat flux and ignition characteristics are controlled by the properties of the hot gas (for fixed material kinetics).

On the other hand, it was found that under high (shock) pressure conditions, the gas pocket size and material thermal conductivity also affect the ignition characteristics, and the effect of the hot spot size is dominant. Figure 7 shows the computed effect of hot spot radius on the heat flux.

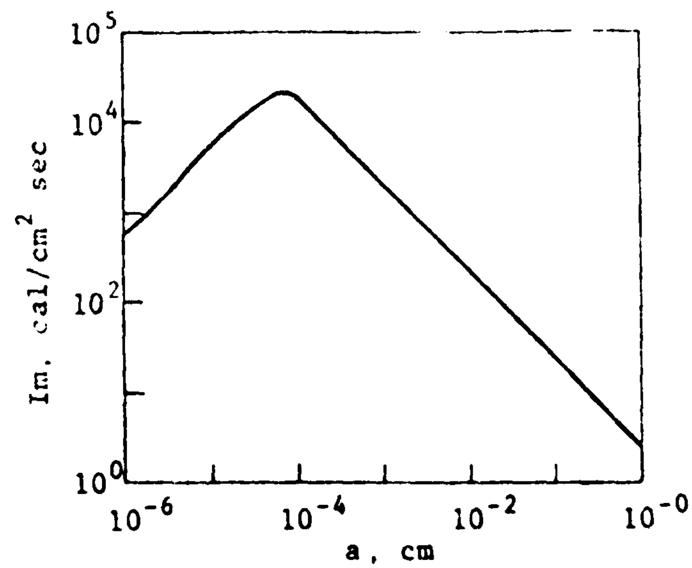

Figure 7. Effect of the Gas Pocket Size on the Heat Flux (Uniform Cooling Model).

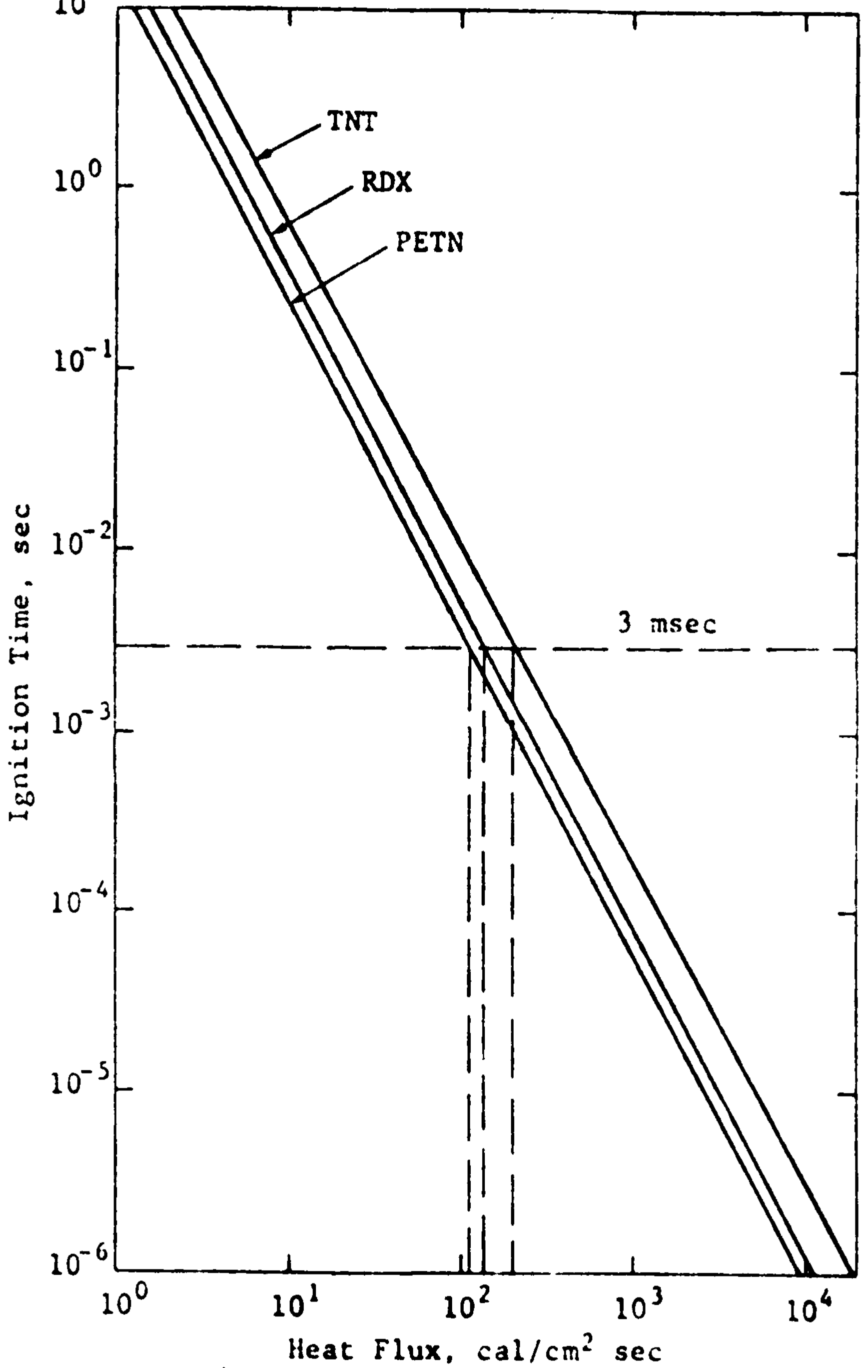

Figure 6. Computed Surface Ignition Time vs Heat Flux for Several Explosives.

It is known experimentally that relatively large hot spots (0.1-1 mm) will sensitize the shock initiation of an explosive, and the ignition occurs in the order of a microsec. However, the calculations (Fig. 7) indicate that relatively large gas pockets cannot provide the high heat flux (10^4 cal/cm^2 sec) that is necessary to ignite the material in microsec time periods (Fig. 6). The calculations thus provide a detailed semiquantitative explanation of the experimental observation that gaseous heating at adiabatically-compressed voids is not the cause of initiation of a shocked explosive. The calculations do support the view, however, that ignition by gas pocket heating is a viable mechanism that helps control the sensitivity of explosive materials to accidental ignition. In this case the impact pressure duration can be relatively long, which reduces the heat flux necessary to cause ignition.

4.3 IGNITION BY FRICTIONAL HEATING

An analysis was also made of the frictional heating ignition of explosives (ref. 23). Frictional heating is a complex phenomenon, and the developed treatment was the first attempt ever made to discuss the subject in a completely apriori manner. An expression was developed for the friction coefficient of a material in terms of the factors and parameters that control the friction shear. This expression when combined with the frictional heating equation describes the hot spot temperature produced in the friction event. The form of the resulting equations depends on the conditions. For illustration purposes, the temperature rise (neglecting melting) of the hot spots located on the friction surface under certain conditions is given by

$$\Delta T = \frac{0.418(f\beta_e P)^{0.5} P_{xy}\ vd}{(K_1+K_2)} \qquad (5)$$

where v is friction velocity, d is the diameter of the explosive particles, P_{xy} is the shear strength of the material, P is loading (shock) pressure, β_e is the effective compressibility of the material, K is the thermal conductivity of the material and f is a constant. Thus the hot spot temperature increases with an increase in the particle size and shear strength of the material, with an increase in loading pressure and friction velocity, and with a decrease in material thermal conductivity. These predictions are all in qualitative agreement with experiment. The predicted effect of particle size is also consistent with several recent studies (ref. 6, 7) which have shown that the shock ignition sensitivity of a material increases with an increase in particle size. However, it is not presently known whether the observed effect is actually due to frictional heating, or rather is the result of other heating mechanisms such as shock compression.

The developed frictional heating equations were discussed in terms of their implications regarding the factors that control the sensitivity of an explosive or propellant to frictional heating under various conditions, and the results of experimental studies given in the literature. It was shown that frictional heating followed by adiabatic reaction will not explain the strong experimental effect of projectile diameter on critical impact velocity (Fig. 1, 3, 4); or the critical energy relation (Eq. 1). Thus if frictional heating is involved in the impact (or shock) initiation of an explosive, other processes must also help control the ignition event. As in the case of ignition by hot gas pocket heating, frictional ignition is, however, a viable mechanism in helping to control the sensitivity of explosive material to accidental ignition.

4.4 EFFECT OF PORE CLOSURE TIME

Recent studies have shown that the closure time of pores in a shocked material may (depending on conditions) depend on the pressure level (ref. 24, 25). The rate of closure was found to be viscosity controlled. Wackerle et al (ref. 24), following earlier work by Taylor, showed that the analytical form of the rate of energy buildup at a void was related to the general form of Eq. (1). They stated that if it is assumed that initiation is effected by the void attaining some critical energy, the equation resorts to the critical energy form.

During the current program the concept that the closing of the shocked pores controls the hot spot formation time in an impacted material was examined in some detail. However, it did not prove possible to develop this concept to a degree that semi-quantitative calculations could be made of the impact ignition characteristics. Moreover, it was found that there appears to be certain incompatibilities between this concept and the critical energy relation. Further study is necessary to clarify the problems.

In the course of these studies the rudiments of a model was developed that describes the closing of the pores in terms of a simple shear flow (ref. 26). This model leads to the conclusion that viscous flow controls the pore closing time, and that the inertial term can be omitted. This agrees with the very complex treatments given in ref. 25. The linear decrease in porosity with increasing time over most of the pore closing time (as found in ref. 25) was also obtained, and a unique expression for the pore closing time as a function of material and shock wave properties was developed. Some further work is necessary to complete the model.

4.5 ADDITIONAL COMMENTS

As the result of the preceding studies, certain additional concepts were acquired regarding the processes that control the impact ignition event. These concepts are undergoing investigation on the current program, and will not be considered here.

5. CONCLUSIONS

The results of this investigation have provided quantitative support to the concept that the ignition and reaction buildup in an impacted propellant are independent processes, and that the critical energy relation pertains to the ignition process. They have also provided additional details regarding the fundamental processes that control the overall ignition event.

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APPENDIX A

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APPENDIX B

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