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Critical Impact Initiation Energies for Three HTPB Propellants

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The instrumented drop weight impact machine is one possible candidate for establishing the hazard response of solid rocket propellants to impact. The plastic work done on the propellant prior to initiation can be measured by equating it to the loss in drop weight kinetic energy, provided energy storage in the machine is negligible. Three HTPB/AP propellants were studied with an instrumented impact machine. Data are given for impact velocities ranging from 5.54 m/s, at which no sample was consumed, to 16.14 m/s, at which nearly all of the sample was consumed. These data are interpreted in terms of a proposed mechanism based on other impact tests. On bare steel tools ignition, as opposed to hot spot formation, is assumed to occur at impact velocities greater than 10.3 m/s, when more than 90% of the sample is consumed during the test. At higher impact velocities, for the present data, times to reaction are short and the change in impactor kinetic energy during the initiation delay is defined as the critical initiation energy. Some of the trends in the data are correlated with the propellant formulations. The present test is contrasted with others suggested for impact sensitivity characterization in terms of both initiation threshold and response severity.

Introduction

THE drop weight impact test has been used extensively to evaluate the low rate impact sensitivity of energetic materials, although such results are known to be both machine and operator dependent.[1] For many years the accepted manner of obtaining data with a drop weight tester was the 50% Go/No Go method in which the initial drop weight height required to cause a reaction in half of the tests is determined. One shortcoming of this method is the inability to separate the distribution of dissipated drop weight kinetic energy between elastic energy stored in the machine and plastic work done on the sample.[2] This makes the determination of a quantitative measure of impact sensitivity with the 50% test impossible. To overcome this problem, the method of critical initiation energy was implemented by workers at the Naval Surface Warfare Center.[2] This procedure increases the impact velocity of the drop weight, which brings the ignition probability to near 100% and shortens the time to initiation from impact when compared to the 50% test.

The dissipated impactor kinetic energy in either test is distributed in five different forms: the elastic and plastic strain energies of both the sample and machine, and the sample kinetic energy. The sample kinetic energy is negligible and due to the relative hardness of the sample and impactor, no plastic deformation of the machine occurs. At the short reaction times of the critical energy test, the elastic energy stored in the machine has been argued to be negligible.[2] Hence, the dissipated drop weight kinetic energy up to the time of reaction is mostly transferred to the sample as elastic and plastic strain energy and is called the *critical initiation energy*. The critical energy is, thus, that delivered to the sample between impact and initiation and analogous to the minimum ignition energy for electrostatic discharge initiation of solid rocket propellants, discussed elsewhere.[3]

Coffey has previously conducted critical energy experiments on both propellants and explosives. It has been argued for an ammonium perchlorate (AP) propellant that the critical energy is independent of impact velocity in the range of 1.4–5.4 m/s for a 10 kg drop weight.[2] For shotgun tests at up to 170 m/s, the critical energy remained of the same order of magnitude. In critical energy tests reaction is distinguished by visible light emission from reacting hot spots in the sample. Hence, the critical energy test measures the kinetic energy dissipated before hot spots formed within the sample begin to react chemically (the first of two steps in ignition). The initial hot spot chemistry may or may not cause growth of the reaction and self-sustained ignition (step two).

Hot spots are generally accepted as the origin of initiation in the drop weight test and other methods of mechanical initiation. Miller et al.[4] have measured hot spot temperatures greater than 400°C for AP crystals in drop weight impact, and they also showed that in the absence of localized heating, the bulk sample temperature increase in RDX, 0.2°C, is insufficient to cause a reaction. Many theories for mechanical hot spot formation in energetic materials have been postulated, but all seem to recognize the importance of various forms of plastic work. For crystalline materials, Coffey et al. have postulated that when a critical shear stress value within a crystal is reached, dislocation pileups collapse and release energy preferentially in the direction of slip.[5–8] Workers at Cavendish Laboratory have observed jetting and melting in layers of explosive materials in drop weight tests and postulated that hot spots are a result of locally obstructed plastic flow or the closure of gas pockets.[9,10] More recently, they have observed shear bands in explosive samples for impact tests at subcritical velocities not leading to ignition.[11] In other tests, Frey and co-workers have examined the ignition of explosives in combined pressure and shear. The results were analyzed using a model, based on viscoplastic heating, developed to compute the temperature rise in a shear band within the explosive.[12,13]

The existence of a two-step ignition process can mask the true meaning of ignition in a solid rocket propellant hazards test. The creation of hot spots, or detection of light, sound

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or smoke during a test do not ensure the ignition of a propellant, but in the conservative approach required for risk analysis are the usual criteria for onset of reaction. However, ignition occurs only when the reaction becomes self-sustaining. For example, in thermal ignition tests with rocket propellants, Boggs et al.[14] have observed this two-step process: as shown schematically in Fig. 1, at lower energy fluxes to the sample, two threshold times describing stimulus levels for first, gasification reactions and second, self-sustaining ignition could be distinguished. These thresholds are separated by a pre-ignition reaction region, and if the incident flux is removed below the second threshold, then the reactions quench and the propellant extinguishes. Similarly, two threshold stimulus levels should, thus, be defined in impact sensitivity tests for propellants (for explosives, the distinction is probably unnecessary). These are the minimum stimulus level to create chemically reacting hot spots (local ignition), and the minimum stimulus level for sustained ignition. A similar differentiation has been introduced[15] in a detailed mechanism for the response of composite solid propellants containing aluminum to electrostatic discharge. Occurrence of sustained ignition is favored by confinement, high ambient pressure, and so forth. To properly compare the results of various small scale impact tests the definition of ignition in each test must be understood and interpreted in the context of the test configuration.

For the classical 50% Go/No Go test, where any reaction of the above types is considered a Go, it is clear that the sample is not necessarily ignited. In other tests, Ho and Fong have examined propellants using both a modified Hopkinson Bar and a shotgun test.[16,17] For the Hopkinson bar test, they measure a critical impact velocity, the minimum impact velocity for ignition to occur. They define ignition as the detection of light emission from the sample and the minimum velocity for ignition as the velocity at which the percent probability of emitting light deviates from zero. This is also not clearly an ignition in the classical sense. In the critical energy test light is also used as the detection method. However, here the sample is impacted with sufficient speed to cause a sustained reaction in nearly 100% of the tests. The relative locations of the Hopkinson bar, critical energy, and the 50% Go/No Go tests on a reaction probability curve are summarized on Fig. 2. The lines corresponding to two hypothetical propellants, X and Y, will be discussed below.

In hazard classification the second step, the growth of reaction, is equal in importance to hot spot creation, because this second step is one aspect of reaction severity or explosiveness. Ho and Fong determine the explosiveness of a material in their Hopkinson bar test by the slope of their ignition probability curve. Alternatively they examine the light intensity from the reaction.[16,17] Coffey et al. have used a ballistic impact chamber to determine the reaction severity of explosives and propellants.[18] This chamber is essentially a drop

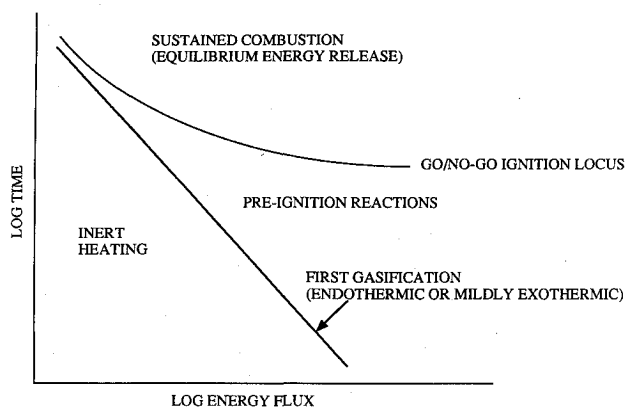

Fig. 1 Two-step thermal ignition process suggested by Boggs et al.[14] Removal of incident flux prior to Go/No Go locus results in propellant extinguishment.

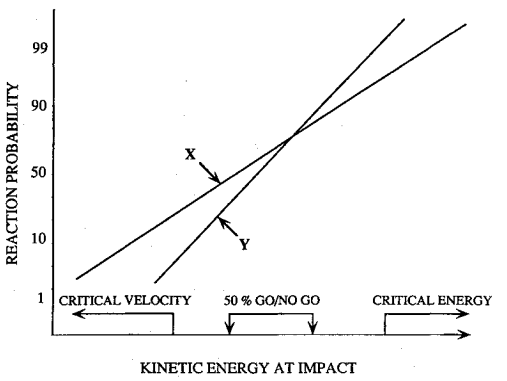

Fig. 2 Relative location of various impact tests on a percent reactions curve. Propellant Y is less sensitive than propellant X for hazards purposes, but ignites more easily.

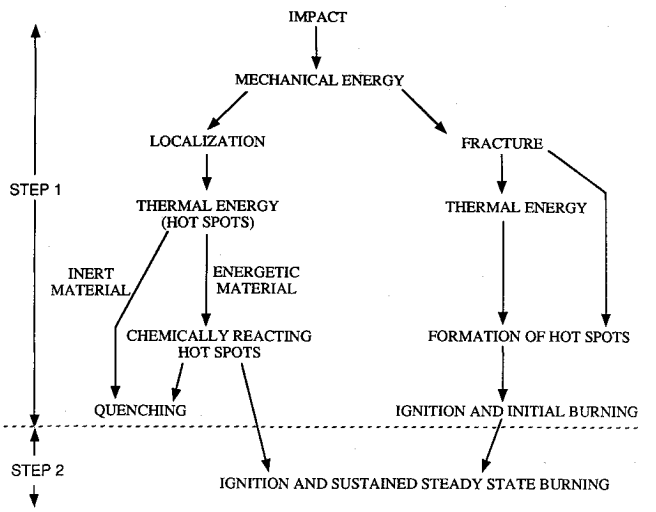

Fig. 3 Impact ignition mechanism. Left side postulated for drop weight impact. Right side suggested by Ho and Fong.[16]

weight machine with the sample confined to a small volume between a striker and anvil. The chamber pressure is monitored and the integral of the pressure-time history is used to determine the reaction severity. The growth of the reaction can be examined by observing the initial pressure rise rate.

The basic two-step ignition process does not address the actual method of creating hot spots or the transfer of energy from the hot spot to the surrounding material. For the Hopkinson bar, a slightly more detailed ignition mechanism, in which the mechanical energy transferred to the sample leads to fracture, was postulated by Ho and Fong[16] and Ho et al.[17] and is shown on the right side of Fig. 3. This fracture releases thermal energy, which causes the formation of hot spots simultaneously (step one), thus leading to the second step involving ignition. We believe that fracture is not the operative energy localization mechanism for impact initiation of composite propellants. The suggested mechanism on the left of Fig. 3 shows energy localization (within oxidizer crystals) causing localized heating (thermal hot spots). This type of localization also occurs in inert materials.[6] The resulting thermal energy concentration may lead to chemically reacting hot spots for an energetic material, which, as discussed previously, can either quench or lead to ignition.

In the present work, drop weight tests were conducted on three similar HTPB/AP (hydroxyl terminated polybutadiene/AP) propellants at various impact velocities. After each test, the residual mass of the sample was weighed and compared to the initial mass in order to determine the fraction of sample consumed. Additional impact tests were conducted where the drop weight velocity was monitored. Critical energies were calculated for cases where the impact velocity was great enough

to cause an early reaction and keep the energy stored in the machine negligible. At the lower speeds and long reaction times, it is likely that a substantial part of the dissipated drop weight kinetic energy is stored as elastic machine energy. In addition, at the lower speeds the reaction was confined to hot spots and the sample did not undergo self-sustained combustion. Thus, the dissipated drop weight kinetic energy in low-speed impact yields an upper bound to the energy necessary to cause reacting hot spots, rather than a minimum. The actual energy deposited in the sample is less than the measured value due to the stored elastic machine energy.

The goals of this experimental work are to clarify the different definitions of ignition via low-rate mechanical impact in various test procedures now in use through the sample-fraction-consumed experiments; to distinguish between chemical hot spot formation (local ignition) and self-sustained ignition thresholds; and to measure energy requirements for the latter in order to determine if these are independent of the test apparatus and operator procedure.

Experiments

Tests were conducted to determine both the impact sensitivity, via critical initiation energy, and reaction severity, via percent of sample consumed. The impact machine and drop weight used for this study are shown in Fig. 4. The drop weight consists of an aluminum body with a steel striker press-fit into its base. The hardened steel anvil is clamped to the steel base of the machine. The anvil is approximately 8 cm high and 2.54 cm in diameter at its top. The mass of the drop weight is 367 g. Tests were conducted at impact velocities ranging from 5.54 to 16.14 m/s.

Three HTPB/AP/Al solid rocket propellants, A, B, and C, were used. Because each has been tailored for a specific mission, many formulation differences exist between these propellants. The available formulation data and differences are given in Table 1. The samples were cylindrical disks with the diameter held constant at 5 mm. For the percent consumed tests, the masses ranged from 32.4 to 57.3 mg. In the critical energy tests, the masses ranged from a minimum of 31.1 mg to a maximum of 53.0 mg, corresponding to a thickness variation of 0.86–1.47 mm. For both types of tests, the majority of the samples were in the 40–50 mg range.

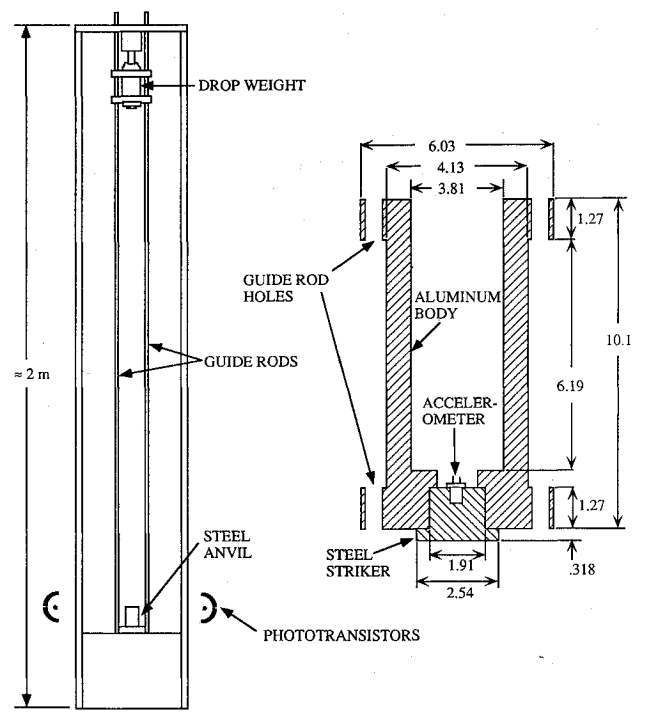

Fig. 4 Instrumented drop weight machine and drop weight with accelerometer (all dimensions in cm).

Table 1 Formulation differences between three HTPB/AP/Al propellants used for critical energy and percent consumed tests

	Propellant A	Propellant B	Propellant C
Total AP, wt %	68.1	68.1	68.1
Density, kg/m³	1.83×10^3	1.83×10^3	1.83×10^3
AP size distribution	Bimodal	Trimodal	Bimodal
Relative material Distributions, wt %			
Coarse AP	C[a]	~0.78 C	~C
Fine AP	F[b]	~F	~F
Ultrafine AP	0.0	~0.22 C	0.0
Al[c]	1.0	1.0	1.0
Bonding agent 1	1.0 B[d]	0.0	0.67 B
Bonding agent 2	0.0	0.5 B	0.0
Plasticizer[c]	1.0	1.0	1.5
Burn rate catalyst[c]	1.0	0.56	1.0

[a]C = Weight percent of coarse AP in propellant A.
[b]F = Weight percent of fine AP in propellant A.
[c]Normalized by the weight percent for this ingredient in propellant A.
[d]B = Weight percent of bonding agent in propellant A.

For critical energy tests, an Endevco Model 2255-005 B accelerometer is placed on the rear of the striker and used to monitor the drop weight acceleration, as shown in Fig. 4. The rise time and resonant frequency of the accelerometer are ~7 μs and 300 KHz, respectively; its maximum permissible load is 100,000 g (200,000 g in shock loading). Time to reaction of the sample after impact is determined by using two phototransistors placed at the same height as the sample. The light and amplified accelerometer signals are sent to a dual channel LeCroy 9400 oscilloscope. Garnet paper, 180 grit, was placed between the sample and the anvil to prolong accelerometer life. The garnet paper increases friction and, hence, shear on the propellant, which allows hot spots to be created more easily, shortens reaction time, and increases the extent of reaction. This results in lower impact velocities required for ignition, which decreases the maximum accelerometer load (approximately 60,000 g at 12.95 m/s) and allows more tests before accelerometer failure. The velocity change of the drop weight prior to sample reaction is determined by integrating the accelerometer trace on the oscilloscope from the time of impact to the time of first light. For high impact velocities the elastic strain energy of the machine is negligible, and once the change in drop weight velocity is known the critical energy is determined by

$$E_{\text{critical}} = E_{\text{plastic}} = \Delta E_{\text{kinetic}} = -m_w[V_0 \Delta V + \tfrac{1}{2}\Delta V^2]$$

where E_{plastic} is the plastic work done on the propellant; $\Delta E_{\text{kinetic}}$ is the change in kinetic energy of the drop weight; m_w is the mass of the drop weight; V_0 is the impact velocity, which is taken to be negative; and ΔV is the change in drop weight velocity, which is positive.

Qualitatively, for experiments at any velocity, the accelerometer output, as shown in Fig. 5, can be used to determine if substantial energy has been stored in the drop weight. If reaction occurs after the first large minimum in the acceleration trace, then substantial elastic energy is most likely stored in the machine. The large oscillations in the traces have periods, $\approx$ 40 μs, of approximately the time required for an elastic wave to travel the length of the drop weight and return. Hence, they are thought to indicate elastic strain energy storage in the test apparatus. As expected, the amplitude of the elastic wave increases with impact velocity (curve 3 is $\frac{1}{8}$ vertical scale of curve 1), but the longer reaction delay times at low speeds lead to multiple wave reflections prior to light emission. Consequently, for low speeds stored elastic energy in the machine comprises a large part of the drop weight kinetic energy transferred to the sample and machine at reaction time.

The presence of garnet paper in the critical energy tests precludes the measurement of the sample residual. Consequently, the percent consumed tests were conducted using a

bare steel anvil and striker without any instrumentation present. Therefore, the results from the critical energy and percent consumed tests are not directly comparable at a given impact velocity.

Results and Discussion

Percent Consumed

Tests were conducted to determine the weight percent of sample consumed during the impact test for various impact velocities from 5.54 to 16.14 m/s. The data were collected in two sets of experiments using a bare steel striker and anvil, as noted previously. Propellant B was tested in the first set, and A and C were tested in the second set. The temperature was approximately 18°C for all tests, and the ambient relative humidity in the laboratory was 20–30% for the B tests and ~40% for the A and C tests. Initially, an effort was made to trap any small pieces of sample that might fly out radially from between the striker and anvil as the sample was initiated. After several tests, it was decided that the amount of sample lost this way was negligible and no further effort was made to catch any particles. Table 2 shows the data for the averages of initial and final mass of the samples plus the fraction consumed. Figure 6 shows all of the data for the latter from these tests. Three samples were tested for almost all cases, and the unbiased standard deviation is given in Table 2 for the fraction consumed data.

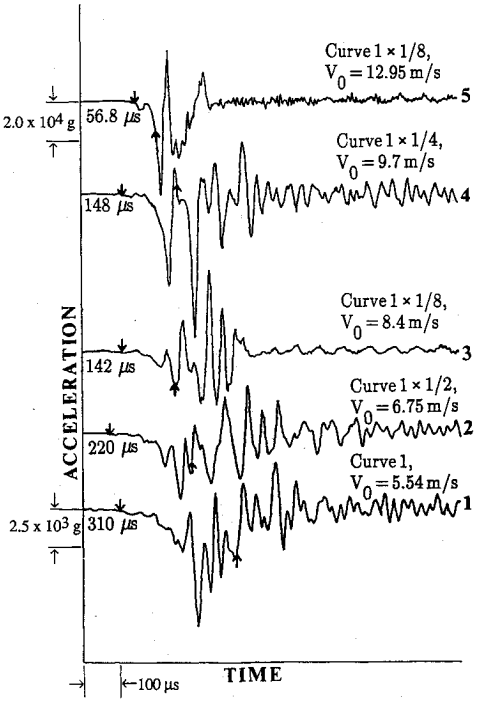

Fig. 5 Typical accelerometer traces for various drop weight impact velocities for propellant B. The vertical scales differ with respect to curve 1 as indicated, e.g., the scale for curve 5 is ½ that of curve 1. The horizontal time axes are identical. ↓ denotes estimated time of impact, ↑ is time of first light seen by phototransistors, and the time delay is indicated.

The impact velocities used for these tests span the range of what is necessary for only a hot spot reaction, denoted by less than 10% consumed, to what is required for ignition, defined here as greater than 90% consumed. The usual ignition criterion is the chemical heat release rate exceeding the rate of heat loss to the surroundings. However, these rates cannot be measured using available instrumentation. Because ignition should result in essentially complete sample consumption, and the percent consumed data in Fig. 6 for high impact velocities approach 95%, ignition is therefore defined as 90% sample consumption.

At 5.54 m/s no reaction other than hot spots was present. For propellant A no reaction occurred, while for B and C hot spot reactions were observed in the outer half of the sample where the strain and strain rate are higher than close to the anvil center. At any impact speed the residual was the center of the remaining sample, in the region of higher pressure and lower shear. Because any voids present would reach their highest temperature in the sample center, this suggests that adiabatic compression of gases and microjetting in voids are not important hot spot mechanisms for the relatively voidless propellants studied here.

It is interesting to compare these results to those of Ho and Fong. For propellants B and C, the minimum impact velocity of 5.54 m/s here is above Ho and Fong's critical impact velocity initiation threshold because a hot spot reaction occurred. For A their threshold lies between 5.54 and 6.75 m/s in the present test. The HTPB/AP propellants tested by Ho and Fong have critical impact velocities in the Hopkinson bar test of approximately 13–16 m/s,[16] which are different from those shown in Fig. 6 and Table 2 due to the differing impactor and sample masses, and sample geometry.

Percent consumed data such as these provide information on the growth of reaction from step 1 to 2 in propellants due to varying stimuli. The consumption of more propellant is analogous to moving from the first gasification line towards the Go/No Go ignition locus in Fig. 1. For propellant C substantially more propellant was consumed at velocities from 5.54 to 8.4 m/s than for A and B, which would suggest that in this impact velocity range C is more apt to reach sustained reaction and ignition and, thus, will exhibit the highest severity. The increased sample consumption with increased impact velocity could result from either an increase in hot spot temperature or an increase in the number of hot spots. A comparison of ingredient concentrations and AP size distributions in the three propellant formulations shown in Table 1 suggests that either explanation is reasonable via the bond-

Table 2 Average fraction of propellants A, B, and C consumed on bare steel tools[a]

Velocity, m/s	Propellant A			Propellant B			Propellant C		
	Average mass, mg		Fraction consumed	Average mass, mg		Fraction consumed	Average mass, mg		Fraction consumed
	Initial	Final		Initial	Final		Initial	Final	
5.54	40.9	40.9	0.00 ± 0.00	42.9	39.8	0.07 ± 0.04	41.5	38.3	0.09 ± 0.08
6.75	40.6	27.9	0.31 ± 0.13	41.1	33.6	0.18 ± 0.05	40.3	20.4	0.50 ± 0.10
8.4	46.2	23.3	0.51 ± 0.09	44.1	21.8	0.50 ± 0.09	45.9	11.2	0.75 ± 0.10
9.7	41.9	12.5	0.71 ± 0.09	41.8	12.6	0.70 ± 0.12	47.7[c]	10.5	0.78 ± 0.05
10.3	43.6	8.1	0.82 ± 0.04				43.6	4.1	0.90 ± 0.03
12.95	52.8[b]	3.4	0.94	39.6	2.6	0.94 ± 0.03	42.1	2.7	0.94 ± 0.01
16.14				42.4	1.3	0.97 ± 0.01			

[a]Three samples of each propellant were tested at each velocity unless otherwise noted.
[b]Represents one sample.
[c]Represents two samples.

ing agent and plasticizer variations in propellant C (through their effects on mechanical properties).

Based on the results of these tests, it was determined that a sustained reaction would occur at velocities of approximately 11.0 m/s and higher for all propellants. The presence of garnet paper in the critical energy tests is expected to shift the data in Fig. 6 to the left on the impact velocity axis and allow ignition to be defined at lower impact velocities.

Critical Energy

Energy-to-reaction results were obtained for the three propellants in two different sets of experiments with the propellant resting on 180 grit garnet paper. In the first set impact velocities of 8.4, 10.3, and 12.95 m/s were tested with the ambient temperature and relative humidity (RH) in the laboratory ranging from 21 to 22°C and 50 to 60%. The second set utilized impact velocities of 5.54, 6.75, and 9.7 m/s in laboratory air at approximately 18°C and 20–30% RH. Table 3 gives results of the average dissipated kinetic energy prior to hot spot reaction for extent of reaction ranging from hot spot reaction only, 6.75 m/s and below, to nearly complete sample consumption, taken as 10.3 m/s and above. Table 3 also shows the average time from impact to reaction and the number of data for each condition. The unbiased standard deviations are also shown for the dissipated energies and reaction times. For all impact velocities the dissipated drop weight kinetic energy is only measured up to the time of detectable hot spot reaction (determined by visible light emission). However, only for the low-speed impacts does the stored elastic machine energy comprise a large part of the dissipated kinetic energy, and only at the higher impact velocities do the hot spots lead to reaction growth and ignition. Therefore, the critical energy values for high-speed impacts and indicated energy values for low-speed impacts are not quantitatively comparable.

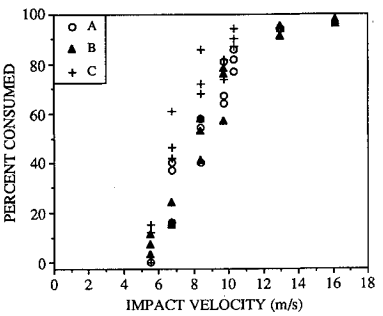

Fig. 6 Percent consumed for propellants A, B, and C at various impact velocities.

At 8.4 and 9.7 m/s the elastic machine energy is considered negligible, although due to the length of the reaction times and possible elastic energy storage, including these results with the critical energies is suspect. However, reaction usually occurred before the largest minimum on the accelerometer trace (see Fig. 5), and the drop weight velocity decreased less than 60% of its impact speed prior to reaction, so these data were included here. Numerical analysis could either justify or discredit including these results.

Low-Speed Results, 5.54–6.75 m/s

The lowest impact velocity, 5.54 m/s, is very close to a reaction threshold for propellants A and B. For all three propellants, the dissipated energies of the drop weight prior to reaction were greater than 90% of the available kinetic energy. This is similar to the situation in the 50% Go/No Go test where a large amount of elastic energy is stored in the machine at the time when reaction is observed. Even when light emission was not detected, reaction at a few hot spots within the sample was evident from post-test visual inspection. Therefore, an undetected reaction can occur within the sample and cause the measured values of energy and/or minimum impact velocity for reaction to be unrealistically high. Results can also be misleading due to unexpected deviations in the data. These deviations can cause the required stimulus for one sample to be considerably lower than usual for that propellant. For example, with propellant B at 6.75 m/s the dissipated drop weight energy in one test was only 86 J/g, but the mean value was 155 J/g. This was the most extreme deviation for the low velocity data. Aberrations like these pose a great threat to safety and show the need for a large number of samples to be tested when close to the reaction threshold.

Propellant C, which reacted to a greater extent in the percent consumed tests, is the most sensitive of the three propellants at low impact velocities, where only hot spots were created. At 5.54 m/s a sharp increase in light emission was observed in three of three valid tests for C compared to one of five for A and B. In addition, at 6.75 m/s the mean dissipated energy for C is considerably less than for A and B, which implies that less stimulus is needed to create reacting hot spots in C (assuming the elastic machine energy time history is relatively independent of propellant at this speed). The extent of reaction at these impact speeds is comparable to the critical velocity test, and the results agree qualitatively with observations by Ho and Fong[16] and Ho et al.[17] For HTPB/AP propellants they observed that both the addition of plasticizer and absence of bonding agent increase the sensitivity of the propellant.[17] Here, propellant C has both less bonding agent and more plasticizer than A, and C is the more sensitive of the two propellants at these impact speeds. However, there

Table 3 Average indicated and critical energies for reaction and average times to first light for propellants A, B, and C on 180 grit garnet paper[a]

	Indicated energies[b] Hot spot reactions only		Critical energies			
			Ambiguous[c]		Ignition	
Velocity, m/s	5.54[d]	6.75[d]	8.4[e]	9.7[d]	10.3[e]	12.95[e]
Energy, J/g						
A	114 (1)[f]	173 ± 24 (5)	226 ± 41 (5)	261 ± 61 (5)		345 ± 26 (4)
B	132 (1)	155 ± 53 (4)	277 ± 38 (5)	263 ± 36 (4)	269 (1)	216 ± 56 (7)
C	117 ± 12 (3)	141 ± 19 (5)	231 ± 20 (5)	207 ± 30 (4)	372 ± 35 (8)	335 (1)
Time to first light, μs						
A	316 (1)	157 ± 24.3 (5)	160 ± 27.4 (5)	119 ± 10.5 (5)		82 ± 11.5 (5)
B	310 (1)	193 ± 51.1 (5)	152 ± 15.1 (5)	133 ± 16.5 (4)	95 (1)	67 ± 11.1 (8)
C	273 ± 18.6 (3)	171 ± 16.2 (5)	148 ± 5.3 (5)	125 ± 10.8 (4)	93 ± 13.2 (8)	68 ± 8.5 (2)

[a]Unbiased standard deviations are shown.
[b]Represents an upper bound for critical energy due to elastic machine energy storage.
[c]Sample residual in Table 2 suggests ignition threshold not reached.
[d]Datum set 2.
[e]Datum set 1.
[f]Number in parentheses is number of data for each condition.

are also slight particle size distribution differences between A and C indicated only schematically in Table 1.

Effects of Impact Velocity

All of the energy data for the three propellants at velocities of 8.4 m/s and greater are shown in Figs. 7–9. At higher impact velocities it is not possible to distinguish between the sensitivities of A and C. This is evidence that relative impact sensitivity rankings of propellants can change when ignition is defined by sustained reaction and not simply light emission, as is shown schematically in Fig. 2. Here propellant X would be more sensitive than Y at low levels of impactor energy, where the hot spot reactions would not propagate, and less sensitive than Y at high levels of impactor energy where a sustained reaction may occur.

At velocities above 5.54 m/s in datum set 2 (see Table 3), the dissipated energy of the drop weight prior to light emission increases. Therefore, at the elevated strain rates of higher impact velocities more energy must be deposited in the sample prior to hot spot reaction. This is most likely due to changes in the mechanical properties of the propellant with strain rate. At 8.4 m/s and above the trend of dissipated kinetic energy prior to hot spot formation with impact velocity varies with propellant, as shown most clearly in Figs. 7–9. Propellant A shows a trend of increasing critical energy with impact velocity, whereas propellant B has a slight decrease in critical energy from 277 J/g at 8.4 m/s to 250 J/g at 12.95 m/s. The critical energy of propellant C seems to have no trend with impact velocity. However, if the set 2 datum points at 9.7 m/s are ignored (see ambient effects discussion below) and the single datum point at 12.95 m/s is valid, it would seem that C has a relative maximum for critical energy somewhere between 8.4 and 12.95 m/s.

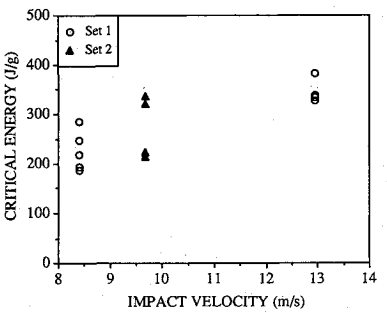

Fig. 7 Critical energy for propellant A.

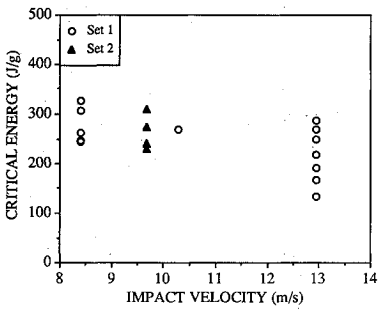

Fig. 8 Critical energy for propellant B.

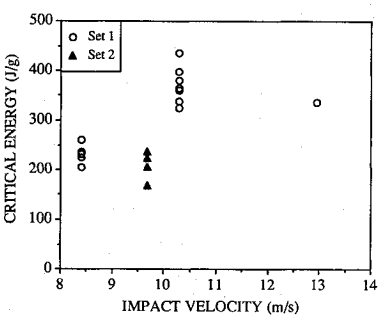

Fig. 9 Critical energy for propellant C.

In the past the critical energy of an HTPB/AP propellant was thought to be independent of impact velocity.[2] For that propellant, the ignition times were less than 100 μs and light emission was used to detect initiation. Percent consumed data were not recorded, but it is reasonable to expect that with the short ignition times and large drop weight (10 kg), the samples ignited. By inspecting Coffey's data more closely, it was found that the deviations in critical energy (coefficient of variation greater than 0.3) with impact velocity are greater than the deviations for the present data (in datum set 1, 0.25, 0.22, and 0.23 coefficients of variation for A, B, and C, respectively) over the velocity range of 8.4–12.95 m/s. However, it seems from the present data that critical energy is not constant, but instead a function of impact velocity that depends on the propellant mechanical properties. This is expected because the binder is viscoelastic and both the work needed to move dislocations in the oxidizer crystals and the rheological characteristics of the propellant vary with strain rate.

High-Speed Results, 8.4–12.95 m/s

Differences in the propellant formulations can help explain the relative magnitudes of the critical energies for the three propellants at certain velocities. At 12.95 m/s, B has a lower critical energy than A and is likely lower than C. This is most likely an effect of the ultrafine AP in B, which is not present in A and C. These small particles replace a substantial amount of larger AP present in greater abundance in both B and C. This decreases the effective viscosity of B with respect to A and C, which allows B to flow more easily in high strain rate and shear situations where AP particles must flow past one another. Consequently, for B the drop weight will slow less for a given amount of deformation. If hot spot reactions occur first in the largest AP at approximately the same amount of deformation for all three propellants, then the ultrafine AP in B causes it to have a lower critical energy. The relative constancy of the critical energy of B with impact velocity implies that the relevant mechanical properties of B are less strain rate dependent than A and C. At 8.4 m/s propellant B has a higher critical energy value than both A and C. Apparently, the high strain rate effects of the ultrafine AP are not as influential on the results at this lower speed. In fact, the lower strain rate dependence of B compared to A and C is not a factor at the lower impact velocities, 5.54 and 6.75 m/s. Based on the similarity of the reaction times for the propellants at any impact speed, the greater yield strength of the small particles is not delaying the onset of reaction in B.

The critical energy of a soft propellant can be either higher or lower than that of a harder propellant depending on the reason for its softness. Here the smaller particles in B apparently cause a lower energy requirement to shear the propellant at high strain rates. However, the large particles in B are the origin of hot spots, so the reaction still starts at approximately the same time, and most likely thickness, as for A and C. Therefore, the critical energy is lower for B. If, instead, all of the large AP in B were replaced with small AP, it is likely that the creation of hot spots would be delayed long enough for the critical energy of B to be greater than A and C, at the higher velocities. The delay would be caused by both the increased shear strength of the smaller AP and the reduction in thickness required to cause binding of the AP particles in their relative motion.

Environmental Effects

Inconsistencies in drop weight data can also be attributed to temperature and humidity variations.[19] For propellant C the critical energy at the velocity of 9.7 m/s for datum set 2, as shown in Fig. 9, is lower than would be estimated by datum

set 1. This can be an effect of either aging the propellants (datum set 2 was acquired about three months after set 1) or changing environmental conditions in the laboratory. Although nothing quantitative can be said about aging, a definite drop in the amount of moisture in the ambient air existed from datum set 1 to 2. In fact, the decrease in relative humidity, from 50–60% to 20–30%, when coupled with the temperature decrease, approximately 4°C, could lead to a reduction in the specific humidity ratio of over 60%. This decrease in atmospheric moisture can cause a decrease in the moisture within the propellant, particularly close to the surface, which leads to an increase in shear stresses as the propellant deforms. This increased shear means that less drop weight deceleration is necessary for sample reaction. Hence, the critical energy is decreased. Note however that the B data from sets 1 and 2 are more consistent.

Conclusions

It is apparent that both particle size distribution and impact velocity influence critical energy. Propellant B, which contains ultrafine AP, exhibits the lowest critical energy at high impact speeds, yet requires energy values similar to A and C at lower speeds. At impact speeds of 8.4 m/s and greater, the critical energy data exhibit less scatter than the previous data presented by Coffey et al.,[2] but trends with impact velocity are apparent (Figs. 7–9).

It is postulated that energy localization and initial reaction occur at the large AP particle sites, as opposed to the fracture suggested by Ho and Fong,[16] and all propellants have the same large AP size. The dissipated drop weight energies prior to hot spot reaction are approximately equal at the lower impact velocities and increase with impact velocity near the threshold for reaction. This increase may, however, simply reflect more energy storage in the machine, but not in the propellant.

At low velocities it seems that propellant C is more susceptible to hot spot formation and local ignition than A and B, based on the percent reacted tests. Because C has decreased bonding agent and increased plasticizer, this result agrees with those of Ho et al. for critical impact velocity.[17] At these velocities in the drop weight test only hot spots are initiated (step 1 in Fig. 3), and, thus, results from the drop weight and Hopkinson bar are comparable (by reporting critical velocity, defined as the zero point of the reaction probability curve, Ho and Fong have also reported the necessary stimulus for hot spot reaction and, thus, have evaluated impact sensitivities of propellants with this criterion). It is possible that the propellants would be ranked differently if the sensitivities are based on sustained ignition (step 2).

Thus, although the critical energy and Hopkinson bar tests both have similar impact velocities and strain rates, 10^3–10^4 s^{-1}, results from these and other tests must use consistent definitions of ignition in order for meaningful comparisons and ranking of propellant sensitivities. It was suggested with the reaction probability curves X and Y in Fig. 2 and observed in the present drop weight percent of sample consumed tests summarized in Fig. 6 that relative ranking based on critical impact velocity can be different from that based on propellant ignition thresholds. We have also distinguished between hot spot reaction (local ignition) and sustained ignition (and combustion) analogous to the distinction made by Boggs et al.[14] for thermal ignition. Although local ignition is the important threshold for risk assessment in propellant hazard studies, we prefer the traditional criterion of self-sustained reaction for ignition. Critical energy is reported only if the latter occurs.

Note, however, that hot spots are precursors of ignition, and that the critical energy values reported here also, thus, reflect the energy required to form hot spot reactions. It is expected that at high impact speeds, which correspond to a large energy flux, both the rate of hot spot creation and the number of hot spots created will increase and therefore ignition becomes more likely. The time delay between hot spot initiation and sustained ignition will also decrease as impact velocity increases. However, there is no way to distinguish these events in the present test method using first light sensed by the phototransistors of Fig. 4 to terminate the measurement of energy removed from the drop weight.

Both severity of response and sensitivity are related to the distinction between hot spot initiation and self-sustained combustion, which always follows ignition. Critical impact velocity (at 0% reaction probability) and 50% Go/No Go drop weight heights (at 50% reaction probability) do not provide a quantitative measure of the ignition stimulus. In contrast, critical energy (at >90% reaction probability) measures the requisite energy stored in the sample for ignition (and the precursor hot spots) and should be relevant to other impact scenarios, because it is in principle a property of the energetic material. In fact, attempts have been made to do just this.[20] In the Hopkinson bar test one could also report critical energy for ignition with existing instrumentation, currently used to obtain high rate propellant material properties, such as fracture toughness.[21,22]

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References

[1]Mellor, A. M., Boggs, T. L., Covino, J., Dickinson, C. W., Dreitzler, D., Thorn, L. B., Frey, R. B., Gibson, P. W., Roe, W. E., Kirshenbaum, M., and Mann, D. M., "Hazard Initiation in Solid Rocket and Gun Propellants and Explosives," *Progress in Energy and Combustion Science*, Vol. 14, No. 3, 1988, pp. 213–244.

[2]Coffey, C. S., DeVost, V. F., and Yergey, B. A., "Critical Initiation Energy in at Least Some Propellants and Explosives Subject to Impact," *JANNAF Propulsion Systems Hazards Subcommittee Meeting Proceedings*, Chemical Propulsion Information Agency Publ. 446, Vol. 1, 1986, pp. 579–585.

[3]Mellor, A. M., Stoops, D. R., Rudy, T. P., and Hermsen, R. W., "Optimization of Spark and ESD Propellant Sensitivity Tests: A Review," *Propellants, Explosives, Pyrotechnics*, Vol. 15, No. 1, 1990, pp. 1–7.

[4]Miller, P. J., Coffey, C. S., and DeVost, V. F., "Heating in Crystalline Solids Due to Rapid Deformation," *Journal of Applied Physics*, Vol. 59, No. 3, 1986, pp. 913–916.

[5]Coffey, C. S., "Phonon Generation and Energy Localization by Moving Edge Dislocations," *Physical Review B: Solid State*, Vol. 24, No. 12, 1981, pp. 6984–6990.

[6]Coffey, C. S., and Armstrong, R. W., "Description of 'Hot Spots' Associated with Localized Shear Zones in Impact Tests," *Shock Waves and High Strain-Rate Phenomena in Metals*, edited by M. A. Meyers and L. E. Murr, Plenum, New York, 1981, pp. 313–324.

[7]Coffey, C. S., "Hot Spot Production by Moving Dislocations in a Rapidly Deforming Crystalline Explosive," *Proceedings of the Eighth Symposium (International) on Detonation*, Naval Surface Weapons Center MP 86–194, 1985, pp. 62–67.

[8]Coffey, C. S., and Jacobs, S. J., "Detection of Local Heating in Impact or Shock Experiments with Thermally Sensitive Films," *Journal of Applied Physics*, Vol. 52, No. 11, 1981, pp. 6991–6993.

[9]Heavens, S. N., and Field, J. E., "The Ignition of a Thin Layer of Explosive by Impact," *Proceedings of the Royal Society of London, Series A: Mathematical and Physical Sciences*, Vol. 338, No. 1612, 1974, pp. 77–93.

[10]Winter, R. E., and Field, J. E., "The Role of Localized Plastic

Flow in the Impact Initiation of Explosives," *Proceedings of the Royal Society of London, Series A: Mathematical and Physical Sciences*, Vol. 343, No. 1634, 1975, pp. 399–413.

[11]Mohan, V. K., Jyothi Bhasu, V. C., and Field, J. E., "Role of Adiabatic Shear Bands in Initiation of Explosives by Drop-Weight Impact," *Preprints of Ninth Symposium (International) on Detonation*, Vol. 2, 1989, pp. 557–565.

[12]Frey, R. B., "The Initiation of Explosive Charges by Rapid Shear," *Proceedings of the Seventh Symposium (International) on Detonation*, Naval Surface Weapons Center MP 82–344, 1981, pp. 36–42.

[13]Boyle, V., Frey, R., and Blake, O., "Combined Pressure Shear Ignition of Explosives," *Preprints of Ninth Symposium (International) on Detonation*, Vol. 1, 1989, pp. 1–11.

[14]Boggs, T. L., Price, C. F., and Derr, R. L., "Transient Combustion: An Important Consideration in Deflagration-to-Detonation Transition," *Hazard Studies for Solid Propellant Rocket Motors*, AGARD CP 367, Paper 12, 1984.

[15]Mellor, A. M., Dreitzler, D. R., Larson, R. W., and Mann, D. M., "Workshop Summary: ESD Ignition of Composite Solid Propellants," *Workshop on ESD Ignition of Composite Solid Propellants Proceedings*, Army Research Office, 1989, pp. ii–xvi; also *JANNAF Propulsion Systems Hazards Subcommittee Meeting Proceedings*, Chemical Propulsion Information Agency Publ. 538, Vol. 1, 1990, pp. 219–228.

[16]Ho, S. Y., and Fong, C. W., "Relationship Between Impact Ignition Sensitivity and Kinetics of the Thermal Decomposition of Solid Propellants," *Combustion and Flame*, Vol. 75, No. 2, 1989, pp. 139–151.

[17]Ho, S. Y., Fong, C. W., and Hampshire, B. L., "Assessment of the Response of Rocket Propellants to High-Velocity Projectile Impact Using Small-Scale Laboratory Tests," *Combustion and Flame*, Vol. 77, No. 3 & 4, 1989, pp. 395–404.

[18]Coffey, C. S., DeVost, V. F., and Woody, D. L., "Towards Developing the Capability to Predict the Hazard Response of Energetic Materials Subjected to Impact," *Preprints of Ninth Symposium (International) on Detonation*, Vol. 3, 1989, pp. 965–974.

[19]Coffey, C. S., and DeVost, V. F., "Drop Weight Impact Machines—A Review of Recent Progress," *JANNAF Propulsion Systems Hazards Subcommittee Meeting Proceedings*, Chemical Propulsion Information Agency Publ. 446, Vol. 1, 1986, pp. 527–531.

[20]Coffey, C. S., DeVost, V. F., and Woody, D. L., "Towards Developing the Capability to Predict the Hazard Response of Energetic Materials Subjected to Impact," *JANNAF Propulsion Systems Hazards Subcommittee Meeting Proceedings*, Chemical Propulsion Information Agency Publ. 477, Vol. 1, 1988, pp. 121–128.

[21]Ho, S. Y., and Fong, C. W., "Temperature Dependence of High Strain-Rate Impact Fracture Behavior in Highly Filled Polymeric Composite and Plasticized Thermoplastic Propellants," *Journal of Materials Science*, Vol. 22, Aug. 1987, pp. 3023–3031.

[22]Ho, S. Y., and Fong, C. W., "Correlations Between Fracture Properties and Dynamic Mechanical Relaxations in Composite Propellants," *Polymer*, Vol. 28, April 1987, pp. 739–744.