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Frictionally induced ignition processes in drop and skid tests

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Abstract. The standard LANL / Pantex drop and skid tests rely on subjective assessment of reaction violence to quantify the response of the charge, and completely miss non-propagating hot-spot ignition sites. Additionally, large variations in test results have been observed, which we propose is due to a misunderstanding of the basic physical processes that lead to threshold ignition in these tests. The tests have been redesigned to provide control of these mechanisms and to permit direct observation of hot spots at the impact site, allowing us to follow the progression of the outcome as the drop height and ignition source density are varied. The results confirm that frictional interactions between high-melting-point solids are the dominant ignition mechanism, not just at the threshold, but in fact at all realistic drop heights.

Introduction

Oblique impact tests have been used for some time to assess the likelihood of ignition when a pressed and machined charge is accidentally dropped. In the LANL/Pantex drop test, the charge is suspended by a winch arrangement and then dropped onto a 45° target surface; in the skid test it is attached to a pendulum and swung so as to impact a horizontal target surface at either 14° or 45°. Traditionally, the surface may be smooth steel or other metal, may be coated with another material to simulate flooring surfaces found in processing areas, or may comprise a deliberately rough surface such as epoxy-bonded sand on metal. The intent has been to vary surface roughness, thermal conductivity and specific heat capacity. The outcome is assessed according to level of reaction, from no apparent reaction to violent explosion or detonation. The 45° drop and skid tests should, and generally do, produce similar results, since the angle and speed at impact are the same for a given drop height. The pendulum geometry of the skid test leads to a slight additional rotational motion counter to that produced on impact by friction, but only leads to a small change in the apparent relative parallel velocity.

There are at least two problems with this approach. Firstly, only propagating reactions are detected, and so the formation of nascent reaction sites, or hot spots, is not seen unless they propagate. However, from a safety point of view it would be desirable to mitigate hot spot formation entirely, rather than rely on the absence of propagation to avoid a violent outcome. Secondly, large variations in threshold drop height have been observed under nominally similar conditions, which, together with an examination of the experimentally controlled variables, have led us to the hypothesis that the dominant ignition mechanism was, in fact, not controlled at all.

This hypothesis is not actually new or controversial, but based on a substantial body of existing work in the areas of impact, friction and reaction kinetics dating back over 70 years.

In common with all PBXs, PBX 9501 is a weak material (i.e. it exhibits low yield stresses), and at low impact velocities the strain rates are too low for enough mechanical energy to be deposited to get to ignition temperatures, even with localization processes occurring. Heat losses through the usual transport mechanisms are enough to prevent critical hot spots from forming. This accounts for the relatively high threshold impact velocities for reaction in bullet or fragment impacts on bare charges (note that other heating mechanisms dominate in impact on cased charges), which are well over 100 m s^{-1}. A drop from 10 m leads to an impact velocity of less than 15 m s^{-1}.

This leaves friction as an obvious candidate heating mechanism; it has long been known that oblique impacts with explosives are more prone to reaction than normal impacts, and an oblique impact both reduces deformation strain rates and increases the relative material velocity parallel to the impact surface.

Of major importance here is the duration of the impact event; if fast reaction from a confined ignition site in the impact region does not occur before the impact is over (i.e. the charge has bounced), then the reaction will most likely quench, and the lack of confinement will certainly prevent flame propagation into the bulk of the charge – which is necessary to achieve the inertial confinement for violent reaction to occur. As has been observed previously, and confirmed in this study, the duration of a drop or skid test impact is of the order of 1 ms. For HMX-based charges we can use well-established time-to-ignition data to estimate minimum hot spot temperatures required for ignition during the impact. Figure 1 presents these data graphically[1], and shows that temperatures of at least 500 – 600 °C would be necessary in this time regime.

These temperatures are unobtainable by frictional interactions between the PBX and the target, since when two materials interact frictionally, the maximum temperature achievable is limited to the melting point of the lower-melting-point material[2].

However, in a series of elegant experiments, Bowden and Gurton[3] had earlier demonstrated that during the frictional interaction of two surfaces, one of which has a high melting point and in the presence of grit, enhanced heating occurs at grit particles and that the maximum temperatures achieved at such hot spots are dependent on the melting point of the grit. They also found, as would be expected from this observation, that grit only sensitizes an explosive if the melting point of the grit is higher than the ignition temperature of the explosive, and that the results are relatively insensitive to grit hardness.

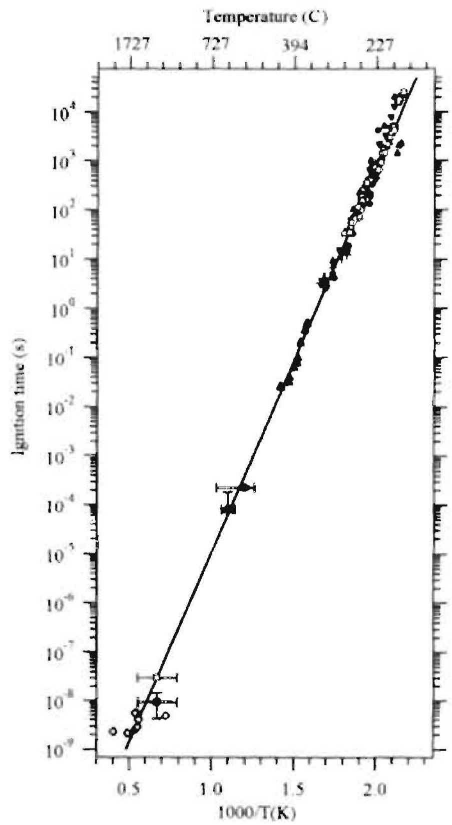

Figure 1. Ignition time for HMX as a function of inverse temperature.

Dyer and Taylor[4] extended this work to examine the frictional interaction between pressed or cast explosives and various surfaces. When rubbed against a metal file or another piece of explosive, no ignitions were observed. With sand bonded to steel, ignition was enhanced by increasing the normal load or sliding speed, but the biggest factor was the presence of loose grit. They concluded that rubbing an explosive against a rough surface in the absence of grit is generally not effective in causing ignition, since most explosives have relatively low melting points, and instead that ignition most readily occurred at hot spots produced by grit on grit or grit on higher-melting-point substrate interactions.

This is a very significant conclusion, implying that it is not frictional processes directly involving the explosive that may be expected to lead to ignition, but frictional interactions between other materials with much higher melting points that are able to produce critical hot spots. In previous accidents in which friction has been implicated as a mechanism, the most likely candidates are sand or grit particles embedded (on impact) in the explosive being dragged across a hard surface (the floor) during an oblique impact.

In much of the previous work using oblique impact tests, the presence of loose grit has been a poorly controlled parameter, and we conclude that this is likely to account for the large variation in results.

Experiment

The drop and skid test target plates were altered to permit direct observation of hot spots; the new target plate comprises a 2 ft x 2 ft laminated glass plate 3 inches thick, held in a welded steel frame. Force transducers were installed between the target plate and the frame to measure the dynamic normal and parallel forces (relative to the target plane) during the impacts. Figures 2 and 3 show schematic views of the two tests. The glass target represents a high-melting-point surface, but from the previous arguments, we do not expect the interaction between the explosive and the glass to yield hot spots.

To demonstrate the effect of the addition of grit particles, tests were performed with the glass target surface either clean or prepared with a light coating of sand, loosely bonded using a very fine coating of spray adhesive.

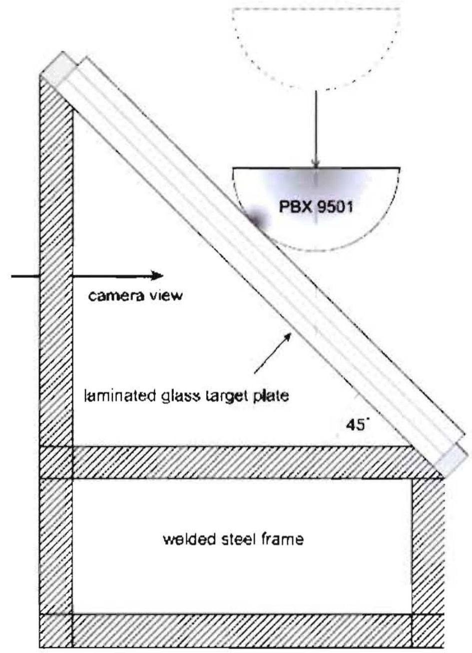

Figure 2. Schematic view of revised drop test.

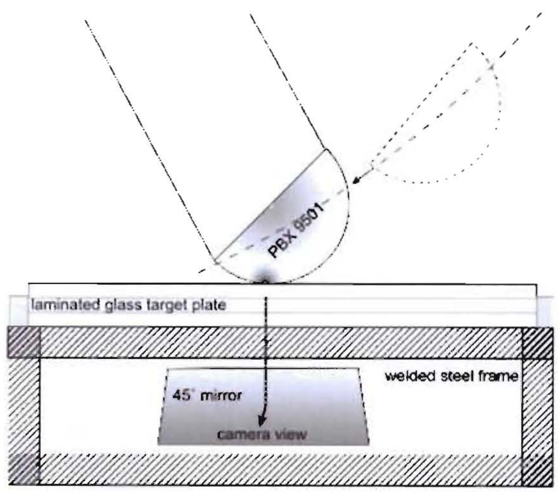

Figure 3. Schematic view of revised skid test.

To investigate the effect of grit without a high-melting point substrate to interact with, similar tests were performed with the glass target plate covered with a thin sheet of polycarbonate (in this context, a low-melting-point solid). High-speed photography was used to observed the impact of the charges through the glass plate, allowing observation of hot spots that would be not be detectable in the conventional test arrangement. IR imaging was considered, but not used in these test series due to the opacity of glass and polycarbonate to the IR frequencies of interest.

Drops were conducted at 3 ft, 6 ft and 12 ft in both the vertical drop and 45° skid test formats – heights that would not be expected to produce positive results by the conventional test methodology. High-speed photography was performed using Vision Research Phantom video cameras running at 10,000 fps.

Results

Clean Glass

Several vertical drop tests were conducted from 12 ft onto clean glass. No hot spots were observed. At this height, charge break up occurred in some cases due to mechanical damage at impact.

Sanded glass: 3 ft vertical drop test

With a light coating of sand on the glass target, hot spots were observed within 100 μs of impact in a 3 ft vertical drop test. Figure 4 shows hot spots and the beginning of flame propagation into a crack that is formed at impact. The reaction quenched within 300 μs (well before bounce occurred) when the crack travelled far enough to intersect the free surface of the charge away from the reaction zone. In the movie of the event, venting is visible from this crack.

Post-shot examination of the charge (figure 5) shows the limited extent of the reaction, and the crack into which the flame initially propagated and then later vented. Sand particles are clearly visible embedded in the explosive.

Sanded glass: 6 ft vertical drop test

Increasing the vertical drop test height to 6 ft leads to more hot spots and more extensive propagation before quenching occurs by the same cracking mechanism. Figure 6 shows the development of reaction from hot spots around 200 μs after impact, with the onset of cracking and propagation of combustion into a crack.

In the 6 ft drop, cracks typically form both horizontally and vertically (relative to the charge orientation at impact), and quenching occurs via venting through both these cracks. In figure 7 venting is visible through the vertical crack at around 600 μs after impact. The charge has not yet bounced.

Figure 4. Hot spots and reaction spread 200 μs after impact onto sanded glass from 3 ft.

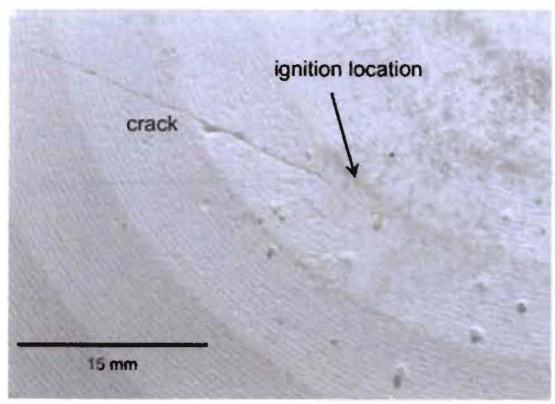

Figure 5. Detailed view of ignition site showing embedded grit and cracking.

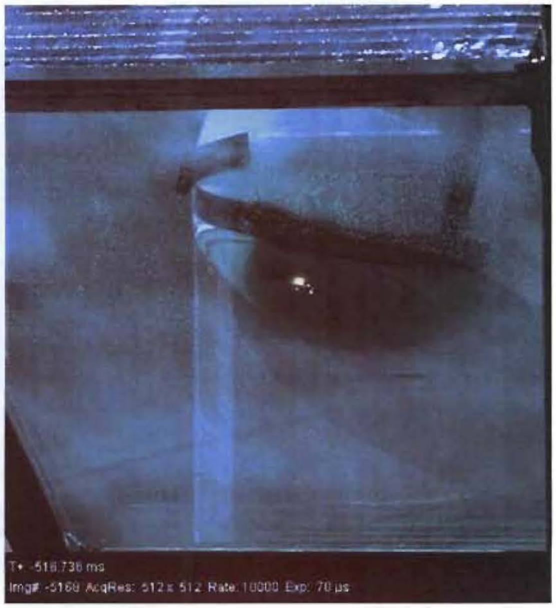

Figure 6. Hot spots and reaction spread 200 μs after impact onto sanded glass from 6 ft.

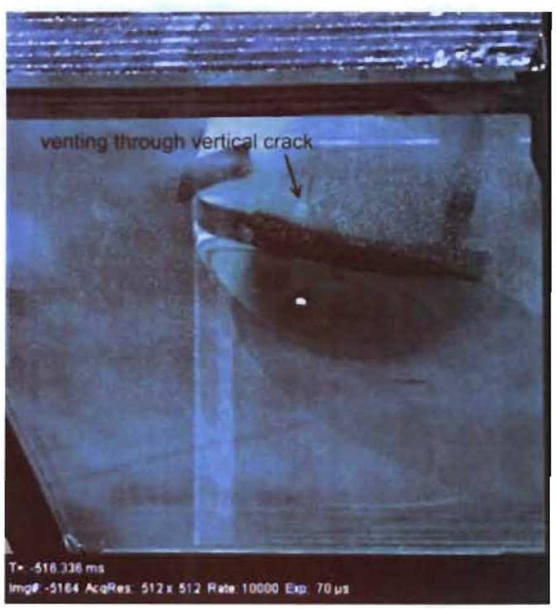

Figure 7. Venting through a vertical crack around 600 μs after impact.

Sanded glass: 12 ft vertical drop test

At 12 ft, numerous hot spots are visible, and there is significant reaction propagation into the horizontal crack network (figure 9). As with the lower drops onto this surface, hot spot formation occurs promptly within 100 μs of impact. Ultimately the reaction quenches, with venting from both horizontal and vertical cracks. This test was accompanied by an audible pop, and one piece of the fragmented charge was propelled some distance by the confined products. However, post-shot examination again revealed only trace evidence of reaction. Figure 8 shows the reassembled pieces and a close up view of the impact area. The horizontal and vertical cracks through which flame propagation are clearly visible.

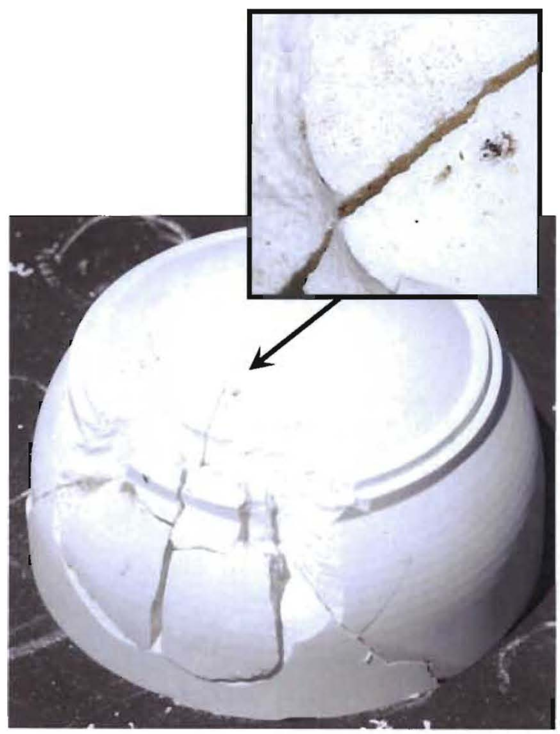

Figure 8. View of impact and ignition site after 12 ft drop.

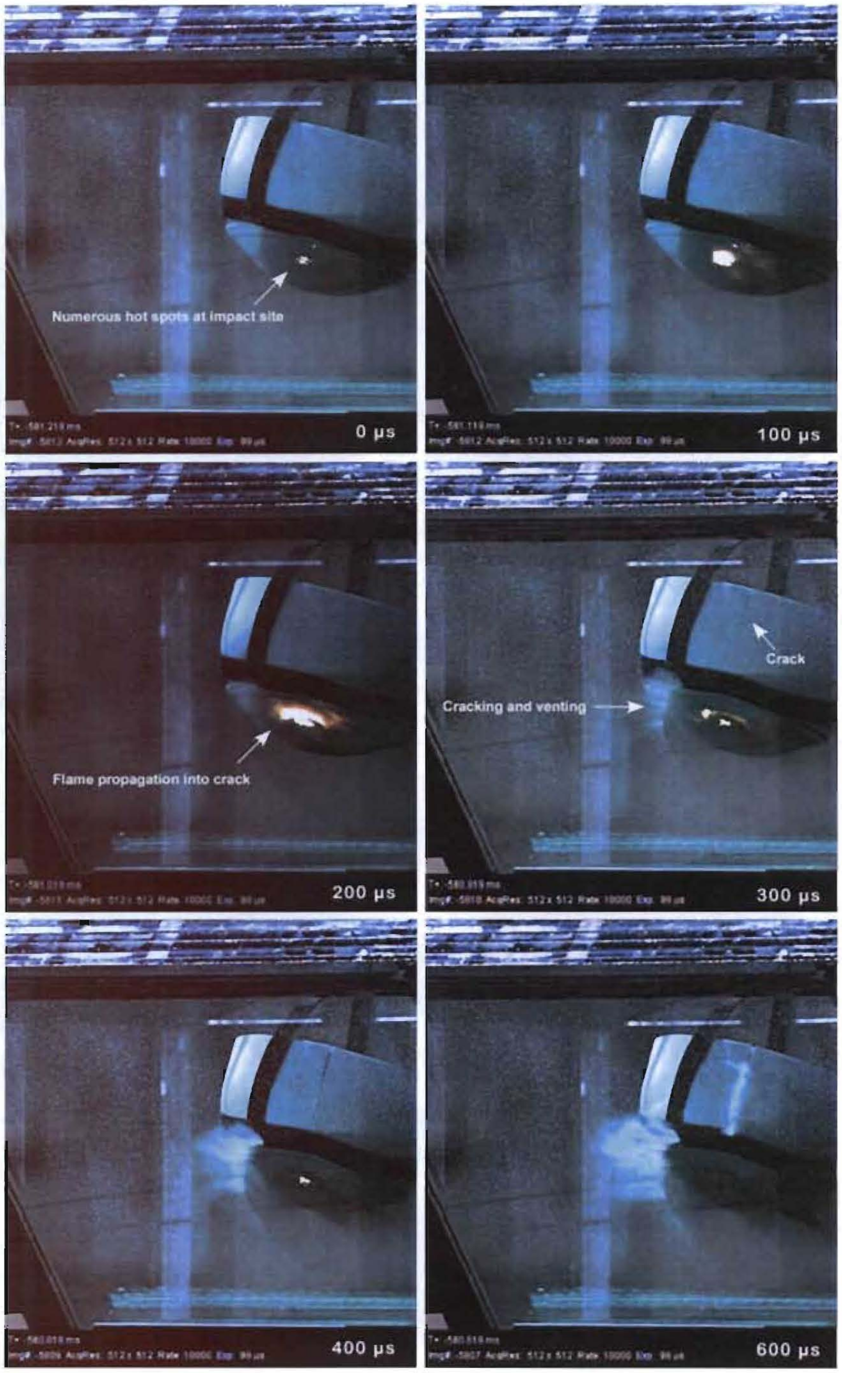

Figure 9. High-speed images of ignition and propagation of reaction following a 12 ft vertical drop test.

Sanded glass: 12 ft skid test

The 12 ft drop with sand was repeated three times in the skid test, giving equal or greater extent of reaction. In one test the reaction fragmented the charge and lead to a fireball that appears to comprise a small dust explosion. Figure 10 shows the evolution of the event, and even though the impact is off-center, the view from below shows how the flame propagates into a roughly horizontal crack and then pressurizes and fragments the charge. As in the case of the 12 ft drop, cracking and fragmentation of the charge lead to depressurization and even though the reaction looks impressive, only a small mass of explosive is involved.

Sanded polycarbonate: 12 ft drop test

Six drops tests were conducted onto sanded polycarbonate. No hot spots were observed in five of the tests. In the sixth test, which was heavily sanded, one hot spot was observed, approximately 700 µs after impact. Level of reaction was less than observed in the 3 ft drop test on sanded glass; the charge did not crack and no propagation was observed. Figure 11 shows the formation of that hot spot; the dark region surrounding it is the contact area.

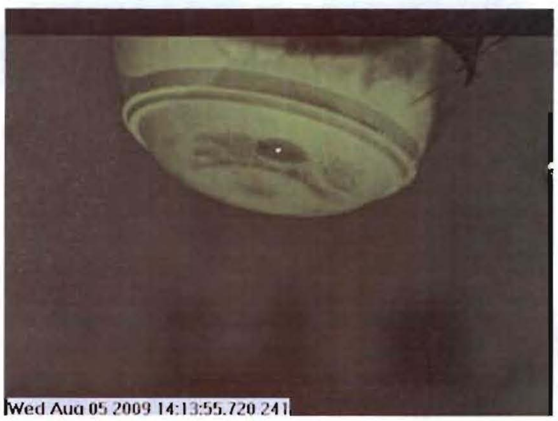

Figure 11. Hot-spot formation: 12 ft drop onto sanded polycarbonate.

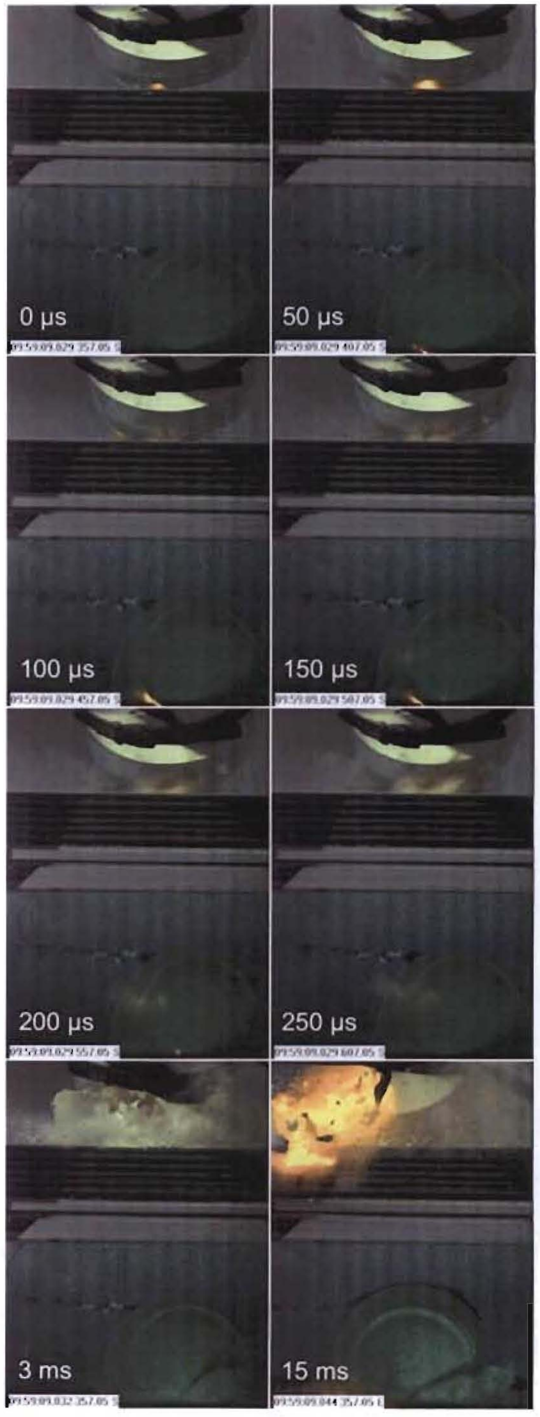

Figure 10. Ignition and propagation of reaction in a 45° skid test impact on sanded glass.

Comparison of the hot-spot location with high-resolution images of the target before impact indicated the presence of an agglomeration of sand particles at or near that location.

Sanded polycarbonate: 12 ft skid test

Three skid tests were conducted from 12 ft onto sanded polycarbonate. No hot spots were observed.

Discussion and conclusions

These tests provide convincing support for the established theories on frictional ignition. The drop tests on clean glass show no sign of any hot spots at the maximum height tested. This is to be expected since the temperatures achieved during the frictional interaction between glass and the HMX in PBX 9501 should be limited to the melting point of HMX, which at around 250°C is too low for reaction to occur on the timescale of the impact.

The introduction of sand, even at the lowest height tested (3 ft), results in visible hot spots, indicating that temperatures of at least 500 – 600 °C have been achieved. Given the high melting points of sand (> 1100 °C) and glass (> 550 °C), it is not surprising that sand particles embedded in the PBX at impact and then dragged across the glass might get hot enough.

In the presence of sand particles, increasing the drop height increases the number of hot spots and the extent of reaction. The duration of the impact seems somewhat independent of drop height for this particular experimental configuration, and so we postulate that the increased extent of reaction is related to three factors:

1. A larger number of hot spots, due to an increased contact area with increasing drop height.
2. Higher-temperature hot spots, due to increased sliding velocity with increasing drop height.
3. Faster crack formation at higher drop heights.

However, it is interesting to note that cracks formed at impact act both as the mechanism to allow deflagration to penetrate into the bulk of the charge, after which the charge itself may provide the inertial confinement necessary for transition to violent reaction, and as the mechanism for venting once they reach a free surface. Thus, the outcome results from a competition between two processes controlled, at least in part, by the same parameter.

The lack of hot spots, after the introduction of a polycarbonate sheet over the glass target, illustrates the essential role of the glass in the hot spot formation process, and confirms that it is interaction between the sand particles and the glass, not between the sand and PBX, that is the source of the high temperatures.

Acknowledgements

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