DIRECT OBSERVATION OF COOK-OFF EVENTS USING A NOVEL GLASS-WINDOWED VEHICLE AND PIPE BOMBS

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Experiments were performed to examine the cook-off responses of two secondary explosive formulations, RDX/TNT 60:40 and RDX/HTPB 85:15, studied at different heating rates. The experiments were performed using two types of test vehicle, one a closed pipe-bomb sealed by screw-on end-caps, and the other a novel vehicle incorporating a thick glass window through which the filling could be observed. The pipe bomb experiments were further subdivided into two categories: heat was either applied to the entire surface of the vehicle, or to only a portion of the vehicle. Thermocouples were used to record the external temperature, and the temperature within the filling. In all experiments RDX/TNT 60:40 gave responses that were more violent than those displayed by RDX/HTPB 85:15. In one partially heated pipe bomb experiment there is strong evidence that a detonation occurred. The tests on RDX/TNT 60:40 using the glass-windowed vehicles showed melting and bubbling in the explosive just prior to ignition. These results are discussed.

INTRODUCTION

In order to understand the Cook-Off behaviour of energetic materials charge-scale tests have been developed to examine the response of explosive compositions to both fast and slow heating rates[1]. In the UK, a mild steel pipe 300mm in length, with an internal diameter of 31mm and a 6mm wall thickness, is used as a test vehicle. At typical explosive densities this vehicle has a capacity of approximately 350g. Strong screw-on end-caps are used to close the vessel and provide sealing against internal pressure. The vehicle has been designed to fail in the centre of the tube rather than at the end-caps. In the early days of Cook-Off test development, such tubes were placed on a tray over a small liquid fuel fire. This test became known as the ‘Mini Fuel Fire’, and the tubes were referred to as ‘Burning Tubes’ (see Figure 1). However, in a typical run of ten tests variable results were often obtained. For example, anomalies have been observed in Cook-Off experiments on RDX/TNT 60:40; in the mini fuel fire tests eight out of ten stores give mild pressure bursts while two detonated. Similar variable results have been found in all-up weapon trials. To date these results are not properly understood, yet it is vital to try to understand the reason for this variability. More recently, an electrical heating method has been developed. This has given increased control over the heating rate, and also how and where the tube is heated. These factors can play a crucial role in the outcome of the test.

Current knowledge suggests that, in most cases, when a weapon is heated a point is reached when a thermal explosion occurs. This thermal explosion usually occurs near the outer edge of the energetic material for all but the smallest weapons. This is often the case even for Slow Cook-Off where the heating rate can be as low as 3.3°C/hr. There is a fundamental need to identify the location and nature of the reactions leading to a thermal explosion in order to get a better understanding of the Cook-Off process as a whole. The objective of the work reported in this paper is to help achieve this goal.

EXPERIMENTAL

Three types of experiment were performed on two types of formulations, RDX/TNT 60:40 a conventional melt-cast material, and a cast PBX consisting of 85% RDX and 15% HTPB.

A total of 32 firings were performed to cover the combinations of experiment type, heating rate and filling composition. The sixteen firings performed for each of the two test compositions were subdivided into groups depending on the experiment type: six firings were carried out using a fully heated Burning Tube, six using a glass windowed vehicle, and four using a partially heated Burning Tube.

For the fully heated and glass windowed vehicles, three different heating rates of $20^{o}Cmin^{-1}$, $8^{o}Cmin^{-1}$ and $3^{o}Cmin^{-1}$ were chosen. The partially heated tubes were heated at $20^{o}Cmin^{-1}$ and $3^{o}Cmin^{-1}$. Two firings were performed at each heating rate for the same test vehicle and composition configuration. The heating rates quoted were controlled using the temperature reading on the thermocouple farthest from the axis of the tube, just inside the tube wall.

The vehicles were heated using a nickel-chrome tape of $\sim 4\Omega m^{-1}$ resistance connected to the 240V AC mains supply through a manually controlled variable transformer. This transformer allowed the applied voltage, hence the applied current and heating effect, to be adjusted. For the fully heated tubes a total length of 3m of heating tape was used; the partially heated and glass windowed vehicles required a shorter length of heating tape. It was necessary to exercise caution when controlling the applied current to avoid melting the heating tape. Connection to the mains supply was made using a ceramic connector block of suitable current rating.

Since bare nickel-chrome tape was used, it was necessary to prepare the heated surfaces of the vehicles to prevent short circuits. The vehicles were cleaned and de-greased and then coated with a heat-resistant paint. Once this had dried, a layer of glass-fibre tape was wound over the surface of the vehicle, followed by a layer of self-adhesive Mylar tape that completed the electrical insulation. Figure 1 shows an example of a prepared vehicle.

The PBX (RDX/HTPB 85:15) was cast under vacuum to eliminate void formation, while the RDX/TNT 60:40 was cast using the conventional method. In each case the vehicles were over-filled and machined flat to minimise ullage. Other workers have shown that the presence of voids in the filling can have a dramatic effect on the time to explosion and its violence[2,3].

After filling and final assembly the vehicles were taken to the firing facility. Prior to heating, the ambient air temperature in the firing cell was recorded.

FIGURE 1: PREPARED BURNING TUBE

In the case of the small glass-windowed vehicles, a mirror was placed at 45° to normal over the top centre of the charge in order that a close up video record could be made of each firing. An electric fan was used to remove smoke from burning material, that might obscure the view of the vehicle.

EXPERIMENTAL VARIATIONS

In the first set of firings a conventional Burning Tube was heated electrically over its entire cylindrical surface. Six thermocouples were inserted into the vehicle through one of the end-caps, and were silver soldered in place to provide sealing against internal pressure. The thermocouples were positioned at different distances from the central axis of the tube, and were arranged in a spiral pattern to maximise the distance between each probe. The active ends of the probes were positioned at the centre of the tube. A seventh thermocouple was placed on the outside of the vehicle to monitor surface temperature. A sketch of the vehicle is shown in Figure 2.

A second set of firings were carried out using the same vehicle design, but in this instance only half the tube length was wrapped in heating tape. Again six thermocouples were silver soldered through one end-cap, but in these experiments three probes were positioned with their tips at the centre of the heated portion of the tube, and the other three with their tips in the unheated portion of the tube. Two further thermocouples were placed on the surface of the vehicle to monitor the temperature at the heated and non-heated zones of the vehicle. A sketch of this type of experiment is shown in Figure 3.

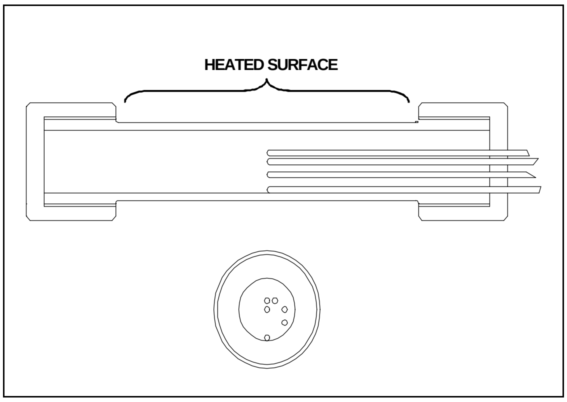

FIGURE 2: SKETCH OF FULLY HEATED BURNING TUBE SHOWING THERMOCOUPLE ARRANGEMENT

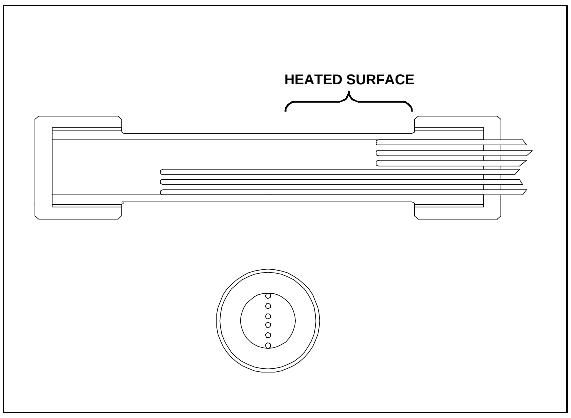

FIGURE 3: SKETCH OF PARTIALLY HEATED BURNING TUBE SHOWING THERMOCOUPLE ARRANGEMENT

In the third set of experiments a new type of test vehicle was used. This consisted of a section of steel tube of 3.5mm wall thickness containing the filling. A 19mm thick glass window was placed on top, and the assembly was clamped between two flat steel plates of 10mm thickness.

The end plates were clamped together with four tie bars to complete the confinement of the test sample. The upper plate was drilled with a large diameter hole through which the glass window and filling were visible. The steel tube section containing the test sample was 41mm in diameter and 55mm long, and had a capacity of approximately 100g of filling at typical explosive densities. Figure 4 shows a sketch of the vehicle configuration, whilst Figure 5 shows a photograph of a fully assembled vehicle ready to fire. This work was inspired by previous workers who have demonstrated the value of direct visual observation of cook-off experiments[4].

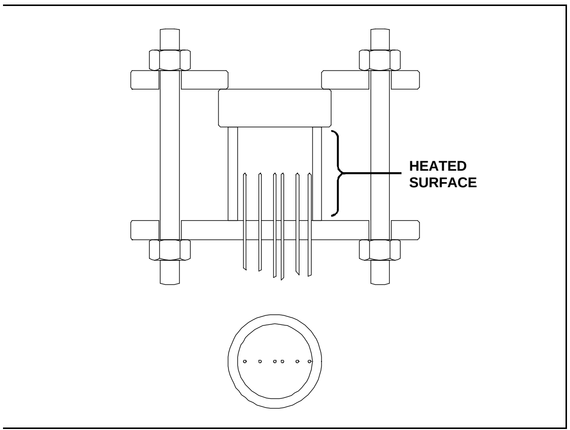

FIGURE 4: SKETCH OF NOVEL GLASS-WINDOWED VEHICLE

FIGURE 5: PHOTOGRAPH OF GLASS-WINDOWED VEHICLE

Six thermocouples were fitted to the lower plate to record the temperature profile within the filling during the experiment. The thermocouples were soldered in place at different distances from the central axis, and were inserted so that their tips were positioned halfway along the tube. A grid of coloured lines was marked on the surface of the explosive, to emphasise any movement of the upper layer during heating. It should be noted that in none of the experiments were the vehicles lagged.

INSTRUMENTATION

The temperatures were recorded using 'K' type mineral insulated thermocouples connected in parallel to two types of data logging devices. In the case of the Burning Tube experiments the thermocouples were commercially available 3mm diameter, 500mm long devices. In the glass windowed vehicle experiments, the thermocouples were of 1.5mm diameter. The fully heated and glass-windowed vehicles were additionally instrumented with a single welded-tip thermocouple on the outside surface of the tube; the partially heated vehicles had a further two welded tip thermocouples on the outer surface.

The main data-logging device used was a Nicolet Odyssey transient recorder sampling at 10Hz; this was the prime method of recording the time-temperature profile for the experiment. A second data logging device was attached to a lap top PC, and was used to monitor the heating rate at the explosive/vehicle inner interface and to provide backup data capture. The secondary device sampled at 1Hz. Stills photographs were taken using both film and digital stills cameras.

In addition, individual video frames have been captured and used as illustrations. The video camera resolution was standard 625-line PAL format, so that each pixel of the image of the glass-windowed vehicles covered approximately 0.25 sq. mm.

RESULTS OF RDX/TNT 60:40 FILLED CONVENTIONAL BURNING TUBES

All experiments carried out on RDX/TNT 60:40 charges gave very violent events compared with the PBX (RDX/HTPB 85:15) charges. Typically the events (thermal explosions) took the form of pressure bursts. The cylinders were usually split into three, but sometimes into many more pieces, indicating a relatively rapid and violent pressurisation of the vehicle. In each case the vehicle failed in the centre of the tubular section, most often on the uppermost part of the tube. In one experiment the vehicle suffered considerable damage and was broken into approximately 40 small and medium-sized fragments.

In four of the six tests beads of RDX/TNT were found in the test arena, indicating ejection of molten material from the vehicles. In those experiments where the temperature profiles indicates solid material in the vehicle at the point of ignition, solid material was often recovered in the test arena. This material showed signs of local melting, but otherwise appeared to be in good condition. Figure 6 shows an example of recovered RDX/TNT material.

FIGURE 6: RDX/TNT RESIDUE

In four of the six experiments, the temperature-time plots showed anomalies in the temperature profiles. These took the form of a rapid and simulatenous reduction in the measured temperature on all six thermocouples in the experiment. These were labelled 'endotherms'. In each case the endotherm occurred as the core temperature of the vehicles reached 85-90ºC. The endotherms were only observed on slow and medium heating rate experiments. In one experiment two endotherms were observed, the second occurring as the core temperature probe recorded 120^{o}C. The cause of the endotherms is unclear, but may possibly be due to mass melting of the filling, manifested on the temperature probes as absorption of latent heat. A second possibility may be that the seals on the vehicle failed, resulting in a fall in pressure and an associated drop in temperature. Further tests with additional instrumentation are required to understand this process.

RESULTS OF RDX/HTPB FILLED CONVENTIONAL BURNING TUBES

All six experiments with the PBX (RDX/HTPB 85:15) filled charges gave relatively mild events, regardless of heating rate. The tubes all failed at the very centre portion and always on the upper face. In five of the experiments, the tube split along the axis producing an opening through which the enclosed gas and filling were ejected. In the sixth experiment, a small section of the tube became separated at the site of the ignition. This was the only instance of fragmentation in any of the six experiments.

In three of the six experiments, the contents of the vehicle burnt away completely in the minutes following the explosion. The residue from the burning was in the form of a low-density porous black ash. In the remaining three experiments, substantial proportions of the original filling were recovered from the test arena. These observations indicate that only a small amount of the filling took part in the reaction that caused failure of the vehicle.

One point of interest was that the explosive residue recovered showed marked discolouration in areas where it had been in contact with the hot inner surface of the test vehicle tube. Figure 7 shows an example of the material recovered from these experiments. This phenomenon was also noted where the explosive had been in contact with the thermocouples. By contrast, the appearance of the freshly broken surfaces of the material was pristine.

FIGURE 7: RDX/HTPB RESIDUE

The temperature/time plots showed no evidence of the endotherm anomalies that were seen in the RDX/TNT experiments. Of the six experiments, two showed an unusually low ignition temperature, these occurring in the fast heating rate tests. There is evidence from the temperature recordings that an external fire occurred, resulting from the ignition of the electrical insulation on the tube. This undoubtedly led to localised and intense heating of the vehicle.

In one of the slow heating experiments there is clear evidence of thermal runaway in the period just prior to ignition. This was the only instance of thermal runaway observed in any of the experiments.

RESULTS OF HALF-HEATED BURNING TUBE EXPERIMENTS WITH RDX/TNT

Of the four experiments with RDX/TNT in a partially heated vehicle, three resulted in a violent pressure burst centred within the heated portion of the tube. In these three experiments, the non-heated end of the tube showed less damage than the heated end, indicating a localised reaction of the filling. The fourth experiment in this set showed an interesting and very violent response. In this case the vehicle was completely destroyed, and more than 100 small fragments of casing were recovered. Figure 8 shows the recovered fragments of the vehicle.

It was interesting to note that the unheated end of the vehicle contributed most of the small fragments, whilst the damage to the heated end was similar in extent to that observed in the other three experiments.

FIGURE 8: VEHICLE REMAINS FROM PARTIALLY-HEATED RDX/TNT EXPERIMENT

In all four experiments there was evidence of beads of filling in the test arena, indicating ejection of molten material from the tube. The quantity of solid material recovered from the experiments was very small, even in those experiments whose temperature/time recordings indicate that a considerable proportion of the filling was solid at the point of ignition.

In two of the four experiments, endotherms similar to those observed in the fully heated tests were observed. Again these were only observed in the slow heating rate tests. Figure 9 shows the temperature history plot for the slow heating test on RDX/TNT. An ‘endotherm’ is clearly visible at 3200s.

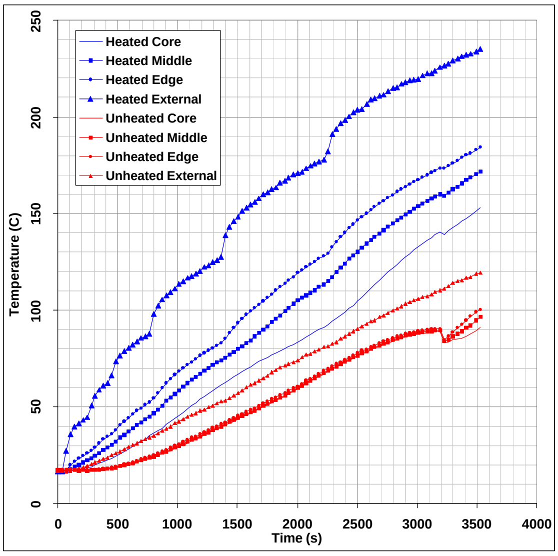

FIGURE 9: TEMPERATURE HISTORY OF PARTIALLY HEATED RDX/TNT EXPERIMENT

RESULTS OF PARTIALLY HEATED BURNING TUBE EXPERIMENTS WITH RDX/HTPB

The PBX (RDX/HTPB 85:15) gave relatively mild pressure bursts, again on the upper surface at the centre of the heated zone. In each experiment the vehicle split open with a crack aligned with the tube axis. The entire vehicle remained in one piece.

In all four experiments the material inside the vehicle burned in the period immediately following the event. In three of the experiments a significant proportion of the filling, in addition to that which had burned, was ejected from the vehicle and was recovered. The material inside the vehicle that had undergone burning remained in the form of a porous black ash. It is likely that this ash results from the binder component of the filling.

OBSERVATIONS FROM RDX/TNT FILLED GLASS-WINDOWED VEHICLES

In all but one firing of the melt cast RDX/TNT 60:40 filled vehicles the glass window was shattered, the steel cylinder was broken into several pieces, and the end plates and tie bars were deformed. Figure 10 shows the extent of damage typical of this type of reaction. In the remaining experiment the glass window was broken and the filling burned in the open vehicle.

FIGURE 10: TYPICAL REMAINS FROM RDX/TNT EXPERIMENT

In the two fast heating rate experiments, approximately 40% of the filling was recovered after the event. This was in the form of relatively large pieces of material whose outer surface was melted, but whose freshly broken surfaces showed little evidence of degradation. Figure 11 shows an example of the material recovered from these experiments.

It should be noted that in both these experiments the ignition temperature was unexpectedly low: the outer thermocouples registered a temperature of approximately 100°C in each case. Furthermore, in both these experiments the electrical insulation was seen to ignite and burn for a short period just prior to ignition, so that locally the temperature experienced by the filling could have been much higher than that recorded on the thermocouples.

FIGURE 11: RDX/TNT RECOVERED FROM GLASS-WINDOWED EXPERIMENT

Observations through the glass window showed a darkening of the sample surface as the heating progressed. This started at the edge and worked evenly towards the centre. The colour change was coincident with the temperature achieving 88ºC, and appears to be due to melting of the TNT component of the explosive. Once the whole surface area had darkened, and just prior to the explosion, some of the liquid component of the filling leaked from the vehicle and ignited. Bubbling was seen just under the glass in the liquid phase. The bubbling was indicative of an imminent explosive event.

OBSERVATIONS FROM RDX/HTPB FILLED GLASS-WINDOWED VEHICLES

At the point of ignition in the experiments with RDX/HTPB 85:15, three of the six firings resulted in an explosion while the remainder showed burning of the filling within the vehicle. The explosions typically resulted in destruction of the glass window along with the viewing mirror sited directly above it. The steel components of the vehicle remained largely intact. There was only slight deformation of the tube body and the end plates.

In the two slow heating rate experiments, both of which displayed a small thermal explosion, almost all of the filling was recovered after the test. Examination of the filling showed that there was discolouration of the surfaces that had been in contact with the heated vehicle, while freshly broken surfaces appeared pristine. The third vehicle, which displayed an explosion, ignited and the contents burned away. In the remaining three experiments, which displayed an ignition and slow burning reaction, the contents of the vehicle burned away completely and were not recovered.

Three of the firings resulted in concentric burnings from the outer edges of the explosive inwards. In these firings the material ignited at ~160^{o}C, began to burn inwards, and then quenched. The material re-ignited and quenched in a repeating process of increasing frequency, until the filling had been completely consumed. Figure 12 shows the burning reaction in the filling, and Figure 13, taken a few seconds later, shows that the reaction has quenched. In Figure 13, the grid marked on the surface of the unburned explosive is visible. Figure 14 shows the contents of the recovered vehicle.

Another feature of the majority of RDX/HTPB 85:15 firings was that at 120ºC there was evidence of explosive oozing out under the glass window at the interface with the steel cylinder top. This material would sometimes catch light, and then extinguish after a short time. No discolouration of the surface of the filling was observed.

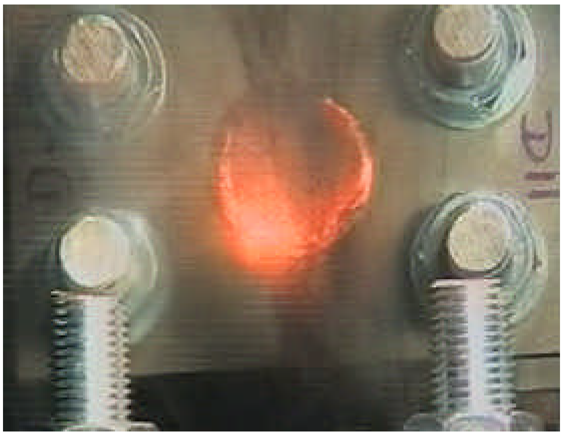

FIGURE 12: VIDEO FRAME SHOWING BURNING IN RDX/HTPB 85:15

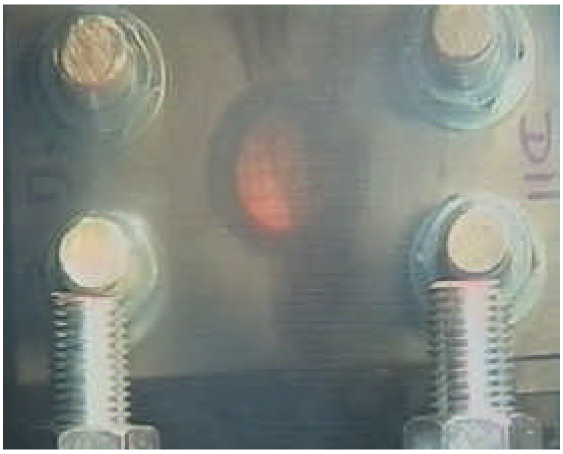

FIGURE 13: VIDEO FRAME TAKEN APPROX 5s AFTER FIGURE 12

FIGURE 14: RESIDUE FROM 'CIGAR BURN' OF RDX/HTPB 85:15 IN GLASS-WINDOWED VEHICLE

DISCUSSION

The experimental results reported here give a comprehensive insight into the Cook-Off behaviour of two different classes of secondary explosives when heated.

All the RDX/TNT experiments which, at the point of ignition, were known to contain solid material, show low-order reactions. However, it should be noted that these were all more violent than any of those observed with the RDX/HTPB composition. The only high-order reactions observed were in those experiments where the thermocouple recordings indicated that the filling was largely molten.

Of those glass-windowed vehicle tests on RDX/TNT which resulted in explosions, the explosions were immediately preceded by bubbling in the filling. This is perhaps to be expected because the glass-windowed vehicles were not well sealed, and hence the internal pressure was near atmospheric. All the events in the glass-windowed vehicles were relatively violent, resulting in fragmentation of the vehicle.

The ‘endotherms’ observed in the Burning Tube experiments with RDX/TNT are most likely associated with melting, probably combined with the failure of the seals on the vehicle as the hydrostatic pressure from the molten contents increased. Sealing failure would lead to a drop in pressure, and hence a simultaneous and rapid drop in temperature across the entire filling. This corresponds to the behaviour observed in the Burning Tube tests.

The two Burning Tube experiments that showed the most violent responses also showed ‘endotherms’ in their temperature records. It is therefore likely that the internal pressure in these experiments at the point of ignition was low, and that under these conditions, bubbling of the filling would be possible. The results therefore appear to indicate that the violent events observed in RDX/TNT correspond with bubbling.

These results seem to support the hypothesis that violent responses result from the increased shock sensitivity of hot, bubbling material. The ramped pressure wave from the thermal explosion is presumed capable of initiating a detonation in the liquid phase under these conditions. From this work it may be suggested that the propensity of RDX/TNT to produce violent responses depends on the strength of the pressure wave produced by the thermal explosion, and the state of the surrounding material. Similar conclusions have been reached by Kondrikov[5].

There were no instances of violent responses in any of the RDX/HTPB experiments. In each case the failure of the vehicle was consistent with a pressure burst. In the partially heated tests, the failure of the vehicle was centred on the heated portion of the vehicle. This indicates that the ignition, although producing a relatively slow pressurisation of the vehicle, proceeds sufficiently quickly to cause localised damage.

The nature of the ash remaining after burning of the RDX/HTPB filling indicates that this is composed of binder material. This is notable when the high flame temperature evident from the melting of the glass window is considered. It would appear, then, that this type of binder may be capable of resisting or reducing the propagation of flames in the early stages of the growth of the reaction.

In all the glass-windowed experiments there is no evidence of large-scale damage to the filling during heating. No visible cracks were observed, although the smallest feature visible was approximately 0.25 mm sq., and therefore features smaller than this may have been missed.

Comparison of the RDX/TNT and RDX/HTPB experiments suggests that the molten phase of the filling is important in its propensity to produce violent responses to cook-off. Most modern PBXs would not be expected to have a molten phase on heating, and this may explain their mild behaviour when heated. However it should be noted that some PBXs having a low volume of binder (less than 10%) are known to respond violently to cook-off. This may be the result of their greater shock sensitivity and/or ease with which they are damaged.

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