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Heavy Fragment Impact Testing of Large General Purpose Bombs Filled with Cast Cured PBX Formulations

Abstract

This paper will provide an overview of work undertaken on charge scale testing in the form of fragment attack on cast cured PBX explosives formulated from RDX, Aluminium and HTPB, and system level fragment attack to investigate susceptibility to Deflagration to Detonation Transition (DDT). A combination of fragments has been used, ranging from the UK's standard 13.15 mm fragment, the NATO IM 14.3 mm conical fragment and 50 g, and 200g threat fragments. Clear differences in the explosiveness of cast cured PBX materials have been observed. DDT has not been induced in the systems tested to date.

Introduction

Cast cured PBX explosives formulated from RDX, Aluminium and HTPB are in widespread use in General Purpose (GP) bombs and penetrator warheads. These explosives exhibit low explosiveness and relatively low shock sensitiveness in charge scale testing, and these properties contribute to very good responses in full scale vulnerability testing. For example STANAG 4496 fragment impact testing (standard velocity) of Paveway IV resulted in a Type V burning reaction. The STANAG 4496 threshold for IM compliance is however, only a snapshot of the vulnerability of a munition, and in real world situations, safety authorities need to understand whether more violent reactions could be induced by the much larger fragments that munitions might encounter. To do this a thorough, quantitative understanding of the mechanisms that can be activated by fragment impact is required.

STANAG 4496 specifies an 18.6 g fragment projected at 2,530 ms^{-1}; this combination is believed to capture the reactions that can be induced by >95% of all real fragments, and exercises the Shock-to Detonation Transition (SDT) mechanism at a high stimulus level. SDT is a function of fragment geometry, case thickness and explosive shock sensitiveness; quantitative read across between the STANAG fragment and other fragment geometries is possible. DDT requires the generation of surface area to support burning and is strongly coupled to the amount of mechanical damage created by the incoming fragment as well as confinement. There is no robust quantitative method for interpolating responses between fragments of different masses, or for extrapolating beyond the experimental data available. DDT is known to occur in large warheads filled with TNT based explosives at impact velocities below the SDT threshold.

The experiments reported here used fragments more massive than that specified in STANAG 4496 to explore whether DDT could be induced in large warheads filled with PBX based RDX/Al/HTPB explosives. In a series of tests funded by DOSG and Naval Authority Explosives, a number of 250 kg, 500 kg and 1000 kg class warheads were subjected to attack by single fragments ranging from 27 g to >200 g at velocities in excess of 2,000 ms^{-1}. The largest available warheads were selected to maximise parameters believed to contribute to the propensity of a system to exhibit DDT, particularly the volume of explosive available for mechanical damage, and the amount of confinement provided by the explosive charge itself and the warhead casing. The results showed that violence of reaction increased with fragment mass. The most violent responses observed so far have been explosions.

These results are immediately useful in two ways: They provide confidence that RDX/Al/HTPB explosives are resistant to DDT when subjected to extremes of mechanical damage, and provide quantitative basis for calculations of maximum credible explosive events in risk assessment. Beyond these, they provide data for validation of computer models that couple mechanical damage with chemical decomposition to predict DDT thresholds in explosives.

Further work is planned, to investigate the effect of single heavy fragments in hard target penetrator warheads, and the effect of multiple heavy fragment attack on a single warhead. It is expected that this work will have some relevance to sympathetic reaction.

Deflagration to Detonation Transition (DDT)

The rate at which an explosive burns is a function of the pressure at the reaction front. If a quantity of explosive is confined within a vessel, such as a large steel cased aircraft bomb, and it is ignited at a single point, gas will be generated by the explosive as it begins to decompose locally. The accumulation of this gas will cause the pressure to rise rapidly unless the case is vented. This causes the explosive to burn faster, and unless vented, most cases will mechanically fail and burst. If the amount of explosive and rate of burning are both sufficient, the rate of burning is likely to suddenly increase to that of a detonation with the remaining explosive consumed. This is phenomenon is known as Deflagration to Detonation Transition (DDT).

Fragment impact of a munition casing, provides both ignition of the explosive contents, and to an extent a vent hole, allowing a release of pressure and reduce the rate of explosive decomposition. If the fragment is large enough, sufficient surface area can be created that causes excess burning and pressure rise until either the case bursts or the explosive transitions to a detonation.

Shock to Detonation Transition (SDT)

Initiation by shock from fragment impact is known to be controlled by both amplitude and duration of the shock seen by the energetic material. These shock parameters are controlled by the velocity of the fragment, its dimensions, geometry, and material characteristics of the fragment and casing surrounding the explosive. A sustained detonation can only be supported if the critical diameter of the explosive is sufficient.

Cast Cured PBX Materials

Traditional RDX/TNT (Composition B) melt cast formulations have been steadily replaced by cast cured explosive formulations such as those similar to the UK's ROWANEX (Royal Ordnance Waltham Abbey New Explosive) 1400, and its analogue – PBXN-109, which both contain, in comparable composition; RDX/Aluminium/HTPB. ROWANEX 1400 and PBXN-109 have very good vulnerability characteristics; low explosiveness and relatively low shock sensitiveness is observed in charge scale testing, and these properties result in low levels of violent reaction in the STANAG 4439 IM testing observed within General Purpose Bombs and Penetrator Warheads, as shown in figure 1.

Figure 1. Burnt out Paveway IV after NATO IM 14.3mm fragment impact.

Energetic Material Vulnerability Characterisation with Charge Scale Testing

The UK qualification process for energetic materials, requires two charge scale vulnerability tests: 'EMTAP[1] test 36 – Fragment Attack Test Procedure', which is designed to determine the prompt SDT threshold velocity of an energetic material, and is important in informing on the likely response of a all up round weapon system to a bullet or fragment impact.

The second test is a set of three tests consisting of 'EMTAP 35 – Internal Ignition' 'EMTAP 41 – Fast Heating' and 'EMTAP 42 – Electrically Heated'. Known colloquially as the "Tube Tests", provide information on the violence and explosiveness properties of an energetic material when heavily confined and subjected to ignition and thermal stimulus.

EMTAP 36 provides the velocity threshold of an energetic material at which prompt SDT occurs, using a standard fragment and combination of barrier materials and thicknesses to develop SDT threshold curves.

The test uses a cylindrical fragment with a diameter of 13.15 mm and is 25.4 mm in length a mass of 27g, and hardened to prevent fracture on impact. The projectile is normally housed in a nylon sabot and typically fired through a RARDEN gun, which is capable of achieving velocities from 400-2,000 ms^{-1}.

Figure 2 shows a typical fragment attack set up and 13.15 mm flat fronted fragment.

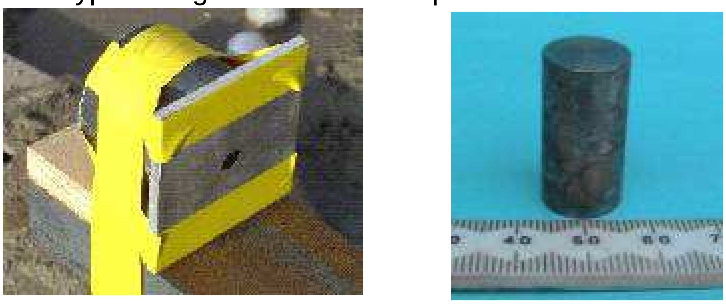

Figure 2. Fragment Attack set up and 13.15mm Fragment

[1] EMTAP Manual of Tests Volume 1 Issue 4, November 2007

This projectile has a flat fronted impact face, as this delivers the highest and therefore most severe form of 1D shock impulse loading into the target material. Previous research has shown the effect of fragment geometry; the more acute the fragment angle, the more divergent and less severe the shockwave is at the target.

Fragment Attack testing undertaken on ROWANEX 1400 (and by read across to PBXN-109) using a 5 mm steel barrier plate, has determined the SDT threshold velocity as 1,732 ms^{-1}. RDX/TNT has an SDT threshold velocity of 1,312 ms^{-1}.

Results from Fragment Attack testing are used by IMAP (Insensitive Munitions Assessment Panel), the UK's national body for assigning IM Signatures. Results from the test can be related to 'real' systems, allowing predictions to be made of the likely response of a weapon system to NATO STANAG 4496 Fragment Impact testing. The Standard or Alternative velocity test selected for IM test purposes is based on the SDT threshold velocity for an energetic material as determined by the Fragment Attack test.

The EMTAP tube tests are designed to test the explosiveness properties of explosives and propellants under a number of plausible hazard conditions; energetic material ignition, and fast and slow heating scenarios. For the purposes of this paper, the fast and slow heating tests will not be discussed any further.

The internal ignition test consists of heavily confining an energetic material in a steel tube, capped off at both ends. The energetic material can be cast directly into the tube, or inserted in the form of pellets to a specified dimension. A small void/ullage space remains at the top of the tube to allow for placement of a small bag of double base propellant, primarily used to ignite the energetic material, but also to introduce a level of mechanical damage. The heavy confinement is deliberately high – far higher than a likely weapon system, so to achieve worst case conditions and reactions accordingly. Ten tests, as a minimum are undertaken and the test is scored by review of the level of damage/fragments produced from the steel tube and any remaining energetic material.

The Internal Ignition test results for ROWANEX 1400 and PBXN-109 are typical of PBX formulations, with consistent demonstration of low explosiveness as shown with pressure bursts of the steel tube with no further reaction of the explosive material. Figure 3, shows example good and poor responses.

Figure 3. Internal Ignition test good and poor responses for cast cured PBX and Comp B.

NATO IM Fragment Impact and Heavy Fragment Impact Testing

STANAG 4496 is the NATO test standard for undertaking a Fragment Impact test of a weapon system. The test specifies the fragment has a conical tip of 160 °, a diameter of 14.3 mm with a mass of 18.6 g is projected at 2,530 ms^{-1}; it is widely believed this combination captures the likely reaction of an all up round system that can be induced by approximately 95% of all real fragments, and exercises the SDT mechanism at a high stimulus level.

The reaction of a munition to the NATO IM fragment is only a snapshot of its vulnerability that is specific to a certain situation, and in real world situations, safety authorities require to understand whether more violent reactions could be induced by the much larger fragments that munitions might encounter. To achieve this a thorough, quantitative understanding of the mechanisms that can be achieved by fragment impact is required.

Within the UK, Naval Authority Group Explosives has developed a Generic Naval Environment (GNE), and has identified a number of threats from fragments that may pose a risk to Royal Navy ships, and any assets that they may be embarked on them.

It has identified fragments more massive than those prescribed in STANAG 4496 as the medium and heavy fragments; weighing approximately 50 g and 200 g with diameters measuring 20 mm and 30 mm respectively. Both fragments have a chisel nose flat fronted profile. Figure 4; show some example NATO and GNE threat fragments.


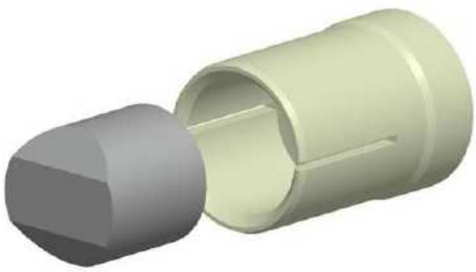

Figure 4. Assortment of 13.15, 14.3, 20, and 30 mm threat fragments.

Charge Scale Testing with the Heavy Fragments

It is known that DDT can occur in warheads, of all sizes, that are filled with TNT based explosives at fragment impact velocities below the SDT threshold. Signs of DDT had never been observed in cast cured PBX formulations when subjected to the 13.15 mm and NATO 14.3 mm fragment tests. It was hypothesised that insufficient mechanical damage leading to a large surface area of burning PBX material was the reason the 13.15 mm and NATO 14.3 mm fragments were not causing DDT.

As high confinement is a prerequisite for DDT, a high confinement vessel was specially designed to study the effect of heavy fragment impact into ROWANEX 1400, and by read across – PBXN-109. A steel cylinder, 150 mm long with an internal diameter of 155mm and wall thickness of 48mm was constructed. A rear plate 25.4 mm thick is held in place with M12 bolts which also secure the front barrier (septum) plate. An additional 25.4 mm front and rear plate are also attached with M12 bolts.

The outer front plate has a central 50 mm diameter hole to allow the fragment to pass through.

Figure 5. High confinement vessel, a detonation and suspected partial detonation.

Fragment attack, using the 13.15 mm flat fronted projectile on heavily confined cast cured PBX materials were unable to produce violent reactions below the SDT threshold, and resulted in burning reactions.

Work then focused on undertaking fragment impact of heavily confined PBX materials using the 30 mm 200 g fragment, in an attempt to investigate the violence of response to see if DDT could be induced. The results of the firings show that a 25 mm steel barrier is required to prevent SDT at projectile velocities up to approximately 2200 ms^{-1}. At an impact velocity of 2,113 ms^{-1} an extremely violent reaction was recorded, it was suggested that a partial detonation may have occurred with ROWANEX 1400 but the actual evidence available was inconclusive. Figure 5 shows the high confinement vessel used along with a detonative response and the suspected partial detonation.

This response of cast cured PBX materials when heavily confined and subjected to heavy fragment attack has lead to a larger programme of work to understand the response of ROWANEX 1400 and PBXN-109 filled General Purpose Bombs to heavy fragment attack.

Gun Launch System

The UK employs a specially designed 40 mm, 10 m long powder gun system to launch the medium and heavy fragments, at velocities in excess of 2,200 ms^{-1} shown in figure 6. The fragments are carried in parasitic sabots, designed to be released upon immediate exit from the muzzle, and are captured via a sabot stripper plate. To achieve the high impact velocities, a smooth bore barrel is utilised, which reduces the effect of drag on the fragments acceleration.

Figure 6. 10 m long 40 mm smooth bore gun

Experimental Findings of Heavy Fragment Impact of ROWANEX 1400 and PBXN-109 Filled General Purpose Bombs

Phase 1 – ROWANEX 1400 250 kg and 500 kg General Purpose Bombs

The results of charge scale tests gave sufficient cause to undertake a number of all up round tests to investigate the propensity of three ROWANEX 1400 filled General Purpose bombs, to undergo DDT, when impacted by the 30 mm 200 g fragment.

This programme consisted of firing the 200 g fragment against two 250 kg bombs and one 500 kg bomb. These bombs were specially commissioned for this trial and had the internal rubber liner removed to ensure that any shock attenuation was reduced, to make the test more severe.

The firing velocities for each fragment for each bomb had to be carefully selected, as the objective of the trial was to subject the bombs to a high velocity and severe mechanical insult, but without the intention to cause a prompt SDT. It was predicted that extreme damage to the energetic material, would lead to extremely fast burning rates and extremely fast rises in pressure that would lead to a DDT reaction, or at least a very violent reaction as previously observed in the small scale tests.

A short modelling study was undertaken to determine the maximum achievable firing velocity that remained below the SDT threshold – using a DYNA 2D hydrocode with the Cook-Haskins Arrhenius Reaction (CHARM) Model. Data generated from 13.15 mm fragment attack test results were used to modify the model fit by adjusting the hot spot parameters, and in conjunction with knowledge of the 250 kg and 500 kg bomb casing thicknesses, SDT threshold values were calculated for the three bombs. The planned impact velocities for each bomb were 100 ms^{-1} below the actual SDT threshold value, and the aim point for all shots was the centroid of explosive.

The results for the first firing revealed the explosive underwent a violent but non-detonative reaction at an impact velocity of 1590 ms^{-1}. Pressure recordings were below that of a detonation output with high speed video evidence also confirming this. At fragment impact, ignition was observed 50 μs after impact with burning debris ejected from the impact site. Severe damage at the point of impact was observed with casing material from this area shredded into large pieces approximately 13x25 cm. The nose and base were found completely intact, though separate with large pieces of explosive material from the base region also recovered. This reaction, which was at most, an explosion, was below the SDT threshold. Figure 7, shows some recovered remains of the 250 kg GP Bomb casing.

Figure 7. Violent mechanical break up and burnt out remains of 250 kg GP Bombs.

Due to the reaction of the first 250 kg bomb, the fragment impact velocity was increased for the second 250 kg bomb to see if a more violent reaction could be induced. High speed video evidence shows ignition on impact at 1,669 ms^{-1}, leading to a fireball, fuelled by damage material being projected from the impact site. Approximately two-thirds of the of the nose end of the bomb were found in one piece, though a large tear was present in the steel wall. The steel base ring had dug itself firmly into the ground, while the actual base was thrown in the opposite direction to the nose. Little casing material could be recovered from the site of fragment impact and was presumed to have been broken into smaller pieces.

The casing of the 500 kg was thicker and therefore required much higher muzzle velocity for the impact velocity to be close to but below the SDT threshold value. The actual firing velocity was only 1,860 ms^{-1}, significantly below the target velocity. At this impact velocity, evidence of ignition on impact was seen in the high speed video footage, with an initial cloud of burning material, which was then followed by a dust cloud of unburnt energetic material. A large impact hole could be observed in the casing of the bomb, where a quiet burn with a yellow/orange flame could be seen for approximately 90 seconds before it developed into a brilliant, violent torching flame that had a length of approximately 1m, and lasted until the explosive filling had been consumed, gradually reducing in intensity. Figure 8 shows the burnt out casing of the 500 kg GP bomb.

Figure 8. Burnt out 500 kg bomb.

<u>Phase 2 – PBXN-109 Filled 1000 kg (BLU-109) General Purpose Bombs</u>

Inconclusive results from the 250 kg and 500 kg bombs meant uncertainties still remained over the possibility of a heavily confined cast cured PBX developing into a DDT reaction after being impacted by a medium or heavy fragment.

The BLU-109 containing PBXN-109 is the largest item of explosive ordnance within UK service, and had parameters that made it an ideal target to see if DDT could be induced into large mass of explosive – a high volume (approximately 200 kg) of cast cured PBX in a thick casing, and heavily confined made it an ideal test vehicle.

As with the 250 kg and 500 kg GP bombs, a short modelling study was undertaken using DYNA 2D hydrocode with the CHARM model to predict the likely SDT threshold velocities for the 50 g and 200 g fragments. The CHARM predictions for the 50 g fragment supported the initial view - the SDT threshold velocity might be beyond the achievable muzzle velocity of the conventional 40 mm powder gun, given the thickness of the casing of the BLU-109. The predicted threshold velocity was in excess of 4,000 ms^{-1}. The threshold velocity for the heavier 200 g fragment was much lower – approximately 2,400 ms^{-1}.

The first firing at a BLU-109 with the 50 g fragment was at an impact velocity of 2,110 ms^{-1}, and was significantly lower than the previous test firings (2,330 ms^{-1} to 2,340 ms^{-1}). The response of the explosive in this test was typical to that expected had a NATO IM 14.3 mm fragment been used; initially, copious amounts of smoke emitted from the entry hole with a gradual build up to an obvious jetting and torching flame. At one point, the jetting became so severe that it was able to provide enough propulsive force to move the BLU-109 from its sand plinth. Apart from the entry hole and thermal damage to the casing, no other damage could be observed. No further testing was undertaken using the 50 g fragment as it was concluded that it would not be capable of inducing a more violent reaction close enough to the SDT threshold velocity of PBXN-109.

The same set up and aim point were repeated with the 200 g fragment. The impact velocity of the 200 g fragment was recorded as 2,090 ms^{-1}, resulting in a much more violent reaction compared to the 50 g fragment. High speed video shows, immediately post impact, a large amount explosive filling being ejected from the impact site and forming into a large burning fireball, followed by the base of the BLU-109 being ejected through a build up of internal pressure and flame. The base plate and ring were recovered approximately 300 m from the test site, and bomb casing some 60 m. Examination of the bomb casing showed that it had split entirely along its length, starting at the impact point. Large quantities of unreacted explosive were recovered in the immediate area and around the test site; approximately 50 kg were recovered in large pieces and collected for demolition.

Figure 9. Reaction of two BLU-109 to heavy fragment impact

The third shot also used the 200g fragment to see if the reaction seen in shot two could be repeated, or lead to a more violent event. The measured impact velocity was slightly below the previous shot at 2,063 ms^{-1}. High speed video shows immediately post impact; a large amount of explosive debris is ejected from the impact hole and ignited forming a large fireball. High speed video also shows the base plate and ring 77ms after impact, being ejected from the bomb casing along with burning energetic material. As with the previous shot, the base ring was projected some distance and recovered 46m from the test site; however, it had been stopped by a rather violent impact into a Pendine block, causing severe damage. The bomb casing was found 58m from the test site. Inspection of the casing revealed it exhibited a very similar failure mode to the previous shot – a long longitudinal split along the casing length, though slightly more ‘opened’ up. Evidence of fresh and large pieces of energetic materials were recovered from the immediate and surrounding areas, with an approximate 70kg recovered.

Firing and Reactions Summary of Results

Target	Explosive Filling	Fragment	Impact Velocity	Response
Paveway IV*	PBXN-109	18.6 g (14.3 mm)	2,530 ms^{-1}	Burning
250 kg GP Bomb	ROWANEX 1400	200 g	1,590 ms^{-1}	Violent Burst/explosion
250 kg GP Bomb	ROWANEX 1400	200 g	1,669 ms^{-1}	Violent Burst/explosion
500 kg GP Bomb	ROWANEX 1400	200 g	1,860 ms^{-1}	Burning
BLU-109	PBXN-109	50 g	2,110 ms^{-1}	Burning
BLU-109	PBXN-109	200 g	2,090 ms^{-1}	Violent burst/explosion
BLU-109	PBXN-109	200 g	2,063 ms^{-1}	Violent burst/explosion
*These items shown for comparison only.				

Table 1. Summary of results.

Discussion

Fragment attack testing with the heavy, 200 g fragment has shown a steel barrier 25 mm thick is required to prevent prompt SDT from occurring within ROWANEX 1400 at impact velocities up to approximately 2,200 ms^{-1}. The high confinement test, while not routinely used, has shown a tendency for ROWANEX 1400 to exhibit reactions that are more violent that has previously been seen. A partial detonation of the material was strongly suspected, and likely, however it was not conclusive.

The response of the two 250 kg GP bombs subjected to a 200 g heavy fragment impact, while below the SDT threshold of ROWANEX 1400, were far more severe than what would typically be expected of a cast cured PBX material. Both bombs showed signs of extreme mechanical damage to the casing and energetic material, from the heavy fragment impacts. Had the NATO 14.3mm IM fragment been used - at an impact velocity of 2,530 ms^{-1}, a burning reaction would have highly likely ensued.

The thickness of the casing on the 500 kg GP bomb required an impact velocity be higher than that used with the 250kg, though gun performance was less than expected and the 200 g fragment impacted at far below a velocity close to the SDT threshold; this caused the 500 kg GP bomb to burn with a violent torching event, considerably different to the heavy fragment impact of the 250 kg GP bombs and comparable to the Paveway IV IM Fragment impact test. These initial tests show that heavy fragment impact at velocities close to the SDT threshold have caused more violent levels of response.

Initial analysis predicted the medium 50 g fragment would require an extremely high impact velocity – above 4,000 ms^{-1} for SDT to occur due to the thickness of the casing. An impact velocity just below this was beyond the capability of a conventional powder gun. The actual impact velocity was 2,110 ms^{-1} causing the explosive contents to burn in a manner consistent with a NATO 14.3mm IM fragment test on PBX materials. A factor limiting the response of this fragment and the response of the 500 kg GP is the distance that the shockwave (generated from fragment impact) will travel at peak pressure through the case and explosive is the dissipation of pressure at the edges of the flat front shock.

Fragment impact using the 200g heavy fragment at 2,090 ms^{-1} and 2,063 ms^{-1} into the BLU-109 targets has clearly generated more violent reactions than a smaller (50 g) fragment at a higher velocity. Both BLU-109 showed similar levels of violence, with the cases being projected greater than 45 m, and the base plate and ring significantly further. It is theorised that extensive break up, damage and sensitisation occurred to PBXN-109 during heavy fragment impact; leading to violent break up and explosion of the cases. The high speed video footage supports this analysis, whilst also showing detonation does not take place, with recovery of large quantities of unreacted explosive recovered.

These violent pressure bursts, which are akin to an explosion, can be attributed to the extensive mechanical damage and break up of the energetic material within the bombs casing, which leads to an extremely high surface area, and allows for large flame propagation fronts. When such a situation arises, the mechanical strength of the confining vessel becomes the governing factor of the ensuing violence of reaction. If the casing strength is sufficiently weak, through design or damage such as that caused with a heavy fragment, a low confinement situation arises and subsequent pressure venting of the decomposition gases will take place. If the casing retains its strength after heavy fragment, and mechanical insult with a rapid increase in internal pressure from a large volume of burning, damaged energetic material, it is probable that a DDT reaction will be the outcome.

Conclusions

Charge scale testing using heavy 200 g fragments compared to 18.6 g (14.3 mm) and 27 g (13.15 mm) fragments has shown a tendency for more violent reactions in cast cured PBX materials.

IM Fragment impact testing with the 14.3 mm fragment has consistently demonstrated it is not possible to shock initiate or cause a DDT reaction within PBX formulations used in GP Bombs and Penetrators.

The UK’s Generic Naval Environment medium and heavy threat fragments have caused more violent reactions at the charge scale and system level in cast cured PBX materials.

Concern rested on burning PBX material that was severely damaged with a large surface area whilst also heavily confined, could lead to a DDT reaction. The experimental work on actual in-service munitions has shown that it has not been possible to induce a DDT reaction, even with the most severe and demanding fragments. In the largest penetrator warheads in UK service the results show that with a larger burning surface area due to significant mechanical damage; the reactions do start to become more violent but are still no where near what could be defined as a detonation.

Having explored the boundaries of self confinement (volume), future work will explore the effect of high mechanical confinement in penetrator warheads in their propensity to undergo DDT.