Title: Development and Execution of a Large-scale DDT Tube Test for IHE Material Qualification

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Development and Execution of a Large-scale DDT Tube Test for IHE Material Qualification

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Purpose

Insensitive High Explosive (IHE) Materials are defined in Chapter IX of the DOE Explosive Safety Standard (DOE-STD-1212-2012) as being materials that are mass-detonable explosives that are so insensitive that the probability of accidental initiation or *transition from burning to detonation* is negligible[1].

There are currently a number of tests included in the standard that are required to qualify a material as IHE, however, none of the tests directly evaluate for the transition from burning to detonation (aka deflagration-to-detonation transition, DDT). Currently, there is a DOE complex-wide effort to revisit the IHE definition in DOE-STD-1212-2012 and change the qualification requirements. The proposal lays out a new approach, requiring fewer, but more appropriate tests, for IHE Material qualification[2]. One of these new tests is the Deflagration-to-Detonation Test.

According to the redefinition proposal, the purpose of the new deflagration-to-detonation test is "to demonstrate that an IHE material will not undergo deflagration-to-detonation under stockpile relevant conditions of scale, confinement, and material condition. Inherent in this test design is the assumption that ignition does occur, with onset of deflagration. The test design will incorporate large margins and replicates to account for the stochastic nature of DDT events." In short, the philosophy behind this approach is that if a material fails to undergo DDT in a significant over-test, then it is extremely unlikely to do so in realistic conditions.

This effort will be valuable for the B61 LEP to satisfy their need qualify the new production lots of PBX 9502. The work described in this report is intended as a preliminary investigation to support the proposed design of an overly conservative, easily fielded DDT test for updated IHE Material Qualification standard. Specifically, we evaluated the aspects of confinement, geometry, material morphology and temperature. We also developed and tested a thermally robust igniter system.

Background

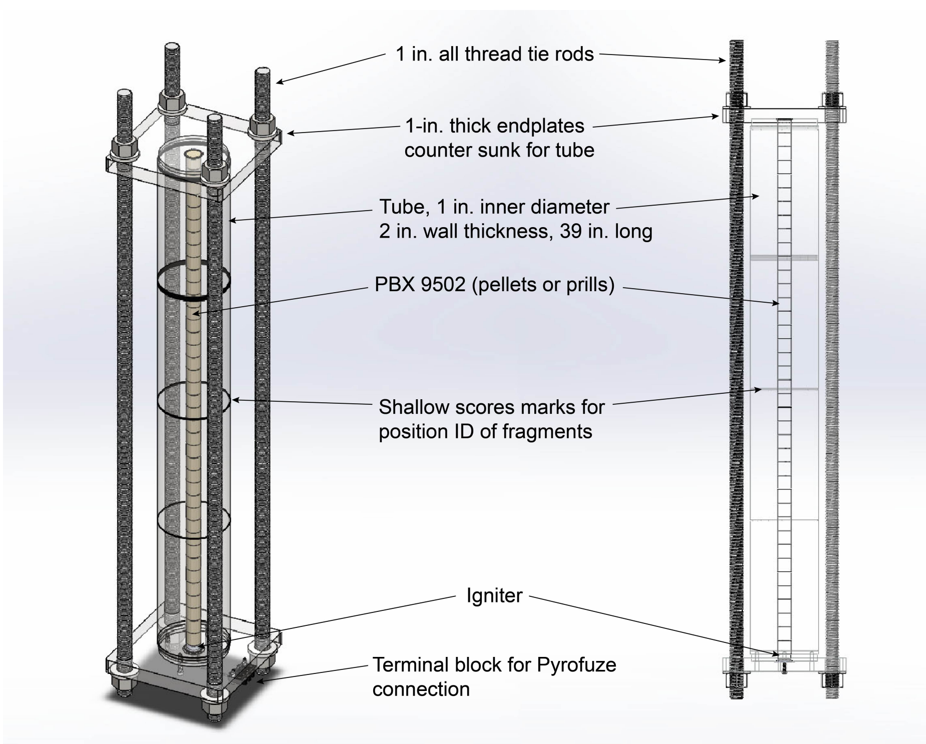
DDT has never been observed with PBX 9502 or other TATB-based formulations[3-6]. However, some of the testing done with these materials has not been performed under conditions that would be described as stockpile relevant "worst-case". DDT research with conventional high explosives has taught us that many factors influence a material's propensity for DDT. These include:

- Confinement – Strong, heavy confinement increases DDT propensity,
- Geometry – the HE charge must be thicker than the detonation critical diameter and of sufficient length in the direction of motion to allow a compaction-driven DDT mechanism to operate,
- Morphology – Porosity and internal surface area are both known to increase DDT propensity,
- Temperature state – Hot conventional high explosives tend to have a higher propensity for DDT (this is demonstrably true for HMX) and TATB exhibits increased shock sensitivity at elevated temperatures.

During Fiscal-Year 2016, we designed and fielded a DDT test design incorporating these factors. We offer recommendations for future improvements in the conclusions section.

Design and Methodology

To address the need for overly conservative confinement and scale, we designed a test (Fig. 1) comprising a steel tube, 1 meter long with and 1-inch diameter bore and 2-inch wall thickness. The tube was capped on both ends by 1-inch thick steel plates. Metal o-rings were emplaced on each end to contain gaseous combustion products and build the high pressures needed to accelerate burning.



[7]

Figure 1. Design overview.

The tubes were filled either with PBX 9502 pellets (1” diameter × 1” high) pressed to full density (~1.90 g cc^{-1}), or PBX 9502 molding prills loaded at pour density (~0.84 g cc^{-1}). The molding prills were used to examine the effect of increased surface area and porosity (Fig. 2). There was some concern that PBX 9502 molding prills would not sustain a detonation at such low density at a 1-inch diameter. To eliminate this concern, an intentional detonation test was performed with a 1-inch diameter column of molding prills in a steel tube: the detonation did not fail.

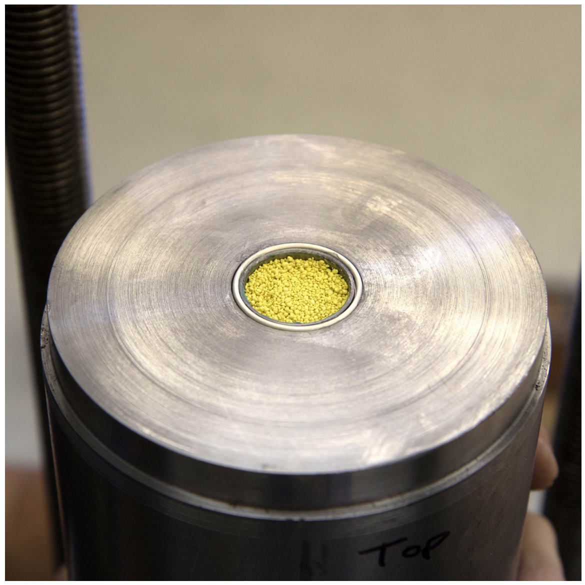


Figure 2. PBX 9502 molding prills during test assembly.

Because it is known that the shock sensitivity of PBX 9502 increases at elevated temperatures, we designed this test to be performed at 250 ˚C[8, 9]. During the design phase, materials were chosen to survive these temperatures. The tube was wrapped in heating tape in three zones; top, middle and bottom (Fig. 3, left). Each zone was independently controlled to minimize thermal gradients along the length of the tube. Considerable effort went into thermal control tuning tests with a mock-up configuration prior to execution of the live-HE tests. In addition to zonal temperature control, we learned from the mock testing that an overwrap with aluminum foil and fiberglass insulation (Fig. 3, right) was beneficial for minimizing thermal gradients. In the end, we were able to heat the assembly at a rate of 2 ˚C min^{-1} with a middle-to-end thermal gradient of less than 2 ˚C in both directions (Fig. 4). The initial plan was to soak the assembly at 250 ˚C for 30 minutes, however, evidence of possible self-heating during the first test caused us to change plans and ignite at 25 minutes into the soak. For consistency, we also ignited the other tests after a 25-minute soak.

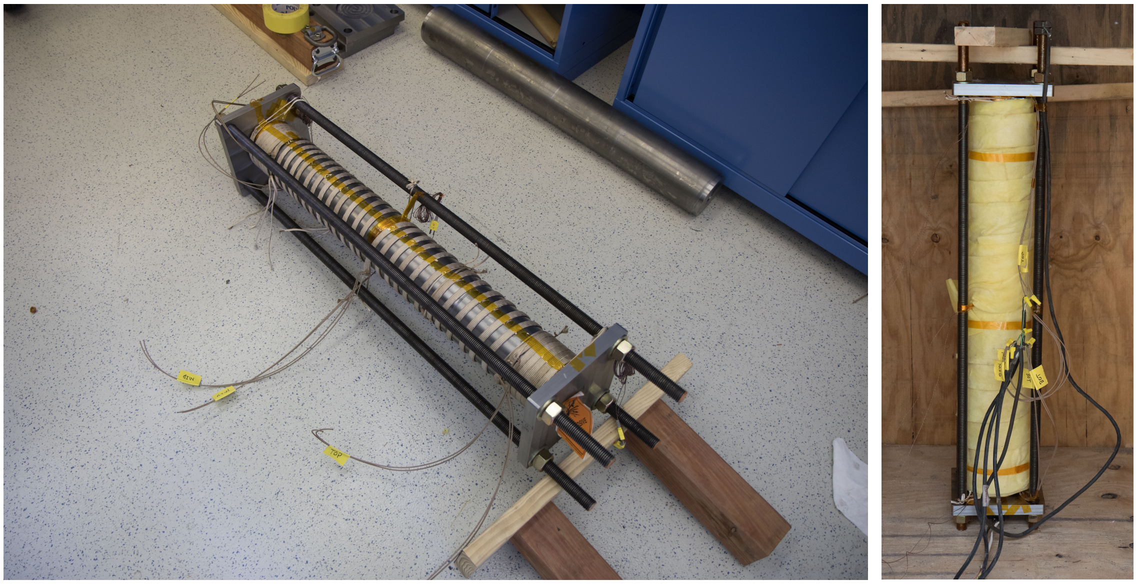


Figure 3. Fully assembled DDT tube with wound heating tape arrangement (left). The spacing of the tape was closer on the top and bottom zones to overcome thermal losses from the unheated endplates. The DDT tube on firing point, wrapped in insulation (right). All tests were oriented vertically and ignited on the bottom end.

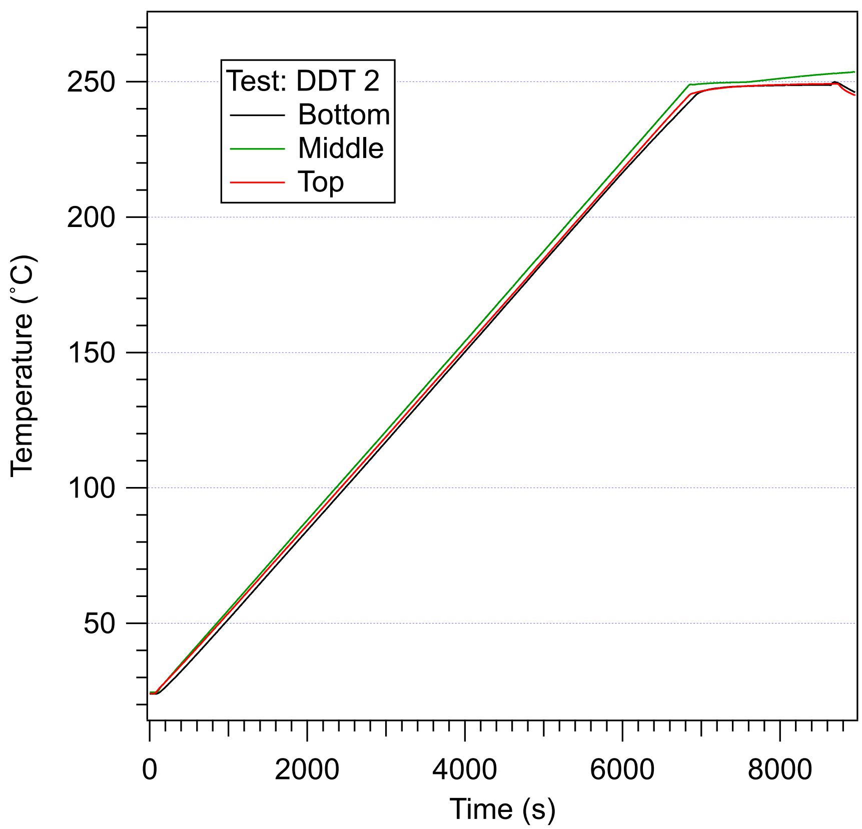


Figure 4. A typical thermal profile showing a linear ramp rate and small thermal gradient from middle to ends.

The igniter was a crucial element to the success of this project. Inspired by a Naval Ordnance Laboratory (White Oak) design, we developed at robust gasless igniter that was sealed within the end of the DDT tube (Fig. 5). It consisted of a thin walled aluminum cup (0.030"), filled with stoichiometric blends of Fe_3O_4 Al thermite (0.25 g) and TiB_2 pyrotechnic (3.5 g). The powders were layered inside the cup and capped with a ceramic tamper. Two lengths of Pyrofuze® wire were passed through the ceramic tamper with 20cm of each in contact with the thermite. Once the ignition time was reached, the Pyrofuze® was ignited by application of direct current. In turn, the Pyrofuze® ignited the fast-burning thermite and then the slower burning TiB_2 to produce a ceramic at ~2950°C. The glowing hot ceramic then melts through the aluminum cup and causes a nearly planar ignition of the explosive.

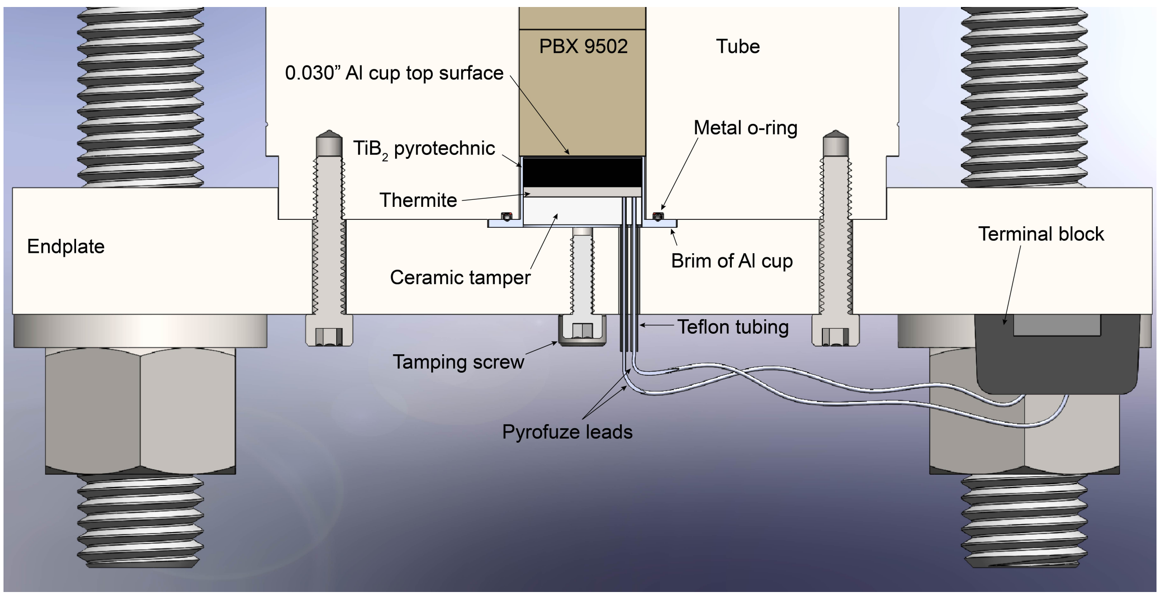


Figure 5. Igniter-end detail of DDT tube assembly.

Determination of DDT would be made from post-mortem analysis of the damage to the steel tube and endplates. To benchmark the damage some baseline tests were performed by detonating 12-inch lengths of IHE, at both full and pour density, inside tubes of the same dimensions.

Results

Six tests were performed in this series. Temperature control was excellent and quite reproducible between tests (Fig. 6). A summary of results can be found in Table 1.

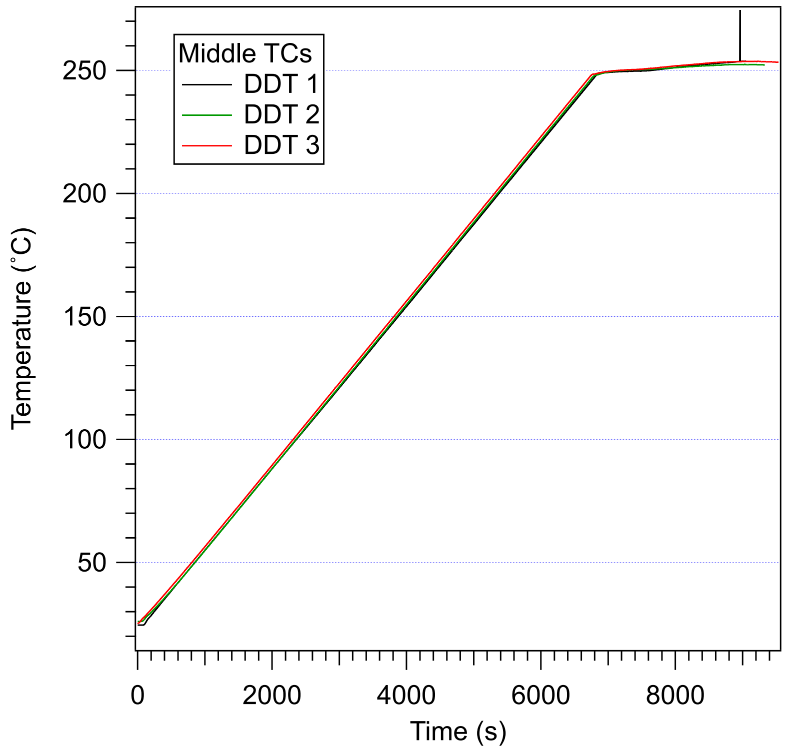


Figure 6. Thermocouple data from the middle position from each of the three tests. Temperature control was highly reproducible.

Table 1. Test details and results summary

Test #	IHE form	Density (g cc^{-1})	Purpose	Result
Baseline 1	Prills	0.84	Failure diameter evaluation	1 inch is above the failure diameter for molding prills, detonation sustained
Baseline 2	Pressed pellets	1.90	Assess damage caused by detonation at this density	Highly fragmented the steel tube, and deeply dented the end plate
Baseline 3	Prills	0.84	Assess damage caused by detonation at this density	Distended the steel tube, increasing the inner diameter to 1.33 inches
DDT 1	Pressed pellets	1.90	Evaluate propensity for DDT at 250°C	No DDT, burned 3.75 inches and quenched. Cookoff 8 minutes later. The endplates were deformed.
DDT 2	Prills	0.84	Evaluate propensity for DDT at 250°C	No DDT, burned 8 inches and quenched. No deformation of the metal.
DDT 3	Prills	0.84	Repeat test DDT 2	No DDT, burned 5.75 inches and quenched. No deformation of the metal.

The three baseline tests demonstrated the following: 1) 1 inch is above the failure diameter for PBX 9502 molding prills at pour density in heavy steel confinement, 2) full density PBX 9502 pellets detonate with enough power to fragment the steel tube (Fig. 7, left), and 3) pour density PBX 9502 molding prills detonate with less power, causing plastic deformation—but not fragmentation—of the steel tube (Fig. 7, right).

Figure 7. Tube fragmentation from the Baseline 2 test with full density PBX 9502 pellets (left). Tube distension from Baseline 3 test with pour density molding prills (right).

The first of the DDT tests, with full density PBX 9502, did not undergo DDT. The PBX 9502 burned for approximately 3.25 inches, then extinguished. About 8 minutes later, a secondary self-ignition event occurred in a location between 20.75 and 25.75 inches from the ignition-side of the tube. This was not an unexpected outcome at the elevated temperature at which the test was performed. The test was allowed to cool overnight and was disassembled the following day. The tube was not deformed, but the endcaps were bowed out from the pressure (Fig. 8). The igniter cup showed signs of erosive gas channeling through, and enlargement of, the Pyrofuze® wire feed holes. Inspection of the IHE revealed signs of severe thermal damage. The IHE was discolored and crumbled on the ignition side (Fig. 9, left) while remaining consolidated on the other end (Fig. 9, right).

Figure 8. Endplate deformation (ignition-end) from the DDT 1 test with full density PBX 9502 pellets. Stronger endplates are recommended for future test versions.

Figure 9. Damaged and discolored PBX 9502 from the ignition-end of the DDT 1 test (left). Mostly undamaged PBX 9502 on the opposite end of the tube (right).

The second and third tests (with molding prills) were replicates, and unsurprisingly, behaved similarly. Neither transitioned to detonation. In fact, both burned only short distances; 8 inches and 5.75 inches from the igniter leaving ash in the tubes. Upon scooping out the ash, we could see that the molding prills had been compacted from the burn pressure at the location were the burn had extinguished (Fig. 10, left). Interestingly, the compaction waves appear to have dissipated in both tests before travelling the full length of the tubes, as evidenced by the undamaged and loosely packed prills on the far end (Fig. 10, right). Neither the tubes, nor the endplates, were deformed. As with the first DDT test, the igniter cups showed signs of erosive gas channeling through, and enlargement of, the Pyrofuze® wire feed holes (Fig. 11).

Figure 10. Compacted molding prills on the ignition end of the DDT 2 test (left). Un-compacted prills on the opposite end of the tube (right).

Figure 11. The IHE-side of the aluminum igniter cup with a gas channel eroded at the 6 o'clock position (left). The other side in the igniter cup assembly showing and eroded gas channel through the ceramic tamper at the 1 o'clock position (right).

Conclusions and Recommendations

Three large-scale DDT tests were performed to assess suitability and practicality of certain features for a proposed IHE Material Qualification Test. In addition to proof-testing design features for R&D purposes, we were able to execute three DDT tests with PBX 9502 at two different densities. Despite efforts to contrive a test that would encourage the most violent of explosive reactions from PBX 9502, the results were relatively benign. Neither detonation, nor complete combustion of the explosive mass was observed. At most, 20% of the IHE burned before extinction of reaction. These results serve as further evidence that PBX 9502 is extremely unlikely to undergo DDT in any reasonable confinement or stockpile relevant geometry.

While many of the features in this design performed as intended, there is room for improvement. The first recommendation is to design stronger endplates. In one of the tests, the plates bowed out and prematurely relieved pressure. The next recommendation is to improve the design of the igniter system to reduce the likelihood of erosive gas channeling through the ignition wire feedthrough holes. We suggest an aluminum split-cone design that collapses inward to form a seal when loaded under high pressure. Lastly, we would remove the metal o-ring and add a vent hole on the side opposite the igniter to relieve pressure inside the tube. This feature was suggested in the IHE redefinition proposal, but not included in this series of tests.

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