DOE/NNSA Insensitive High Explosive (IHE) Qualification and Testing

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Abstract

Insensitive High Explosives (IHEs) are defined in Chapter IX of the Department of Energy (DOE) Explosive Safety Standard (DOE, 2012). The qualification and approval process is specific to the DOE/National Nuclear Security Administration (NNSA) nuclear deterrent mission, and it is completely separate from the Department of Defense (DoD) and NATO Insensitive Munitions (IM) requirements.

The experimental series to qualify an IHE Material was changed by vote of the DOE Explosives Safety Committee in 2015. The new criterion contains the following elements: 1. Deflagration-to-Detonation Transition (DDT); 2. Shock-to-Detonation Transition (SDT); 3. Skid Test; and 4. Bullet Test. We discuss the background and technical details of the four experiments.

Introduction

The DOE/NNSA routinely handles large, bare (uncased), charges of plastic-bonded explosives (PBXs), both for high-explosive research and development and during the manufacture of nuclear warheads. A study by the NNSA Office of Defense Programs' Science Council (DOE/NNSA, 2015) recommends that all the PBX's used in nuclear weapons should be Insensitive High Explosive (IHE). That same study also noted expectations for IHE which include improved safety throughout the life cycle of the weapon (in both DOE and DoD custody) and improved production efficiencies. Nuclear warheads in production (either assembly or disassembly) present unique, and grave, hazards. A set of criteria for qualifying an IHE to be used by DOE/NNSA must address these unique risks. Currently, only TATB (2,4,6-Triamino-1,3,5-trinitrobenzene) and its formulations with Kel-F (chlorotrifluoroethylene polymer) are qualified under the DOE Standard (DOE, 2012). Further, although the DoD has protocols for the qualification of Insentive Munitions (IM), these requirements are for the munition system – they are related to, but can be independent of, the high explosive used the warhead or rocket motor (DoD, 2014). Therefore, the DoD IM requirements are not directly applicable to bare charges for DOE/NNSA.

Before the IHE qualification experiments were changed in 2015, the criterion by which an IHE was defined in the DOE/NNSA consisted of eleven tests, articulated in the 1980's by a small committee of subject matter experts at Lawrence Livermore National Laboratory, under the assumption that the requirements would be adaptable and constantly evolving based on the expert judgement of DOE/NNSA scientists. For example, one of the tests, the #8 cap test, had two significant shortfalls. First, it was selected because the group believed "super" insensitivity existed when no commercial cap on the market would initiate the explosive at tap density. While this is a reasonable argument, the committee did not anticipate that the definition of the cap would evolve in time and, in the case of the #8, become more powerful. Second, the cap test was pulled from hazard division definitions (e.g. TB 700-2, DoD 2012, for HD 1.3 and HD 1.6), and directed at over-the-road transport threats which had no relevance to the potential hazards in DOE/NNSA custody. Upon review, many of the other experiments had similar shortfalls; they either addressed threats that were not relevant to nuclear safety (e.g. they addressed worker safety or over-the-road transport, which are covered by DOE/NNSA high-explosive handling protocols and Department of Transportation regulations), or they addressed ignition of the explosive material without speaking to the response of the material.

Early in the review to change the IHE qualification definitions, it was noted that Chapter IX of the DOE Explosive Safety Standard (DOE, 2012) states: "IHE Materials are mass-detonable explosives that are so insensitive that the probability of accidental initiation or transition from burning to detonation is negligible". However, there was no experiment defined in the Standard which addressed this threat. Further, it was noted that only the high power of detonation produced the grave risks unique to a nuclear weapon (DOE, 2013; NRC, 1998). Therefore, the focus of the new definitions shall be to define a threshold for shock-to-detonation (SDT), staying mindful that SDT under all conditions cannot be excluded because an IHE must detonate to function as designed, and then ensure that any material that will not detonate under the shock threshold will also not transition to detonation if it is ignited to deflagration by a non-shock event. Thus, there is no SDT below a specific threshold and there is also no Deflagration-to-Detonation Transition (DDT). Also, the new experiments for qualification assume that the IHE is ignited in a non-shock event. By assuming ignition, and ensuring the IHE will not DDT, it is not necessary to test specific non-shock scenarios (e.g., high temperature, crushing impact, accidents with tooling, etc.) to see if these result in ignition. This greatly simplifies the range of thermal and sub-shock tests that are necessary for the IHE qualification.

Described in detail in the next four sections of this paper are the new experimental series to qualify an IHE material for the DOE/NNSA mission. The experiments contain the following elements:

1. Deflagration-to-Detonation Transition (DDT)
2. Shock-to-Detonation Transition (SDT)
3. Skid Test
4. Bullet Test

For explosives that do not meet the qualification criteria of an IHE Material, there is a separate experimental series to qualify as an IHE Subassembly in a smaller configuration. The IHE Subassembly Qualification Test Series contains the same four elements, but in a smaller – weapon-system relevant – configuration. These tests are described in more general terms in Maienschein (2016). Details will depend on the configuration and materials of the specific IHE subassembly being tested. The IHE Subassembly is not discussed in this paper.

Deflagration-to-Detonation Test

The purpose of the deflagration-to-detonation test is to demonstrate that an IHE material will not undergo deflagration-to-detonation transition (DDT) 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.

DDT in condensed-phase, inhomogeneous, explosives is a significantly more complex process than shock-to-detonation transition (SDT), comprising several distinct steps (adapted from Asay, 2010): ignition of reaction; conductive burning, in which the ignition front advances by thermal conduction; convective burning, in which the ignition front advances by penetration of hot, gaseous, products; compaction of the unreacted explosive ahead of the ignition front by pressurization due to the reaction products, choking off the convective process; downstream plug formation; shock formation at the downstream plug boundary; and, ultimately, SDT.

This process is dependent on both chemistry and mechanical properties of the explosive material. The decomposition chemistry and kinetics are intrinsic properties that control pre-ignition decomposition, which affect the degree of porosity developed at elevated temperature prior to ignition and, consequently, the compaction characteristics of the material. They also determine deflagration rate as a function of pressure; faster favors reaction build up and shorter run-to-detonation distances. The mechanical properties are rate-dependent intensive intrinsic properties that control deflagration rate as a function of accessible surface area via strain-rate-dependent fracture properties, and also determine compaction and plug formation.

This combination of complex factors puts a quantitative understanding of the phenomenon beyond our current modeling capabilities but, since the trends arising from each factor are understood, we can bound the problem by experimental exploration of worst-case scenarios with a limited number of replicates.

Accordingly, the proposed DDT test shown in Figure 1 is highly conservative in terms of the external (to the explosive) parameters of importance, specifically confinement and charge size. The metric is the absence of transition to detonation in a charge size and geometry that permits a significantly longer run distance, and which is subject to much stronger and more massive confinement, than any configuration of relevance to a nuclear weapon.

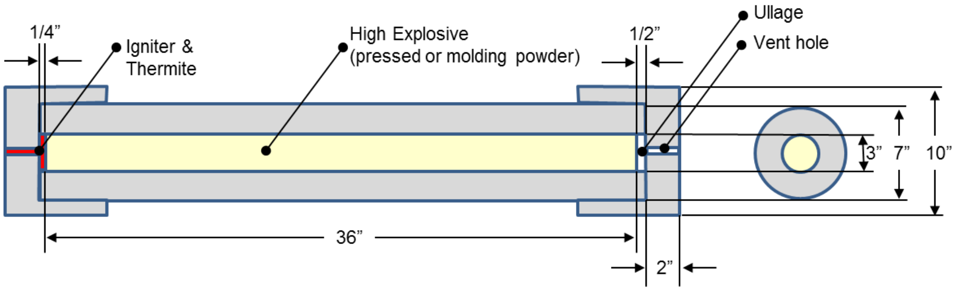


Figure 1: DDT test diagram

The heavily confined explosives samples are externally heated with the temperature monitored (Maienschein, 2016). Slow heating encourages charge ignition at the center axis. Both consolidated (pressed) parts and molding powder (prill) are tested. The former is the typical charge density, and the latter is a surrogate for mechanically damaged material. The first experiment in the series is heated – similar to a cook-off test – until the explosive self-ignites. The second configuration heats to 10-degress below the self-ignition temperature. The diagnostics are thermocouples, and particle velocimetry (e.g. PDV). Three experiments at each condition result in nine tests total and ~60 kg of material. The material qualifies as an IHE if there is no development of a detonation wave within the tube length.

Shock-to-Detonation Test

The purpose of the shock-to-detonation test is to demonstrate that the IHE will not undergo shock-to-detonation transition (SDT) under a defined shock stimulus at ambient temperature, which differentiates the SDT behavior of IHEs from the SDT behavior of Conventional High Explosives (CHEs). In addition to the defined ambient-temperature shock stimulus, an additional SDT test is required at high temperature, to show that the explosive is not sensitized by exposure to high-temperature conditions. Note that any explosive, IHE or CHE, must undergo SDT at some shock stimulus for a nuclear weapon to function as designed.

The ambient-temperature threshold shock stimulus was developed based on consideration of the shock sensitivity of a set of CHEs and currently recognized IHE formulations. As shown in Figure 2, the shock sensitivity of CHEs and IHEs can be represented as a threshold SDT pressure as a function of shock duration.

In the accepted understanding of SDT in composite solid explosives, interaction of the shock front with voids, interfaces, or other irregularities in the solid results in development of localized hot spots. If the shock is sufficiently strong and long-lasting, these hot spots react, coalesce, and release chemical energy fast enough to accelerate the shock wave until it forms a detonation. If the shock is too low in magnitude or duration, the hot spots may not react, or may quench before coalescing, and transition to detonation does not occur.

In addition to shock magnitude and duration, other factors are very important in SDT. The shock duration determines the time until a rarefaction from the rear of the sample reduces the shock pressure and may quench the reaction. Rarefaction waves from the side of explosive samples will have a similar effect, with the rarefaction penetrating farther from the edge as the shock travels from the impact surface. Shocks driven by small-diameter impactors similarly have rarefaction waves from the side that will quench the reaction. Therefore, size of explosive sample and diameter of the impactor driving the shock wave are important. If the shock is not planar or is not parallel to the explosive surface, these interactions are even more complex. If the shock wave at a surface is reflected back into the sample by a higher-impedance material, this also may have a strong effect on the SDT response. To make the IHE test for SDT as unambiguous and reproducible as possible, it is specified as a 1-dimensional planar shock input with long duration. The explosive sample diameter and length are specified to avoid the effect of rarefactions from the side, while also allowing enough distance for the shock to run before side rarefactions come into play.

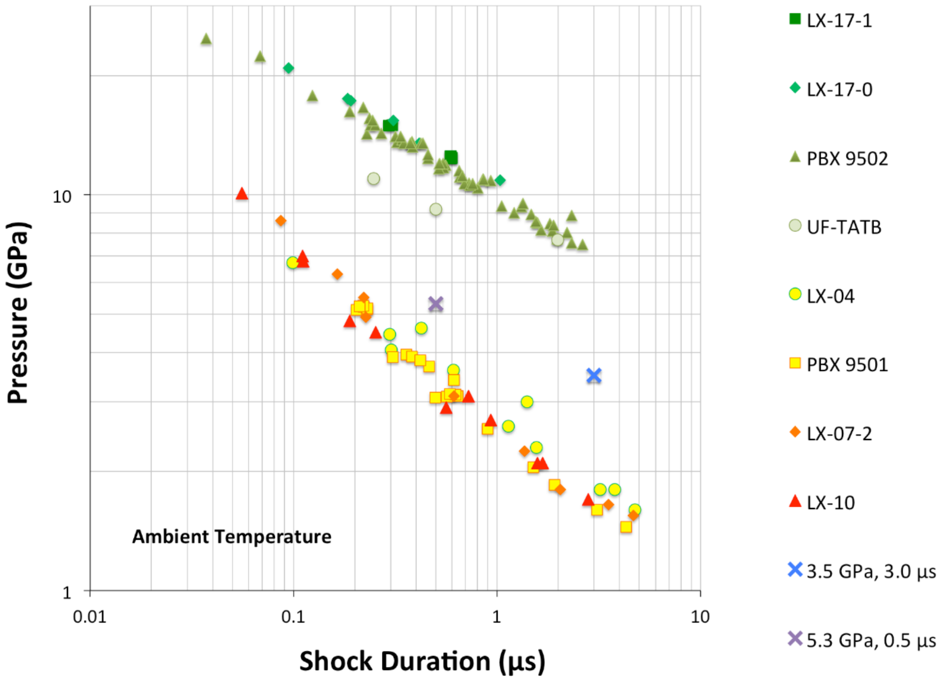


Figure 2: Shock sensitivity of several DOE explosives scaled from Pop-Plot data, showing the separation in behavior between IHEs and CHEs. The TATB-based IHEs (LX-17, PBX 9502, and UF-TATB) form a family with significantly lower shock sensitivity than the HMX-based CHEs (LX-04, PBX 9501, LX-07, and LX-10)

The propagation rate of the shock or reaction front provides a clear delineation between an unreacted shock and a detonation wave. Diagnostics are embedded in the explosive sample to measure either pressure or particle velocity, in situ, also show if the shock wave is building to a detonation or is failing. The use of such diagnostics is an important element of these tests, as a reacting shock wave that may not have reacted detonation conditions is a quite different response than an unreacted or failing shock front.

Figure 2 presents shock initiation threshold data which has been adapted from run-to-detonation, or Pop Plot, data for TATB-based (LX-17, PBX 9502, and UF-TATB) and HMX-based (LX-04, PBX 9501, LX-07-2, and LX-10) high explosives and scaled based on short-pulse initiation data for LX-17 and LX-04 (Gresshoff, 2018). This plot shows that TATB-based materials (considered IHE) and HMX-based materials (considered CHE) form distinct bands. The legacy definition of shock-to-detonation threshold was based on the response of Explosive D in the Gap Test. Gresshoff (2018) used the data in Figure 2, coupled to predictive calculations of Explosive D, to describe a range of shock response and uncertainty bounds. Because there is uncertainty in both scaling of the threshold and the current definition of the Explosive D equation of state, the SDT threshold at ≥3.5 GPa was chosen to represent the safety provided by legacy qualification for a supported wave and it lies between the CHE and IHE. As pressure is decreased, the shock duration required for SDT increases until a pressure is reached where there is no SDT regardless of the shock duration. These cut-offs begin ~3 µs for both TATB and HMX-based explosive with values of 7.5 GPa and 1.5 GPa respectively (Gresshoff, 2018). The SDT literature has shown that SDT does not occur below this pressure even for very long shocks. The figure also indicates the SDT criterion for a sustained shockwave (≥3 µs duration) is 3.5 GPa.

Previous work on IHE Qualification of TATB (PBX 9502, LX-17, and UF-TATB) show data from Pantex Plant (Slape, 1984) which suggest that IHE qualification with the No. 8 Blasting Cap detonator was performed on both molding powder and “compacted” parts at nominal density. Although it was never written in the DOE Standard (the Standard prescribes TB 700-2 protocol for transportation and storage with molding powder), this history suggests a precedence for short-duration, high pressure, Taylor wave-type, loading of pressed parts as a component of the material definition. Hydrocode calculations of the Pantex Modified NOL Card Gap test showed that the upper limit of output for a Taylor wave into Explosive D is approximately 5.3 GPa. The lower limit of duration available for a gas gun flyer plate design is approximately 0.5 µs duration (cap duration is expected to be longer, but a Taylor wave). Therefore, the criterion for short pulse shockwave is prescribed to be 5.3 GPa at 0.5 µs (also shown on Figure 2.

Sensitization of explosives at high temperature is driven by physical transformations in the explosive. For TATB PBXs, the shock sensitivity at 250°C is caused by the irreversible ratchet growth with formation of additional voids that sensitize the explosive to shock; when TATB explosives are physically confined, the shock sensitivity is significantly reduced. For HMX PBXs, the shock sensitivity is only slightly increased by heating to 150°C; the large increase in sensitivity at 190°C is caused by the beta-to-delta phase transition in HMX with the resultant formation of additional voids. Virtually all known explosives are sensitized to SDT at high temperatures.

To evaluate a candidate IHE, a second SDT experiment must be done at a sufficiently high temperature (10-degrees below the temperature at which the sample will thermally explode based on a slow cook-off) to include the effect of phase changes or other physical changes. High-temperature shock sensitivity data for some IHEs and CHEs were also presented by Gresshoff (2018) and are shown in Figure 3. Because short-pulse data is not widely known for HEs at temperature, the data in the graph is still in the standard “Pop-Plot” format revealing pressure and run distance to detonation. Also shown in Figure 3 is the new IHE criterion for hot shock sensitivity – absence of shock-to-detonation transition with a 1.5 GPa shock sustained for at least 3 µs.

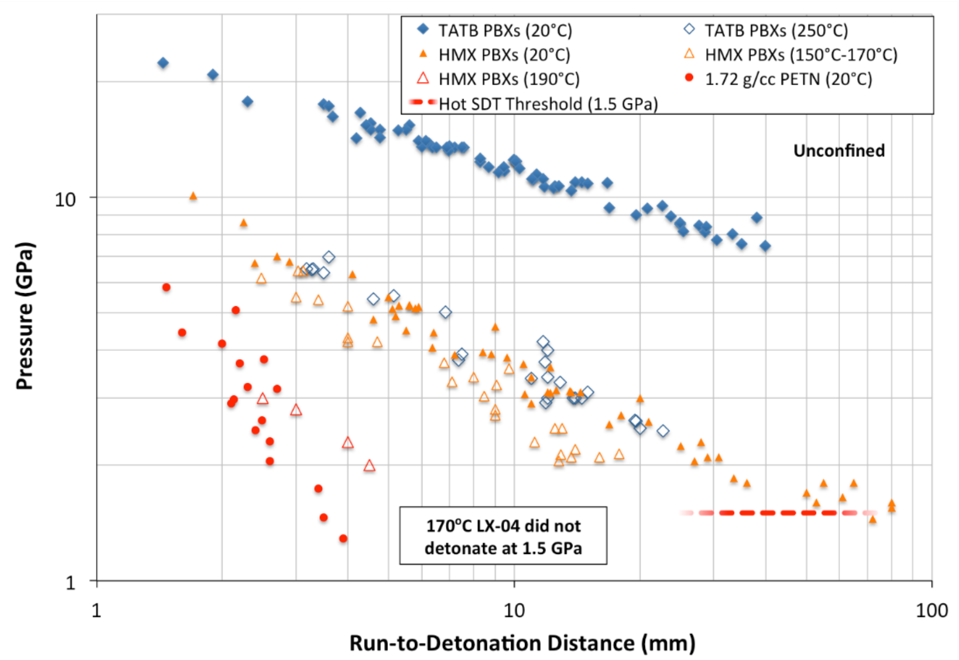


Figure 3: Shock sensitivity of several DOE explosives at high temperature. The criterion at 1.5 GPa is shown as a dotted line as run-to-detonation distance is unknown in future candidate IHEs.

The SDT experiment recommends using a gas gun to achieve reproducible 1-D planar shocks (Maienschein, 2016). There are two ambient temperature experiments (criterion shown on Figure 2): ≥3.5 GPa for ≥3.0 µs and ≥5.3 GPa for 0.5 µs; and a high temperature experiment (criterion shown in Figure 3) at ≥1.5 GPa for ≥3.0 µs. The series begins with a cook-off test to determine the temperature the explosive sample will thermally explode, so the heated experiments are performed 10-degrees under that threshold. Diagnostics are thermocouples and embedded pressure gauges. Three replicate experiments are performed at each temperature for a total of nine experiments and ~ 4 kg of material.

Skid Test

The purpose of the skid test is to show that bare billets of explosive will not react with significant violence when subjected to a severe drop environment which is intended to simulate a worst-case handling accident. For this experiment, which is a worker safety test, the acceptance criterion is based on worker safety concerns rather than detonation. The worst-case response for an explosive that has passed the skid test is non-violent chemical reaction.

The physical mechanisms governing explosive response in the skid test are very complex. Impacts such as those encountered from any conceivable drop height are incapable of driving a shock-to-detonation response. Ignition and deflagration is the worst possible outcome. The initial impact of an explosive causes compression and/or fracture with simultaneous conversion of mechanical energy to heat by frictional heating, which is generally grit-mediated. If the thermal energy is sufficient to ignite the explosive, depending on the surface area that is produced by the fracture subsequently ignited by high temperature, the ensuing reaction may range from a few points of light, to a rapid deflagration, to a detonation. The legacy standard LANL/Pantex drop and skid tests relied on subjective assessment of reaction violence to quantify the response of the charge. Experimentalists could miss non-propagating hot-spot ignition sites, leading to large variations in test results. The legacy standard was therefore redesigned.

The redesigned experiments are shown in Figure 4 (Dickson, 2010). The new experiments provide control of the relevant loading mechanisms and to permit direct visual observation of reaction at the impact site, allowing direct observation of the progression of the outcome as the drop height and ignition source density are varied. The results confirm the dominant friction ignition mechanisms and thresholds at a range of realistic drop heights.

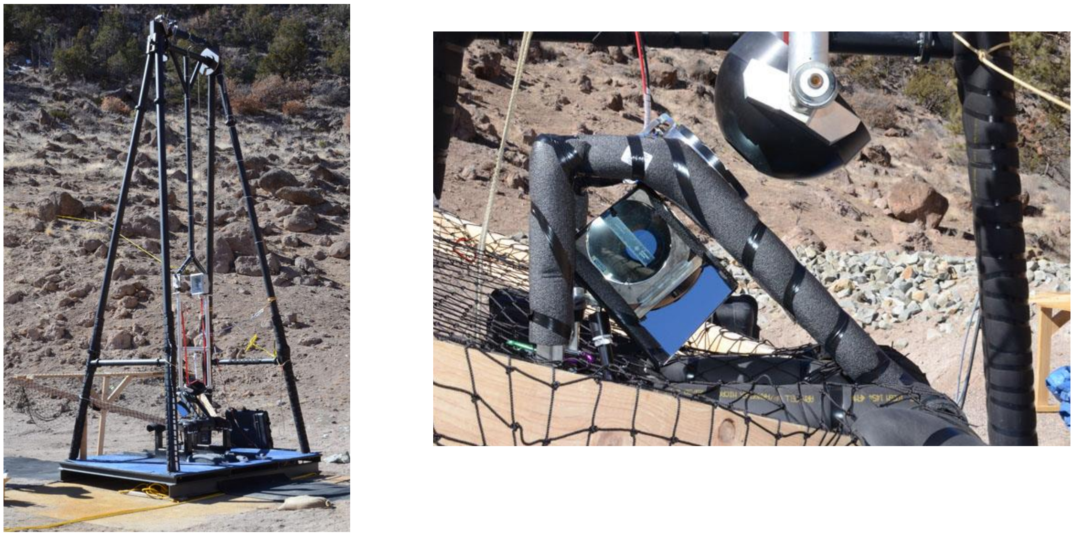
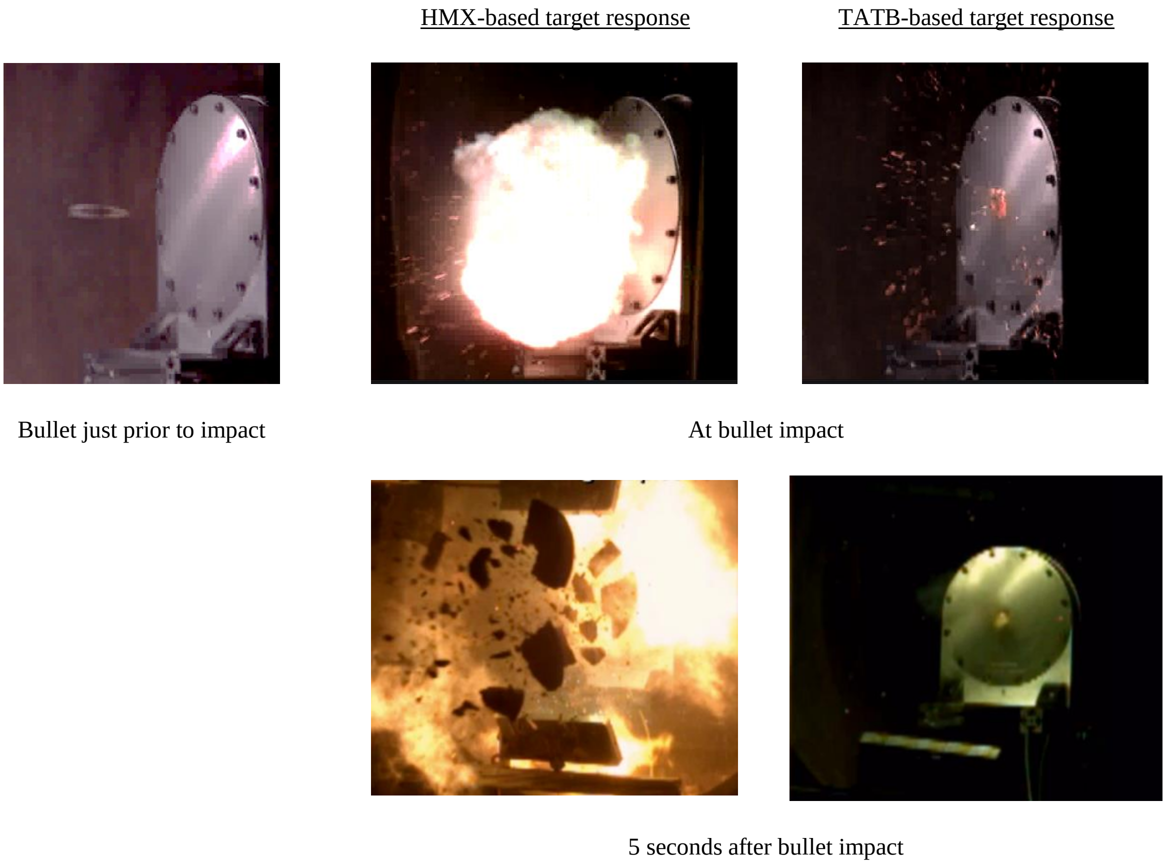


Figure 4: Pendulum skid impact test based on the new LANL Skid Test apparatus. (left), and (right) hemispherical charge resting in cradle, free to escape (bounce) upon contact with target

In the skid test, hemispherical samples of candidate IHEs are slid across a target of sanded glass or steel at 45-degree impact angle and 20-foot drop (Maienschein, 2016). Three tests are performed in triplicate using a total of 30 kg of material. The diagnostic is high-speed video side-on to the impact plane, or through target plate (if transparent). Reaction must not result in a fireball, or have visible smoke or scoring of the explosive surface. Substantial amounts of smoke with jetting, fireball, and disintegration of explosive contact surface due to explosive reaction is not acceptable.

Bullet Test

The purpose of the bullet test is to show that an IHE does not react violently when impacted by a bullet under the conditions described. This is a demonstration that the IHE is relatively unreactive to this type of stimulus and it is not intended to prove that the IHE will not react to any sort of bullet or related stimulus. The ammunition selected is representative of threats to which the IHE will be exposed during its lifecycle and may not represent the worst possible case. The configuration represents the likely worst-case path of least resistance. Figure 5 shows an example of the response from this test for both HMX-based and TATB-based explosives.



HMX-based target response

TATB-based target response

Bullet just prior to impact

At bullet impact

5 seconds after bullet impact

Figure 5. The bullet impact test distinguishes between the reaction violence of an HMX-based explosive and TATB-based explosive to the impact with a 50 caliber armor-piercing round. In this case, the HMX-based explosive does not meet the criteria. The visible light/reaction at impact is acceptable, however the violent disassembly of the undetonated HE constitutes a failure.

Explosive response to the impact from a bullet is very complex. Typically, the bullet does not impart a shock to the explosive in such a way to cause shock-to-detonation transition, but instead provides input of mechanical and thermal energy to the explosive. The mechanical energy of the bullet impacting and tearing through the explosive is converted to thermal energy by the thermomechanical response of the explosive, and thermal energy from the hot bullet is deposited as the bullet travels through. This thermal energy may cause the explosive to ignite, and then may eventually lead to an explosion. The mechanical response of the explosive is very dependent on its configuration and confinement. Just as in DDT, mechanical damage can lead to surface area (hot spot) formation which leads to more reaction violence upon ignition.

The experimental configuration shown in Figure 6 offers a geometry somewhat representative of IHEs in their intended applications. The sample contained in a steel fixture with steel front and back plates (Maienschein, 2016). Bullets are 50 caliber, armor-piercing, at standard muzzle velocity, with one bullet per experiment. Diagnostics are high-speed video. Six replicates are performed using a total of 27 kg of material. Smoke and/ or visible light is acceptable, a burning reaction can completely consume material, and an assembly may be distorted and surfaces blackened. However, any level of damage beyond that is a failure. If the assembly is fragmented, that is a failure.

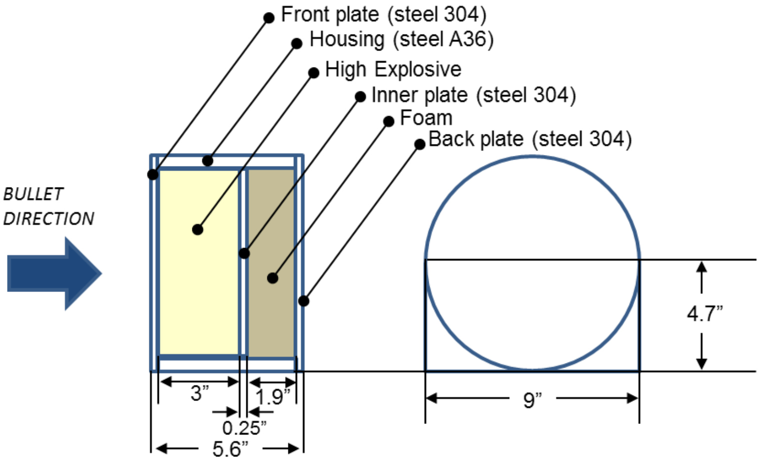


Figure 6: Assembly diagram of bullet test apparatus

Conclusions

A series of four experiments (Deflagration-to-Detonation Transition, Shock-to-Detonation Transition, Skid Test, Bullet Test) have been presented which together encompass the IHE Material Qualification experiments for the DOE/NNSA. These experiments ensure that any new IHE used in the U.S. nuclear deterrence meets the requirements of the DOE Explosives Safety Standard: “IHE Materials are mass-detonable explosives that are so insensitive that the probability of accidental initiation or transition from burning to detonation is negligible”. The experiments described in this paper were accepted by vote of the DOE Explosives Safety Committee in 2015 and are expected to be the basis for IHE Qualification in future warhead programs.

Acknowledgements

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