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PARAMETERS INFLUENCING THE RESPONSE OF MSP-1 PROPELLANT SUBJECT TO FRAGMENT IMPACT

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ABSTRACT

Solid rocket propellants can experience a wide variety of responses when impacted by high speed fragments – detonation being the most severe and least desired response. Investigating the underlying mechanisms that produce the various responses are critical in order to understand and then mitigate them. To this end, the Burn to Violent Reaction (BVR) experiment was developed. These experiments consist of impacting fragments against simplified, simulated rocket motors – square samples of propellant bonded to a flat casing material and placed in series. A solid propellant, known as MSP-1, has been studied using BVR, and parameters such as fragment properties, fragment velocity, propellant thickness, spacing between propellant samples (air gap), and backing material were investigated. Multiple reaction mechanisms were observed, including deflagration, Shock to Detonation Transition (SDT), Unknown Detonation Transition (XDT), and a form of thermal reactions leading to detonation – possibly Deflagration to Detonation Transition (DDT). The resulting reaction depended notably on fragment properties, air gap, and fragment velocity and somewhat on propellant thickness and backing material. A one inch air gap between propellant samples always resulted in a detonation reaction for all fragment velocities investigated. Detonation reactions for other air gaps could be mitigated. Modeling and simulation efforts are also being pursued to provide further understanding into how the studied parameters may influence the reaction process.

INTRODUCTION

Fragment/bullet impact against fielded rocket motors and/or warheads have been investigated for many years with the intent to understand the vulnerabilities and how to adequately mitigate violent reactions. While these efforts have been beneficial, performing tests on full scale systems has made it challenging to identify and study the underlying mechanisms that lead to violent reactions. To address this knowledge deficit, specifically for rocket motors, the U.S. Navy at China Lake, CA, developed a simplified experiment called Planar Rocket Motor Test Model[1,2] (more commonly known as Burn to Violent Reaction (BVR) experiments). Since then, various agencies have used similar tests including the U.S. Army and the United Kingdom Ministry of Defence[3,4].

The simplified experiments typically consist of a projectile of interest impacting square slabs of propellant that are bonded to a motor case material and placed in series, see Figure 1. The main intent of this setup is to provide a geometry that simulates a bore perforation in a rocket motor while allowing for detailed measurements and analysis of the event. Both Ammonium Perchlorate (AP) composite based and Minimum Signature Propellants (MSP) have been studied, providing insight into several of the fundamental reaction mechanisms that lead to violent reactions. For MSP propellants, three reaction mechanisms typically have been observed, including Shock to Detonation Transition (SDT), Unknown Detonation Transition (XDT), and deflagration (Def) – a subsonic combustion process but not necessarily violent.

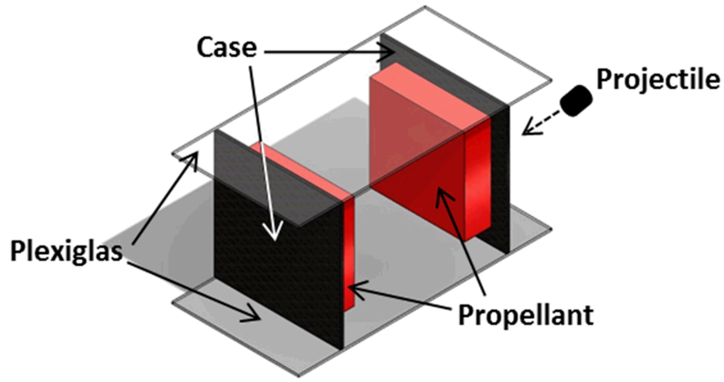


Figure 1 The simplified experimental setup consisting of a propellant bonded to a case simulant and impacted by a moving projectile.

The SDT reaction is caused by a shock wave propagation through a material resulting in a detonation that typically occurs <10 μs after projectile impact. Several factors have been found to influence the onset of projectile induced SDT, including projectile velocity, size, and the type of energetic material employed[5,6]. A projectile velocity threshold can be identified for a specific test article, above which SDT almost always occurs. Below the SDT velocity threshold, the other two types of reactions have been found to occur, depending primarily on test article geometry and projectile velocity[1].

An XDT reaction has historically been used to identify various difficult to explain detonation transition mechanisms, including reactions observed in shotgun, card gap[5], projectile impact[7] and BVR testing of propellants[1-4]. Through the remainder of this document, XDT will refer to the reactions mechanism specifically associated with the BVR experiments. This XDT mechanism results from the projectile impacting the first case/propellant article and forming a debris cloud of propellant on the opposite side of impact. The debris cloud travels across the propellant bore or the air gap separating the propellant samples, in the case of the BVR experiments, eventually impacting the following propellant surface (backing material). The resulting impact produces a reaction that transitions to a detonation at the interface between the leading edge of the debris cloud and backing material. Shock of the debris cloud has been suggested as the initiation mechanism[1,3,4]; however, this is an active area of debate within the community. If an XDT reaction does not occur upon debris cloud impact, deflagration followed by quenching of the debris cloud typically occurs.

A clear region of XDT reactions as a function of test article geometry and projectile velocity, bounded by regions of deflagration, have been previously found for a given test setup[1]. Finnegan et al. proposed and provided evidence that the upper limit of the XDT region is closely coupled to the continuity of the debris cloud[1] – once the debris cloud begins to breakup, it can no longer propagate a reaction back to the original propellant slab. Correspondingly, they showed that increasing propellant thickness and using more rigid casing materials could increase the debris cloud breakup distance and thus possibly extend the upper XDT limit to larger air gaps; however, they were unable to experimentally confirm their theory. It was also suggested that the lower XDT limit was a result of insufficient damage in the debris cloud at small air gaps, but no explanation was provided to support this hypothesis[1].

The focus of the current effort is to further elucidate the complicated mechanisms that govern the XDT reaction observed in MSP subjected to fragment impact. The traditional BVR experimental setup is employed while interrogating various parameters. Specifically, the effects of projectile velocity, projectile geometry, air gap, propellant thickness, and backing material will be investigated followed by a discussion of their effects. To complement these efforts, high fidelity computational models are being developed by Sandia National Laboratories (SNL) and Lawrence Livermore National Laboratory (LLNL) with support from Los Alamos National Laboratory (LANL). The challenges associated with modeling the XDT reaction will be discussed.

EXPERIMENTAL METHODS

A 20 mm powder smooth bore cannon was used to accelerate projectiles at velocities of 1700-6200 ft/s, see Figure 2. Projectiles consisted of either an 18.6 g NATO STANAG 4496 mild carbon steel (100 Rockwell B) Fragment Simulated Projectile (FSP) or a 16.1 g, 5/8 in diameter stainless steel sphere. Both were sabot launched – the sabots were removed midflight via a sabot stripper. Once passing the sabot stripper, the projectile would encounter 3 separate break screens that were used to determine the projectile velocity. The first two break screens and last two were separated by about 4.6 ft and 8.0 ft respectively, with the last break screen on the face of the test article. A light box, covered in a 1x1 in square grid and using one Megga-Flash PF300 Slow Peak Flashbulb for lighting, was placed about 12 in behind the test article centerline. Two rows of PCB Piezotronics 137B23B and 137B24B (50 and 250 psi respectively) pencil gauges were placed at 45° off the projectile flight axis and were placed 5, 9, and 13 ft away from the impact point on the test article. The gauges at 5 ft were model type 137B24B while the others gauges were 137B23B. High speed Phantom Miro 310 and v310 cameras were used to take images at 120k fps (close up) and 78k fps (overview).

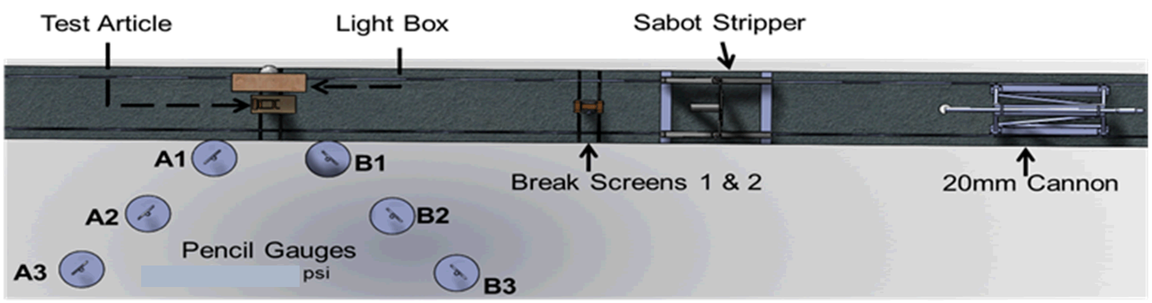


Figure 2 Test setup.

<u>TEST ARTICLE</u>

The test article consisted of 4.5 x 4.5 in square and either 1.25 or 2.5 in thick slabs of nitramine based Minimum Signature Propellant (MSP-1) bonded to 6 x 6 in square and 0.135 in thick composite panels that simulate a rocket case material. The test article consisted of either two sections of propellant slabs bonded to composite plates or a propellant slab bonded to a composite plate followed by a 6 x 6 in square and 1/8 in thick 4130 steel plate. The two sections were epoxied on two sides to clear 6 x 12 in rectangular and 0.093 in thick Lexan sheets in order to provide structural rigidity to the test article. The spacing, or air gap, between the two sections ranged from 0.5-4.5 in.

RESULTS AND DISCUSSION

All three types of reaction mechanisms previously recorded in BVR testing of MSP's were observed in the current, including SDT, XDT, and deflagration. However, a fourth mechanism was observed in the current experiments that resembled more a Deflagration to Detonation Transition (DDT). For this last mechanism, the debris cloud initiates upon impact with the backing material and deflagrates. This subsonic combustion event continues until the flame surrounds the propellant slabs and, instead of quenching, transitions to a detonation. Example images of each mechanism are provided in Figure 3.

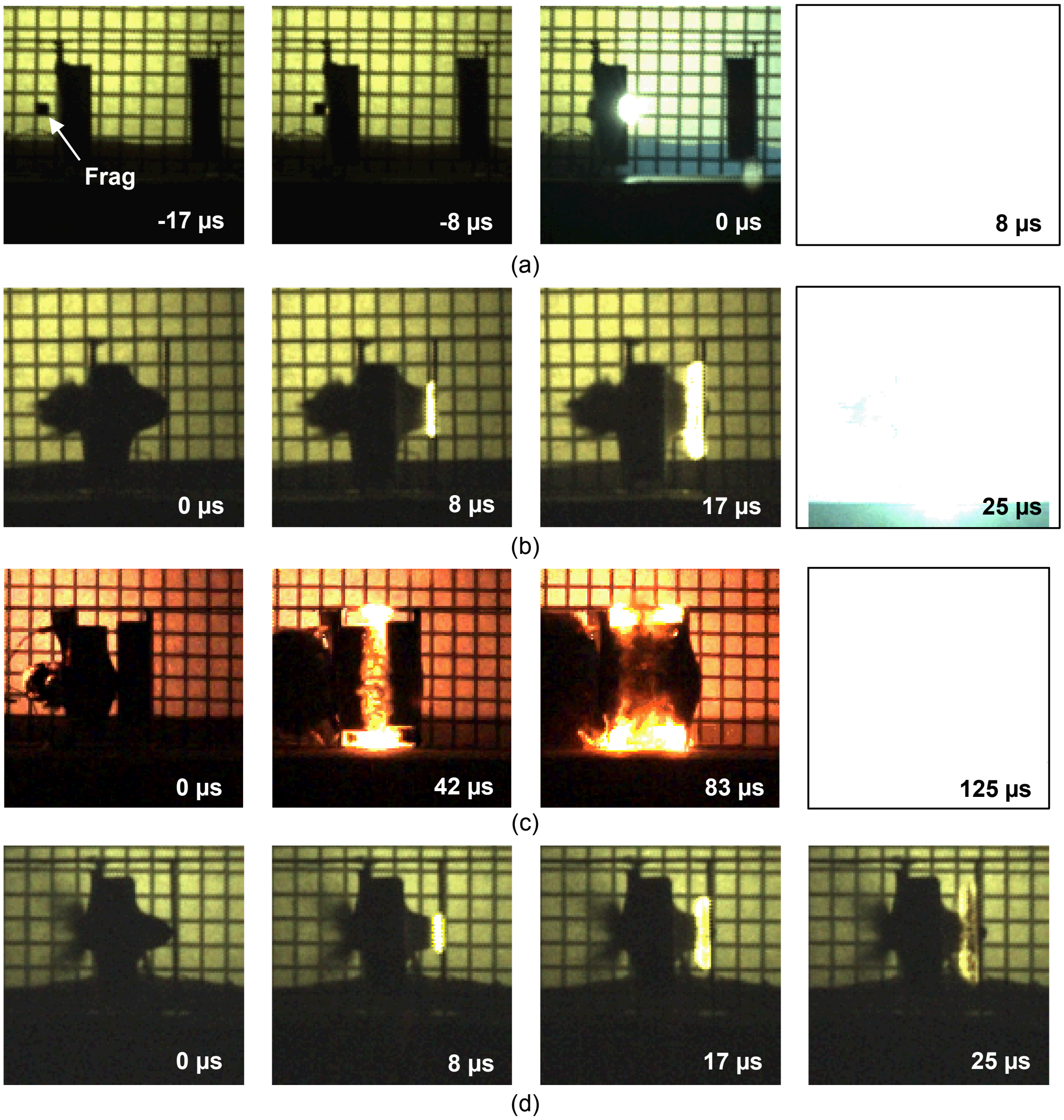


Figure 3 The reaction mechanisms observed in the BVR testing, including (a) SDT, (b) XDT, (c) a form of DDT, and (d) deflagration. Each of the last images in (a)-(c) are white (oversaturated) due to the intensity of the detonation reaction. The first image (b)-(d) is just before the generated debris cloud impacts the backing surface. Images are 8.33 µs apart except for series (c) which are 41.67 µs apart.

Two distinct velocity thresholds, delineating SDT and the other reaction mechanisms, were observed at 4330 and 6120 ft/s, corresponding to FSP and sphere projectiles respectively, see Figure 4. The different thresholds are likely caused by the strength of shock resulting from the projectile geometry and kinetic energy.

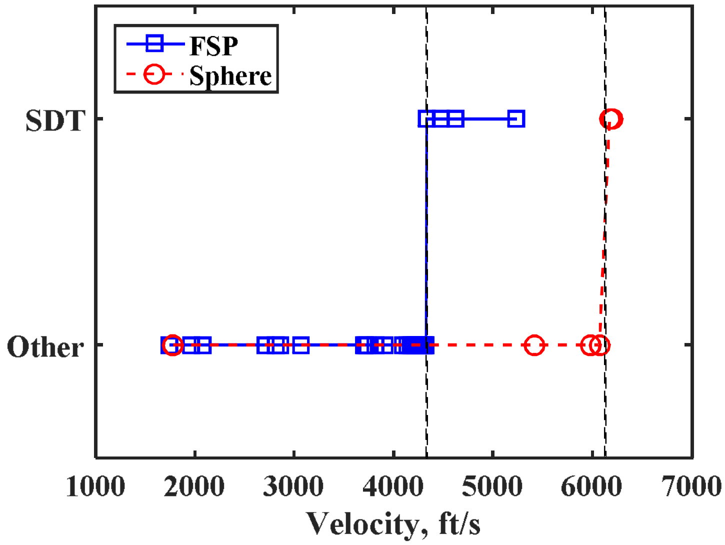
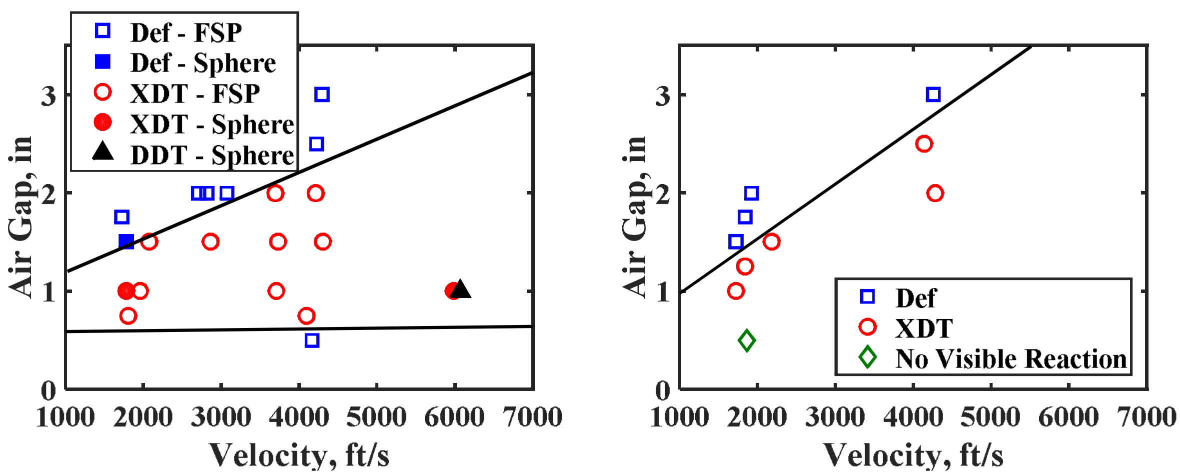
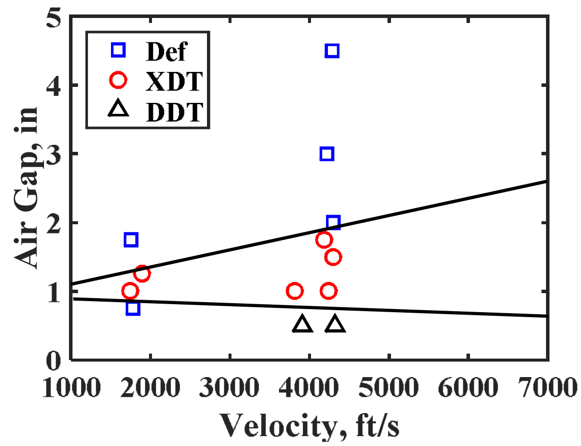


Figure 4 Other or SDT reaction mechanisms observed as a function of projectile velocity, resulting in distinct thresholds corresponding to different projectiles.

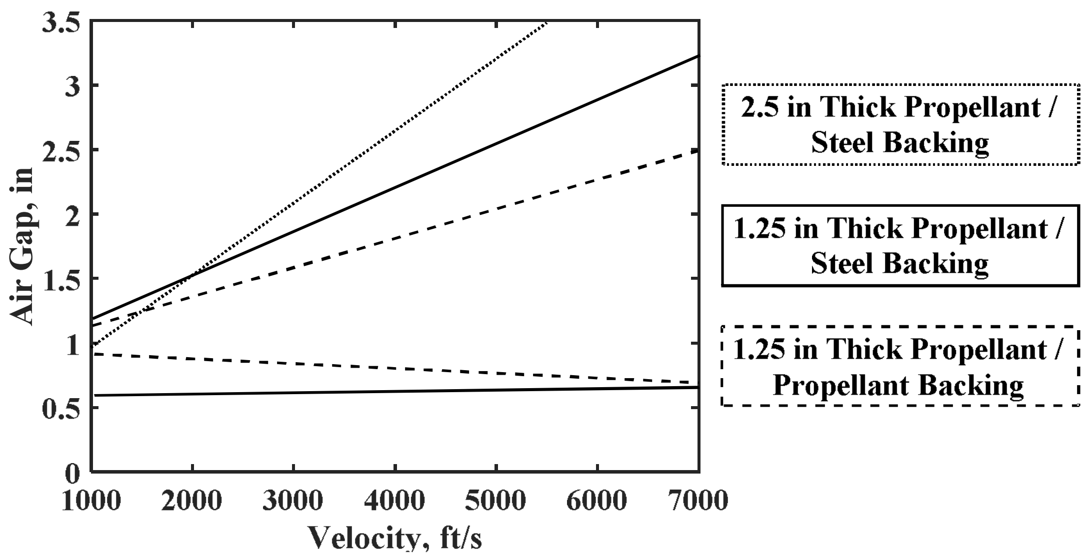
Below the SDT velocity threshold, the other three reaction mechanisms or no visible reaction were observed, depending on the combination of projectile velocity, air gap, backing material, and propellant thickness, see Figure 5. In these experiments, air gaps of 1 in always resulted in a detonation. Lower and upper air gap thresholds that varied with projectile velocity were observed for XDT reactions. In general, an XDT reaction could occur for air gaps of 0.75-2.5 in, depending on testing conditions, with deflagration occurring for air gaps greater than 2.5 in and no visible reaction, deflagration, or DDT occurring for air gaps less than or equal to 0.75 in. The bounds of the thresholds were inferred in several cases based on data available.



(a) (b)



(c)



(d)

Figure 5 The types of reaction mechanisms observed for projectiles impacting a (a) 1.25 in thick propellant/composite case followed by a steel plate backing material, (b) 2.5 in thick propellant/composite case followed by a steel plate backing material, and (c) 1.25 in thick propellant/composite case followed by a 1.25 in thick propellant/composite case backing material. Part (d) provides a comparison of the XDT threshold limits. Projectiles in (b) and (c) are FSP's.

A DDT reaction was more prevalent if the backing material was a slab of propellant, see Figure 5 (c) vs Figure 5 (a), suggesting that reaction of the second slab – resulting in higher pressurization rates and energy release – favored a transition to detonation. Interestingly, DDT reactions were also observed right at the SDT velocity thresholds, see Figure 5 (a) and (c). It is unclear what caused this behavior, but it may be possible that the material in the debris cloud had sufficiently reacted before impacting the backing material such that it was no longer detonable material. This is supported by the fact that visible light, indicating thermal reactions, was emitting from the leading edge of the debris cloud as it propagated across the air gap during the test that produced a DDT result in Figure 5 (a).

The upper and lower XDT thresholds were influenced by both propellant thickness and backing material. Increasing the propellant thickness from 1.25 in, Figure 5 (a), to 2.5 in, Figure 5 (b), caused the upper XDT air gap versus velocity threshold to shift to include even larger air gaps as projectile velocity increases. Conversely, changing the backing material from a steel plate, Figure 5 (a), to propellant, Figure 5 (c), caused the XDT upper and lower thresholds to decrease and increase respectively, resulting in fewer air gaps being susceptible to XDT. Both of these results suggests that multiple mechanisms are influencing the resulting reaction

DEBRIS CLOUD DYNAMICS

In order to better understand what is occurring in the complicated regime where XDT, deflagration, and no visible reactions are occurring, a discussion regarding the debris cloud is helpful. As the projectile passes through the test article, bulging of the propellant slab occurs, and subsequently, a relatively thin walled semi-continuous, semi-elliptical cloud is formed. During this process, it is likely that material is damaged, and it is possible that chemical reactions begin to occur. Thus, multiple properties of the debris cloud, including porosity, particle size, damage, temperature, and others, are changing rapidly as the cloud propagates across the air gap. It is a combination of these changing properties that likely allows and eventually prohibits an XDT reaction to occur.

Similar traits are observed in critical pressure and critical diameter experiments for explosives. An explosive which will not detonate or propagate a detonation under certain circumstances will under others – conditions that depend on porosity, temperature, and particle size of the explosive. Assuming that there is a direct correlation between the debris cloud detonation characteristics and explosives critical parameters, previous explosive critical pressure and diameter results can be used to help explain the observed behavior in the XDT mechanism. Specifically, decreasing porosity, increasing temperature, and decreasing particle size in the debris cloud should decrease the critical diameter/"critical thickness" of the debris cloud, while increasing porosity, increasing temperature, and increasing particle size should decrease the critical pressure[8].

The upper XDT reaction limit appears to depend on the ability of the debris cloud to propagate a detonation. As the velocity of the projectile increases, the amount of material (lower porosity) and the surface area (smaller particle sizes) of that material entering the debris cloud both increase[9]. It is also likely that the amount of damage of the debris cloud, and thus temperature, increase with projectile velocity. The combination of these factors will lead to debris clouds that can sustain detonations at much larger air gaps. By increasing the initial thickness of the propellant from 1.25 to 2.5 in, the amount of material entering the debris cloud increases (lower porosity), further extending the upper limit. By changing the backing material from flexible propellant to rigid steel, it is likely that pressure impulse into the impinging debris cloud increases, allowing the cloud to propagate a detonation at even thinner debris cloud thicknesses. The result of all these factors lead to more air gaps becoming susceptible to the XDT mechanism.

The lower limit of the XDT mechanism is likely dependent the ability of the debris cloud to initiate upon impact. Below the SDT threshold – or critical pressure threshold for pristine material, the initial impact of the projectile does not transfer sufficient energy to cause a detonation to occur. Given that the amount of kinetic energy of the resulting debris cloud will be less than that of the projectile, the propellant must undergo some process – chemical and/or physical – in order for it to be sensitive enough to transition to a detonation some time later in the event. As these processes occur, both the critical pressure and critical diameter values will evolve quickly, until the right conditions are obtained to both initiate and propagate a detonation – the lower XDT threshold. Thus, the experiments with rigid steel plate backing are more likely to produce an XDT reaction for small air gaps as the pressure impulse imparted into the debris upon impact will be higher than that provided by the propellant backing.

MODELING AND SIMULATION

The modeling of fragment impact on rocket motors and their surrogates presents a formidable challenge in that the response of the propellant is highly dependent on the correct modeling of the fragmentation of the propellant, the potential failure of the impacting fragment, and the failure of the case. All of these events have an effect on the initial conditions to the reactivity of the propellant and subsequently can influence the predicted results[10]. The resulting complex and coupled physics require extensive characterization of the propellant, casing material, and fragment material in order to perform proper modeling. To address these challenges, both SNL and LLNL are developing specialized multi-physics packages for CTH and ALE3D respectively, while they and LANL are performing in-depth characterization of the propellant and other system components.

The CTH shock physics code was used to simulate both SDT and XDT behaviors. In order to determine the SDT threshold, the two state HVRB (History Variable Reactive Burn) reactive flow model was used[11]. The HVRB model requires model parameters for the unreacted and reacted products equations of state (EOS), plus four parameters associated with the reaction. At the time of the calculations, the only material properties available were the composition, density, and a sparsely populated pop-plot. The reaction products EOS was constructed in tabular form using CTH-TIGER, a thermos-chemical-equilibrium code[12]. For the unreacted EOS, a Mie-Gruniesen was fit using wedge test data from a similar propellant. The reaction constants were determined through an optimization process in which the error in the least squares fit to the pop-plot data was minimized. With this characterization, the SDT threshold for a BVR experiment with a composite cover plate and 1.25 in thick propellant slab impacted with a NATO fragment was determined to be 4466 ft/s, very similar to the experimental 4330 ft/s threshold.

To investigate the possible mechanisms that were responsible for the XDT reaction, a reactive flow model with additional physics is required. The CDAR-K (Coupled Damage and Reaction - Kinetics) model was constructed to provide a capability of modeling scenarios from prompt reaction and delayed reaction due to damaged material undergoing additional impacts[13]. This model was built upon the reaction kinetics of the HVRB model with the addition of viscoelastic deformation, damage, and fragmentation. Initial results indicate that it is possible to model the damaged propellant sufficiently so that it undergoes an XDT when it impacts the far side surface of the experiment. Further studies will investigate the effects of gap and propellant thickness on the observed reaction mechanism.

At LLNL, BVR simulations are being conducted in the hydrocode, ALE3D, while implementing the HERMES model to describe the behavior of the propellant. The HERMES model[14-18] was developed to describe the behavior of explosives and propellants when subjected to mechanical insults including non-shock ignition, deflagration, and detonation. More recently, developments have focused on incorporating XDT capabilities into the model that describe the process where a mechanical stimulus fragments the propellant, developing the surface area needed for rapid burning to occur once ignited. Evolving porosity is also incorporated into the model, a feature needed to adequately model the pressure generation that transitions into a shock wake as well as capture the enhanced shock sensitivity of the damaged propellant. Figure 6 shows results of initial capability calculations of the XDT model for MSP-1 propellant in a BVR like test configuration. Depending on the air gap size, either a deflagration or a transition to a detonation, shortly after ignition of the fragmented (low density) propellant cloud striking a rigid plate, were observed in these calculations.

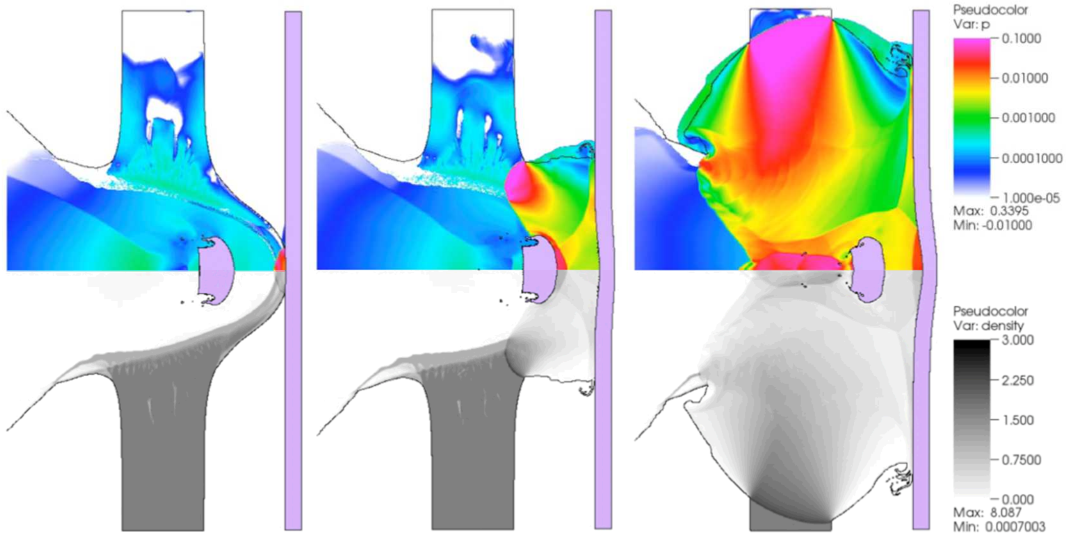


Figure 6. Demonstrative simulation results of initial HERMES XDT modeling in ALE3D of BVR tests. The MSP-1 propellant was found to have a deflagration or XDT response depending on gap size. This example shows an XDT response. Images are temporally spaced by 6 microseconds.

SUMMARY AND CONCLUSIONS

Multiple factors were investigated to evaluate their influence on producing one of four reaction mechanisms when the propellant of interest (MSP-1) is subjected to fragment impact. Projectile type and velocity, air gap, propellant thickness, and backing material all had measureable impacts on the outcome. The four reaction mechanisms observed included SDT, XDT, a form of DDT, and deflagration with no visible reactions occurring in one experiment. The SDT mechanisms was strongly dependent on the projectile shape and velocity with two clearly defined velocity thresholds above which SDT always occurred.

The occurrence of the other three reaction mechanisms depended on projectile velocity and air gap. Increasing projectile velocity made more air gaps likely to produce an XDT reaction. Clear upper and lower thresholds of projectile velocity versus air gap were found for the XDT mechanism with deflagration occurring above the upper threshold and no visible reaction, deflagration, or DDT occurring below the lower threshold. Increasing propellant thickness increased the XDT upper threshold to larger air gaps while changing the backing material from steel to propellant caused the upper threshold to decrease.

The XDT threshold appears to highly depend on the state of the debris cloud, with fragment size, amount of damage, and cloud porosity exhibiting important roles. Appealing to previous critical pressure/diameter investigations for explosive materials, if sufficient amount of damage has occurred, propellant fragment size is small enough, and the expanding nature of debris cloud has not increased the porosity notably, it is likely that an XDT will occur. Outside these bounds of either insufficient damage (XDT lower threshold) or too high of porosity (XDT upper threshold), deflagration or no reaction is a likely result.

High fidelity computational models are currently under development. Initial implementation of these models indicate that sufficient physics is included to capture the SDT and XDT threshold behaviors; however, accurate modeling of the propellant used in these experiments requires further characterization of the propellant properties.

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