2019 Insensitive Munitions & Energetic Materials Technology Symposium
Sevilla, Spain 21-24 October 2019

Insensitive Munitions Hazards Modeling & Simulation — an International Collaboration

Mr. Steven Collignon, NSWC Dahlgren
Mr. Thomas Swierk, Hart Technologies, Inc. (presenter)

Abstract (#22170): The US DoD and UK MOD both have a requirement to field weapons systems that are compliant with their respective Insensitive Munitions (IM) regulations. Improved modeling and simulation tools will reduce risk in the acquisition process and help current and future weapon systems meet present and future IM requirements. To address this need, an IM Project Arrangement (PA) was established by these two government organizations**.**

The overarching goal that challenged the US and UK technical teams was to significantly improve existing weapon design capabilities from an IM perspective using modeling and simulation (M&S) tools applied to selected test programs through focused development activities. The scope of the work planned to support these objectives included material model development supported by material characterization experiments, an integrated sub-scale analysis and demonstration, and a system-level analysis and demonstration.

It was agreed to focus the modeling capability development for a generic high-performance propellant (HPP). Modeling was aimed at determining the propellant response to a fragment impact threat as described in STANAG 4496. The technical challenge for these activities was to develop a predictive capability to determine the propellant response from the impact of a threat fragment as it traveled through the motor sidewall and into the internal cavity (bore) of the rocket motor. As the work on HPP concluded, it was recognized that this modeling capability should also examine another, more challenging class of propellants that was used in several weapon systems in both nations. A generic minimum signature propellant (MSP) was identified as an appropriate candidate for additional model improvement. This candidate propellant and the modeling capability that was developed then became the main components of the system-level demonstration.

This paper summarizes the activities of this multi-year project undertaken by the technical teams in the US and UK. This summary will cite notable achievements in model development to characterize the propellant response for both high performance and minimum signature propellants. Results of pre and post-test predictions of the full-scale demonstration of an analog rocket motor will be presented. The paper concludes with a list of recommendations for future work related to propellant modeling and the benefits realized by each nation as a result of this project.

Project Arrangement Goals and Objectives

The overarching goal of this Project Arrangement (PA) that challenged the US and UK technical teams was to significantly improve existing weapon design capabilities from an IM perspective using modeling and simulation (M&S) tools applied to selected test programs through focused development activities. The stated objectives of this PA were identified as follows:

- To develop modeling and simulations tools for system level IM assessment.
- To exercise these tools in a joint IM assessment of a complete weapon system.
- To demonstrate the ability to integrate validated modeling and simulation into system level design and quantification.

The scope of the work planned to support these objectives included material model development supported by material characterization experiments, an integrated sub-scale analysis and demonstration, and a system-level analysis and demonstration.

Project Arrangement Timeline

The timeline for activities undertaken under this Project Arrangement spanned a 12-year period from its formal inception in November 2006 through November 2018. The stated goal was to develop or modify M&S tools and apply them to a very technically challenging IM topic that would be useful for both nations for future weapon system development and assessment activities. Rocket motors have historically been vulnerable to many of the IM hazards with solid propellants being particularly vulnerable. M&S tools have been successfully used to examine threats to explosive-filled munitions, but that capability was seriously lacking when applied to rocket motor propellants.

It was agreed then to focus the modeling capability development for a generic high-performance propellant (HPP). Modeling was aimed at determining the propellant response to a fragment impact threat as described in STANAG 4496. This modeling approach continued throughout the remaining PA activities. The technical challenge for these activities was to develop a predictive capability to determine the propellant response from the impact of a threat fragment as it traveled through the motor sidewall and into the internal cavity (bore) of the rocket motor. This was a consistent challenge for the modelers throughout this work.

As the Phase I work on HPP concluded, it was recognized that this modeling capability should also examine another, more challenging class of propellants that was used in several weapon systems in both nations. A generic minimum signature propellant (MSP) was identified as an appropriate candidate for additional model improvement. This candidate propellant and the modeling capability that was developed then became the main components of the system-level demonstration outlined in the PA objectives listed above. This paper will thus focus on the MSP model development and the resulting improved modeling capability.

Background Information

The Burn-to-Violent Reaction (BVR) phenomenon was first studied in the US in the early 1990’s at NAWCWD/China Lake. It was also independently examined in the UK around the same timeframe. Similar work was undertaken by the Army at the Redstone Arsenal in the mid 1990’s, thus, the Army BVR (ABVR) test. There are over 30 publications describing work associated with BVR. Many describe detonation regions that exist for nitramine-based propellants. These included first (known) observed demonstrations of XDT related to traversing damaged propellant. Additional work was conducted at the US Army’s Aviation Missile Research & Development Engineering Center (AMRDEC) that was a validation of the ABVR experiments.

Subscale Testing Supporting MSP Model Development

The technical approach that was followed in this Project Arrangement used subscale, simplified tests to identify important parameters (such as projectile velocity, bore diameter and shape, web thickness, case material, etc.) that influence the rocket motor response to fragment impact. Various reaction types were considered, including shock-to-detonation transition (SDT), unknown-to-detonation transition (XDT), deflagration-to-detonation transition (DDT), brief combustion, and no visible reaction. The final step was to correlate the results with more realistic geometries and eventually an analog rocket motor to validate ABVR as an accurate subscale test for minimum signature propellants. Predicting an XDT response in a rocket motor then became the technical challenge for this study. The XDT phenomenon of this event is illustrated in Figure 1. ABVR tests (propellant samples configured as slabs separated by a defined air gap) were the first of the subscale tests conducted to provide information for the model development.

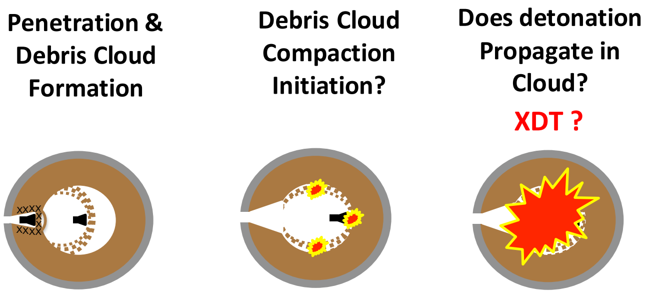


Figure 1: XDT Phenomenon in a Rocket Motor Resulting from a Fragment Impact

Additional subscale tests were conducted at AMRDEC that included test items in a cylindrical configuration. Data obtained from these activities (ABVR and cylindrical tests) were used to support the MSP model development. Details of these tests were given in a paper by Dr. Neidert at the 2018 IMEMTS[1]. The following conclusions were cited by Dr. Neidert in his paper with reference to the chart in Figure 2:

- ABVR reasonably predicts detonative behavior of a full-scale motor to fragment impact.
  - SDT threshold differs by <350 ft/s for the fragment velocity.
  - XDT reaction region is the same for thinner web thickness.
  - Thicker web causes some deviation.
- Insufficient data available to compare non–detonative region.
- Motors can detonate at lower velocities than what is typically expected.
- Non-detonative regions may exist that are bounded by detonative regions at high and low fragment impact velocities.

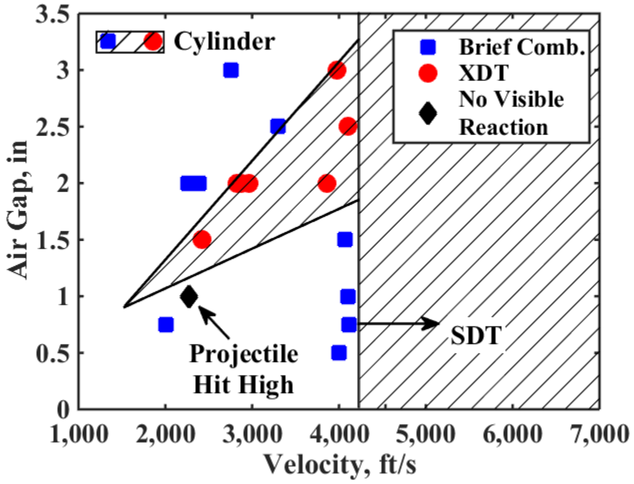


Figure 2: Subscale Test Results – Fragment Velocity vs. Air Gaps

<u>Reference</u> 1: "*Validation of the Army Burn to Violent Reaction (ABVR) Test as a Tool to Predict Full-Scale Motor Response to Fragment Impact,*" J. B. Neidert, M. A. Pfeil, J. A. Stanfield, 2018 IMEMTS.

Rocket Motor Configurations and Fragment Impact Response

The response of rocket motors subjected to fragment impact was examined. Motors containing HD 1.1 propellants can detonate via SDT and XDT. The XDT occurrence is more prevalent than previously thought. Three parameters drive XDT conditions to create cloud density conditions: bore size, web/slab thickness and projectile velocity. The change from brief combustion to XDT is caused by the debris cloud density. A visual breakup of the cloud was observed in the cylindrical tests and correlated to the XDT limit. The variation with fragment velocity appeared to correlate with the amount of material in the debris cloud and other factors that include the kinetic energy of the fragment, thickness of propellant, and presented area of the fragment.

Test observations indicated that a longer distance (i.e., larger air gap) is required for the debris cloud to expand and create the density level (porosity) necessary to inhibit XDT. For example, for a fixed velocity of 3,000 fps, response levels start benign at very small air gaps, transition to XDT in a region where the air gap increases, and transition to a brief combustion at very large air gaps (see Figure 2). A similar discontinuous result can be observed in Figure 2 for a fixed air gap of 1.5 inches where several response levels are noted as the velocity increases.

The prior information led to an examination of a critical density theory. Assume the mass in the debris cloud comes from a partial cone where a smaller diameter is equal to the projectile/fragment diameter and a larger diameter is dictated by the required volume. Now assume the debris cloud to be an ellipse with a diameter equal to the cone diameter and a thickness equal to a fraction of the propellant thickness. The debris cloud density is then determined to be the mass of the debris cloud divided by the ellipse volume. Critical density is achieved when the cloud reaches a specific distance from the propellant surface. It is at this point that the cloud density reaches the correct level of porosity and temperature where ignition and propagation are possible.

Another observation was noted regarding the debris cloud velocity. For low fragment velocities (1835-2958 ft/s) the cylindrical tests demonstrated that there was little effect on debris cloud velocity. For high fragment velocities (3841-4310 ft/s) with 1.25 in. web thickness, the curvature caused a notable increase of debris cloud velocity. For high fragment velocities (3294-4115 ft/s) with 2.50 in. web thickness, the curvature was observed to cause a notable decrease in debris cloud velocity. These test observations demonstrated that both web thickness that defines the bore and the curvature of the bore are key parameters that impact cloud density and ultimately propellant response. An overview of the modeling approach follows.

Pre-test Modeling of the Analog Rocket Motor

The system-level predictive analysis for the analog test series was the opportunity for the modelers to offer pre-test predictions of the propellant response that utilizes the enhanced model capability. Information obtained during the development of the models was used for these predictions and their applicability to predict the response of the fragment impact hazard. Models were developed for the impact response of detonable propellants. The modelers cited the following in their approach:

- **Problem**:_“MSP-1” rocket motors undergo XDT at unacceptably low projectile impact velocities. Validated IM models do not exist for predicting XDT & deflagration in projectile impact scenarios.
- **Objective**:_Develop and validate the Lawrence Livermore National Laboratories (LLNL) High Explosive Response to Mechanical Stimulus model (HERMES[2]) to predict the impact response of MSP-1 rocket motors ranging from SDT to XDT to deflagration.
- **Benefits**:_Munition designers can use the HERMES model in the Arbitrary Lagrange Eulerian 3-dimensional multi-physics code (ALE3D) to develop new rocket motors and barriers that eliminate susceptibility to XDT by design.
- Use the XDT model to aide in the design of new sub-scale experiment that screens new MSP formulations.
- Develop methodology for XDT modeling that can be applied to other energetic materials.

Reference 2: *Reaugh, White, Curtis, Springer (2018), Journal of Propellants, Explosives and Pyrotechnics*

The MSP-1 HERMES model was initially applied to the ABVR and cylindrical experiments. These simulations were used to guide the design of the next integrated experiment and ultimately the pre-test predictions of the reaction violence of an analog rocket motor observed in the fragment impact tests. Calibration of the MSP-1 HERMES model was undertaken to demonstrate model behavior in slab ABVR geometry. Mechanical insults to explosives or propellants result in a broad spectrum of responses. These include: deformation, damage, and fracture without ignition; ignition that self-extinguishes; ignition followed by violent deflagration; delayed detonation; and prompt detonation. HERMES was developed to model this entire spectrum. When the energetic material properties are determined by testing, the HERMES model gives a credible simulation of test item responses.

The XDT response at high velocities is dependent on the in-bore debris cloud velocity during recompaction. The modelers needed the timing of cloud breakout, profile, and velocity to better understand mechanisms that lead to XDT at high velocities and improve/validate their models. Higher cloud velocities resulted in an increased burn rate and pressurization. Additionally, gap/bore size was known to have an effect on XDT thresholds. Large gaps result in a debris cloud that has longer filaments of low density that hinder propagation of reaction fronts back into the slab. Cylindrical geometry produces a debris cloud with anisotropic properties. Simulations showed the slab geometry to be more sensitive than cylindrical geometry.

It was then hypothesized that XDT is essentially SDT in the debris cloud where two things need to happen:

- **INITIATION** needs to occur in the porous debris cloud that is shock compacted by the projectile.
- Most energetic materials show increased shock sensitivity with increasing porosity.
- Initiation occurs at relatively lower projectile speeds for the steel “2nd slab” due to higher shock impedance than the propellant.
- The main reason for suppressing XDT at small gaps was the higher density debris clouds do not have sufficient porosity to initiate at lower fragment velocities.
- Detonation needs to **PROPAGATE** into the rest of the debris cloud (steel 2nd slab) or bulk propellant (propellant 2nd slab). This was the main reason that XDT is suppressed at the biggest gap sizes especially with the steel 2nd slab. There isn’t sufficient material in the debris cloud to continue to propagate detonation.
- XDT requires INITIATION + PROPAGATION to occur.

The next step was to create the configuration for the pre-test model predictions. The generic design of a large-scale rocket motor analog used for calculations in ALE3D is shown in Figure 3.

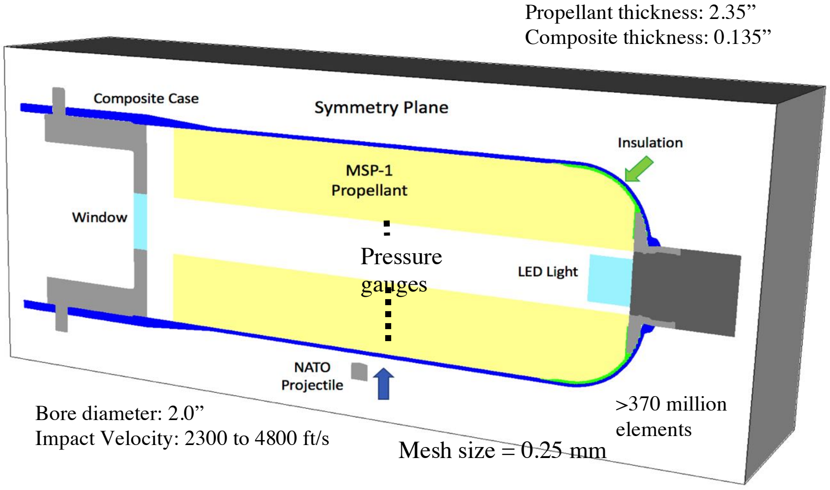


Figure 3: Analog Rocket Motor Configuration for Pre-test Modeling

Analog Rocket Motor Test

A generic rocket motor was designed to simulate a full-scale motor for testing in order to validate the model's predictive capability. Six items were fabricated (see Reference 1). The six test items were each filled with MSP-1 propellant (31.3 lbs.) with a web thickness of 2.41 inches and a 2-inch air gap. For the test setup all were oriented vertically (nose down). A mirror allowed for internal viewing of the motor. Pressure gauges were set in circular pattern or 45° offset from the shotline.

Results of the fragment impact testing conducted on these six test items were documented in 2018 in Reference 1. All test results were compared and included the sub-scale tests where the response thresholds were given for ABVR tests (4536 ± 125 ft/s), cylindrical tests (4219 ± 104 ft/s) and for the analog motors (4675 ± 118 ft/s). The reactions observed in the analog motors were very similar to those observed in the cylindrical test items. Model development and subsequent modeling of the propellant response continued leading up to the analog rocket motor test – the planned system demonstration.

Test Results vs. Modeling Predictions

A comparison of the predicted responses (pre-test modeling) and the responses observed in the experiments (lab-scale and full-scale analog rocket motor) is shown in the chart in Figure 4. Additional findings for three fragment impact velocity regimes modeled included the following as a supplement to this chart:

- At 2400 ft/s a Deflagration response is predicted. Recompaction shock on the opposite side of propellant bore is NOT sufficient to initiate a detonation in the debris cloud. Only deflagration is predicted.
- At 3800 ft/s an XDT response is predicted. Recompaction shock in the debris cloud IS sufficient to initiate a detonation (an XDT response) which propagates to the bulk propellant.
- At 4400 ft/s an SDT response is predicted. Fragment impact on the rocket motor case sidewall initiates a prompt shock-to-detonation transition (SDT) within the propellant web-thickness.

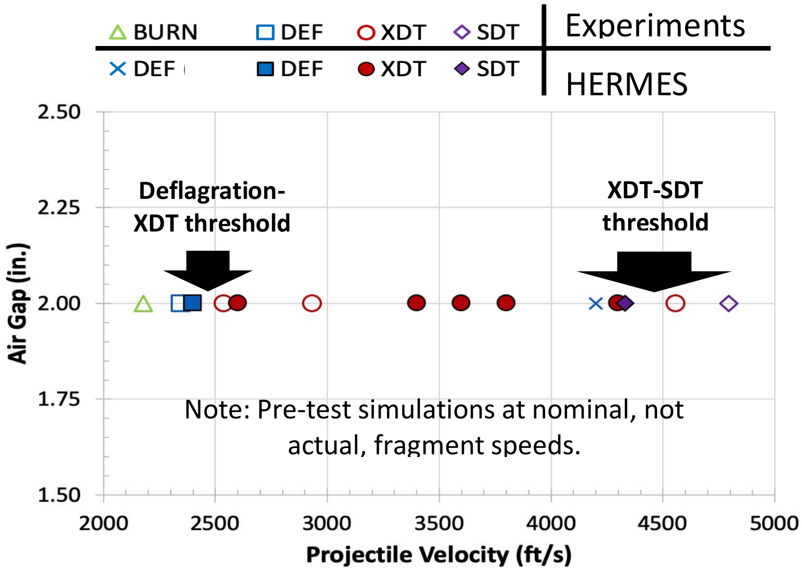


Figure 4: Comparison of Test Results (ABVR, cylindrical and analog rocket motor) vs. HERMES Model Predictions

Major accomplishments

The major accomplishments achieved from the overall IM PA work based on independent and collaborative work include the following:

For the MSP model development:

- Developed the HERMES model for XDT and implemented in ALE3D.
- Conducted subscale testing (slab tests and ABVR tests) to characterize propellants providing needed input data for the model development.
- Parameterized the HERMES/XDT model for MSP-1 based on material characterization and subscale test data.
- Designed and conducted the analog rocket motor tests to enable model validation.
- 3-D simulations predicted the XDT response of the analog rocket motor prior to the test.
- Validated the accuracy of the HERMES model with the pre-test predictions of the analog MSP rocket motor responses.

Predictive models that reproduce the XDT phenomenology have been developed. Responses of rocket motor propellants (SDT and XDT) were successfully predicted by the US for its variant of MSP. The UK was able to predict SDT for their MSP variant. Model development to accurately predict XDT responses is continuing as a work-in-progress in the UK.

Recommendations

The following recommendations were offered by each nation to build upon the modeling capability developed and demonstrated during this PA. The work conducted by the modeling team in the US offered the following recommendations based on the development of an enhanced modeling capability for propellants and improvements thereof. This validated propellant modeling capability is available for use by the development community for new and/or improved rocket motor design applications. Further improvements to enhance the model were suggested by the team and are listed below:

- A better understanding of the damage and fragmentation response of the debris cloud under the correct loading conditions incorporating this knowledge into a model is needed.
- X-ray phase contrast imaging should be used for the following:
  - ➢ The projectile boring through the propellant slab to better understand damage accumulation, burning characteristics, relative velocity between projectile, burn-front, and debris cloud front.
  - ➢ The debris cloud to measure effective density, filament thickness, particle velocity.
  - ➢ Projectile velocity while penetrating.
- High resolution imaging of projectile impact of fragment surface and of the debris cloud for measuring front velocity should be used.
- Small-scale test to characterize damage at high rates and tri-axial behavior at high rates should be conducted.

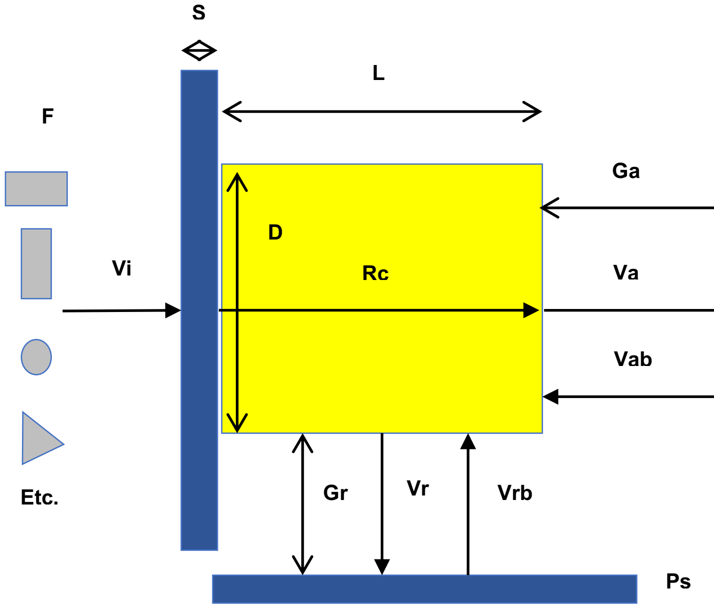
The work presented in the QinetiQ report identified a number of avenues of further study, including theoretical and experimental developments to provide the UK energetics community with a fully predictive rocket motor design capability within the next five years. It was recommended that:

- The road map developed in this program detailed the way that the validated toolset could be used as a general capability by stakeholders. This road map should be adopted and initiated to provide a fully predictive capability within the next 5 years.

- Experimental techniques to measure the interactions between components in an energetic material should be established to support the development of fully predictive material models.
- A technical strategy to develop a comprehensive reactive flow modeling capability for energetic materials should be constructed by the energetics community.

Benefits Realized & Future Direction

The UK provided a high-level summary of the benefits of the PA activities. The personnel and organizations who have been involved and supported this work helped to create and strengthen relationships. This will influence future collaborative activities. The information generated during the execution of this PA helped to create a generalized SDT/XDT experiment (Figure 5) and ultimately a conceptual framework describing the XDT phenomena (Figure 6).



Variables	
F	Fragment (Material, geometry)
S	Septum (Material, thickness)
Pb	Backplate (material)
Ps	Sideplate (material)
L	Charge length
D	Charge diameter
Rc	Radius of curvature
Ga	Gap - axial
Gr	Gap - radial
Observations	
Vi	Fragment velocity at impact
Va	Axial cloud velocity
Vab	Axial burnback velocity
Vr	Radial cloud velocity
Vrb	Radial burnback velocity
	Cloud extent and "density"
	Reaction (SDT, XDT, no DT)

Figure 5: Generalized SDT/XDT Experimental Setup

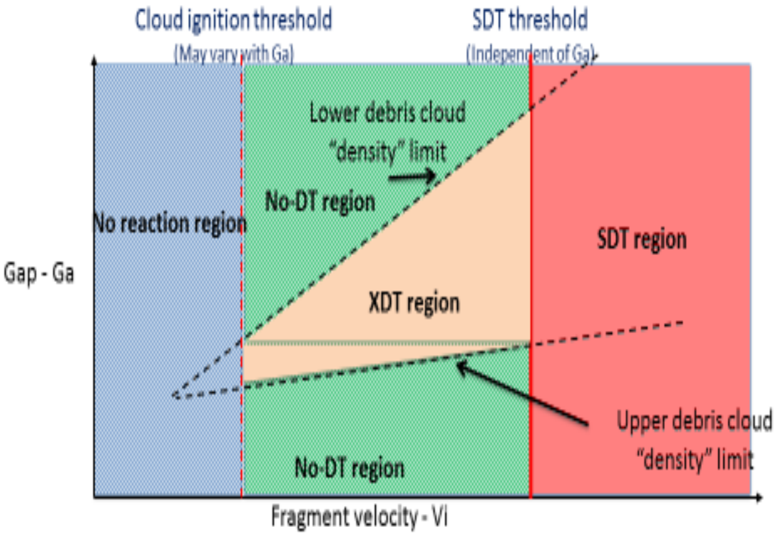


Figure 6: Conceptual framework (for each fragment/target combination):

Acknowledgements & Reference Bibliography

The following personnel and organizations are gratefully acknowledged for their contributions to the successful completion of this Project Arrangement:

US Technical Project Officer
Mr. Robert Garrett, NSWCDD (retired), 2006-2007
Mr. Steven Collignon, NSWCDD, 2008-2018

UK Technical Project Officer
Dr./Professor Adam Cumming (retired), MOD/Dstl, 2006-2013
Mr. Peter Collins (retired), MOD/Dstl, 2013-2016
Mr. Justin Fellows, MOD/Dstl, 2016-2018

The principal technical contributors and their respective organizations who were most instrumental in the successful completion of both Phase I and Phase II are recognized below:

US Technical Team
Mr. Paul Butler, SNL (retired)
Dr. Eric Harstad, SNL
Dr. Lara Leininger, LLNL
Dr. Eric Mas, LANL
Dr. Thomas Mason, LANL
Dr. Jamie Neidert, AMRDEC, team lead
Dr. Mark Pfeil, AMRDEC
Mr. Jack Reaugh, LLNL
Dr. Keo Springer, LLNL
Ms. Jessica Stanfield, AMRDEC
Dr. Bradley White, LLNL

DOE/JMP Technical Advisors (US)
Dr. Dennis Baum
Mr. Paul Butler
Dr. Eric Brown
Dr. Steve DeTeresa
Ms. Kelly Rhodes
Dr. John Bingert
Dr. Chris Cross
Dr. Aaron Brundage

UK Technical Team
Mr. Philip Cheese, MOD/DOSG
Dr. Malcolm Cook, AWE
Dr. Ian Cullis, QinetiQ, UK technical team lead, MOD contract (retired)
Dr. Peter Gould, QinetiQ
Dr. Alec Milne, Fluid Gravity
Dr. William Proud, Imperial College
Mr. Thomas Reeves, MOD/DOSG
Dr. Michael Sharp, MOD/DOSG
Mr. Nathan White, MOD/DOSG
Dr. David Williamson, Cambridge University

The list that follows summarizes documentation of the activities of this PA. Presentation material and papers as published proceedings of technical conferences or symposia are also listed.

- Summary documents – 18 Executive Review Reports
- Technical papers describing work derived from the PA activities published in event proceedings include the following:
  - Insensitive Munitions & Energetic Materials Technology Symposium (2015, 2016, 2018)
  - JANNAF Conferences (US)
  - International Ballistics Symposium
  - International Physics Symposium
- Numerous internal technical reports published by participating organizations in each nation. These organizations include the following:
  - US – US Army (AMRDEC), DOE laboratories (LANL, LLNL, SNL)
  - UK – MOD (Dstl, DOSG, AWE), QinetiQ, Roxel, Cambridge University, Imperial College

Co-author contact information:

Mr. Steven Collignon
Naval Surface Warfare Center Dahlgren Division
6138 Norc Ave., Suite 314
Dahlgren, VA 22448
steven.collignon@navy.mil
540-653-4083

Mr. Thomas E. Swierk (presenter)
US Navy Project Manager (ret.),
IM Technology & System-level IM Integration
Hart Technologies, Inc.
Supporting NSWC Dahlgren
Thomas.swierk.ctr@navy.mil
Tswierk@harttech.com
1-540-653-4458