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Modeling and Simulation — an Enabler for IM Development and Assessments

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Abstract: The defense industry needs a high-fidelity modeling and simulation capability for Insensitive Munitions hazard analysis of propulsion systems in order to quantify the trade space needed for performance vs. safety. Full-scale testing of large propulsion systems is too costly and not practical due to lack of sufficiently large instrumented test facilities. All DoD missile development programs are required to be IM-compliant and will benefit from the knowledge and tools developed under this initiative. The defense and commercial space propulsion industry will similarly benefit.

Work is underway through contracts with the Missile Defense Agency's Small Business Technology Transfer Program (STTR). A Phase I contract was completed in 2007; Phase II and Phase III contracts are nearing completion in 2010. The Phase I effort examined transition critical paths including material models for rocket motor cases and propellants, techniques for predicting initiation and growth of reactions and hydrocode methods for predicting prompt or delayed detonations. The current Phase II work examines M&S capabilities to predict the effectiveness of techniques for mitigating bullet and fragment impact and thermal hazards relative to rocket motor behavior. The current Phase III work applies the M&S tools utilized in the Phase II effort to a specific weapon application scenario.

The technical work is led by Strategic Insight, Ltd. as the integrating contractor for the DoD and is supported by personnel at DOE laboratories who are developing the M&S toolset for these IM applications. This paper summarizes background information and describes the motivation behind these STTR contracts and lays the groundwork for the detailed analyses undertaken by the contract team.

Introduction

The Department of Defense (DoD) seeks to leverage the Department of Energy (DOE) investments in Modeling and Simulation (M&S) tool development and adapt their science-based M&S tools to provide a predictive capability for the DoD acquisition community. The goals are to reduce development risk, acquisition costs and schedule for the design and evaluation of DoD systems in an environment of reduced testing and increasing safety standards. The parallels between the DOE and DoD needs for risk reduction, testing limitations, and predictive tools are striking and represent mutually beneficial opportunities. This is a collaborative environment that will aid both the Insensitive Munitions (IM) and weapon system safety communities.

Modeling & Simulation — a Necessary Analysis Tool for DoD

The Weapons & Munitions M&S Initiative (MSI) in the DoD has many components that independently support its ambitious goals for the DoD acquisition community. They include using the collaborative input from the small business + government/academia partners to meet the MSI goals by: reducing acquisition cycle time and development costs; integrating S&T State-of-Art into weapon acquisition; reducing program risk; and reducing required testing (i.e., testing "smarter"). This should result in the fielding of safe, IM compliant weapon systems while maintaining performance goals. This will further aid in understanding performance margins rather than point solutions. The intended result is to institutionalize M&S advancements into DoD acquisition culture.

In this context, M&S is seen as an enabling capability for DoD. Predictive modeling tools capable of assessing energetic response can be used to aid in the prevention and mitigation of IM hazards and threats. M&S tools can enable the design of subscale tests that often predict the outcome of full-scale IM tests. M&S tools are an aid in test data interpretation. M&S tools can enable the quantification of statistical uncertainties and design margins, supplementing fewer numbers of tests. M&S tools aid in defining the response envelope rather than simple pass or fail — How close was the munition to pass or fail? Pass by chance or by design? M&S tools can enable performance & safety trade-off studies early in the design phase.

Analysis of IM Events

Safety related hazards and hazards related to hostile events fall into two distinct categories when viewed from a physics perspective. "Mechanical insults" from kinetic energy deposition on a weapon that result from bullet, fragment, spall or even shaped charge jet impacts offer a broad spectrum of conditions for an analysis of weapon response. Likewise, a "thermal insult" is the heat transfer within a weapon and has the potential for numerous scenarios that encompass slow heating (slow cook-off), fast heating (fast cook-off) and heating rates that fall between these established standards. Advances in the state-of-the-art of the physics-based models in recent years have created an opportunity for the weapon development community to use these tools effectively to screen design candidates and to predict lab scale or full scale test outcomes. The overall M&S capability addresses a wide range of physics phenomena that relate to the energetic material, its behavior when exposed to threat stimuli and ultimately its final response that determines the outcome of an IM event. Physics-based numerical models function over a wide range of time scales for each of the related events that occur sequentially in an impact event. These phenomenological events and their

Physics Phenomenology \ IM Tests Fastest Time Scales	BI 10^{-3} s	FI 10^{-3} s	SR 10^{-3} s	FCO 10^{+2} s	SCO 10^{+5} s	SCJ 10^{-6} s
Penetration	☑	☑			Physics based Codes • Numerics Must Couple Across Disparate Time Scales • Numerics Must Couple Multiple Physics	
Mechanical Damage & Ignition	☑	☑				
Thermal Ignition	☑	☑		☑ 2nd Gen	☑	
Shock Initiation	☑	☑	☑			☑
Burn & Explosion	☑	☑	☑	☑ 2nd Gen	☑	☑
Integrated violence of Response	☑	☑	☑	☑	☑	☑

Figure 1. Time Scales for Physics Phenomenology during IM Events

time scales are shown in **Figure 1**. This is indeed the Grand Challenge for the physics based models — couple multiple codes in a framework that can be a viable tool for assessing IM event outcomes.

Small Business Technology Transfer Program (STTR)

A topic that relates M&S tool development to specific IM issues was published in January 2007as part of the Missile Defense Agency's STTR Program. This topic *"Expedited Transition of Propulsion Modeling & Simulation Capability"* had the following objective: to facilitate making M&S capabilities more accessible to industry for IM related applications. The primary focus was on propulsion systems and selected potential hazards. The scope of the planned effort included the following: propulsion systems analysis for propellants; confinement & integral mitigation methods for improved IM performance; and system level design solutions for mitigation of threats & consequences.

Propulsion Modeling and Simulation Initiative

Industry needs a high-fidelity M&S capability for IM hazard analysis of propulsion systems in order to quantify the trade space for performance vs. safety. Full-scale testing of large propulsion systems is too costly and may not be practical due to lack of sufficiently large instrumented test facilities as well as the large number of potential hazards and life-cycle configurations[*]. This work provides a parallel, multivariate user interface and data organization knowledge structure, including appropriate testing protocols, to enable industry to integrate the DoD and DOE M&S capability into their programs and technology bases. The primary focus is the development and growth of engineering models and codes to address impact hazards from bullets and fragments. The secondary focus will be on thermal hazards. All DoD weapon development programs are required to be IM-compliant (as determined by IM hazard analysis and testing[1]). Additionally, IM and DoD Hazard Classification[2] testing are now required to be "harmonized" as joint test programs and as such will benefit from the knowledge and tools developed. The defense and commercial space propulsion industry will benefit similarly. This work is being conducted under a contract through the Missile Defense Agency's STTR Program. The technical work is led by Strategic Insight, Ltd. as the integrating contractor and is supported by specialists at DOE laboratories who are developing the M&S toolset.

The STTR Phase I effort examined transition-critical paths, including material models for rocket motor cases and propellants, techniques for predicting initiation and growth of reactions and hydrocode methods for predicting prompt or delayed detonations[3]. The Phase I assessment was that

[*] Multiple logistic and life cycle configurations are associated with the stockpile-to-target sequence and exposure to many potential hazards and threats.

M&S capability is immature for predicting the response violence of propellants confined by rocket motor cases, but mature enough to assess mitigation of bullet/fragment impact and thermal threats. The current Phase II work examines M&S capabilities to predict the effectiveness of techniques for mitigating bullet and fragment impact and thermal hazards relative to rocket motor behavior. The overall effort can be summarized in these terms:

- *Objective*: Facilitate making M&S capabilities more accessible to industry for IM-related applications.
- *Primary focus*: Propulsion systems and a few potential hazards, namely bullet and fragment impact threats and fast-heating hazards (e.g., liquid fuel fires).
- *Scope*: Areas of interest include M&S tools for propulsion systems analysis including propellants, confinement and integral mitigation methods for improved IM performance; and system-level design solutions for mitigation of threats and consequences.
- *Plan:* Develop "knowledge structure" for weapon program managers (PMs) to support integration and transition of M&S tools; and develop and demonstrate M&S tools to address specific IM hazard mitigation analyses for propulsion systems.

This paper discusses the status of the planned knowledge structure for linking weapon acquisition program managers' and safety authorities' IM processes and taxonomy to the M&S phenomenology/ science processes and taxonomy. This linkage provides the common frame of reference needed to integrate M&S in the design and assessment of munitions and mitigation systems that currently rely solely on testing to verify IM compliance. Discussion of the upgraded M&S toolset and the results of their demonstrated capabilities will be the subject for future papers regarding this topic.

Why Is M&S Needed for Propulsion Systems?

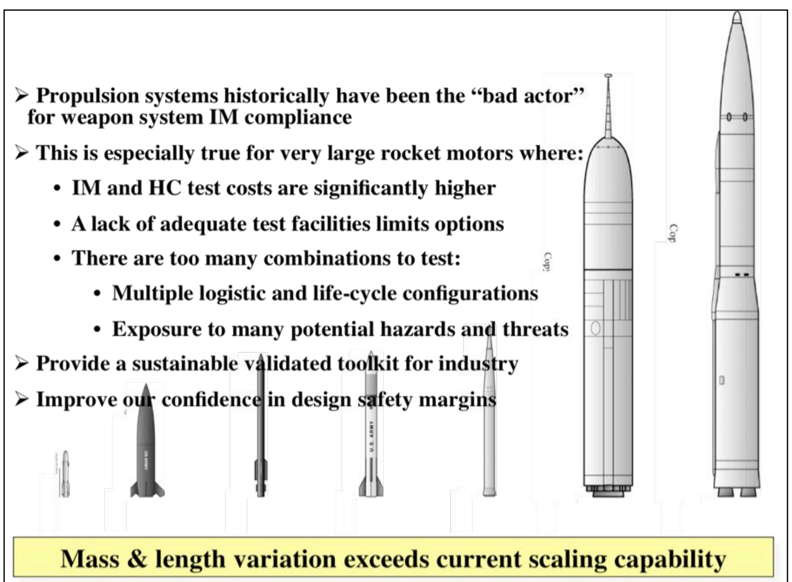

Figure 2. Why M&S is Needed for Propulsion Systems

Propulsion M&S is essential for reasons such as those summarized in **Figure 2**. For very large missiles, full-scale testing is costly and may be impracticable due to the lack of sufficiently large instrumented facilities. M&S is an enabler. It can help establish scalability for reliable sub-scale testing of very large motors. For all motor sizes, it strongly complements testing, which alone cannot feasibly cover all the combinations of system configurations, hazards and threats required to establish confidence in the margins of safety over the weapon's logistic and life-cycle environment.

It is difficult to establish confidence in safety margins because of uncertainty in how the weapon system, propulsion subsystem or its propellant will react to hazard insults (impact and/or heating). Uncertainty causes the number of required trials to be prohibitively large for testing alone. Experiment-anchored M&S can be used to simulate a large number of trials and quantify uncertainty (establishing expected safe operating boundaries and margins). IM-compliant solutions will require coping with the uncertainty of predicting propellant reaction to threat hazards or mishaps via M&S analysis that derives confidence from prior experience supplemented by weapon-specific experiments. This is the central theme underlying the approach to a propulsion M&S knowledge structure.

The Problem: Uncertainty of Propellant Reaction to Hazard Insult

Warhead explosives and strategic missile solid propellants are typically Hazard Division (HD) 1.1 energetic materials. (See Reference 2 for definition of hazard divisions.) Propellants used in tactical missile solid propulsion subsystems are typically HD 1.3 energetic materials. The discussion herein is limited to 1.3 solid propellants, for which reactions to threat or mishap hazard insults (impact or heating) are uncertain. Possible propellant responses range from no reaction to burn to violent reaction. **Figures 3**, **4**, and **5** sequentially address propellant reaction uncertainty, its variability, and the use of M&S to cope with uncertainty. The overall intent is avoidance of damage/ignition (first line of defense) and mitigation (if damage cannot be avoided and ignition/reaction growth occurs).

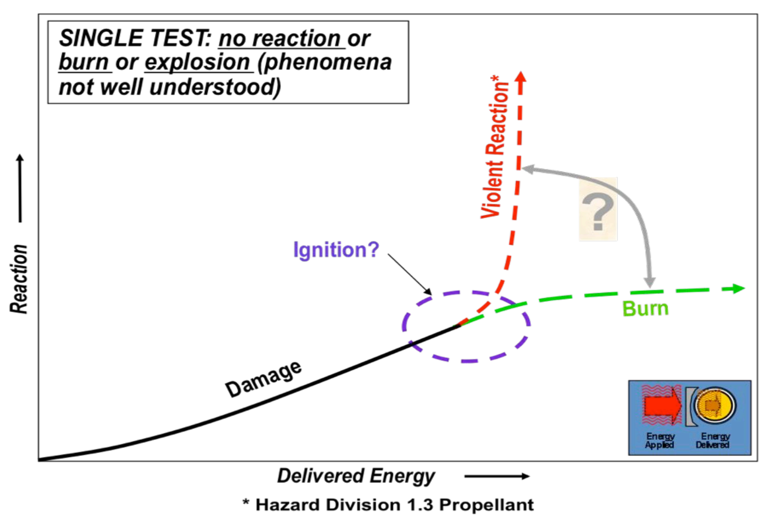

Figure 3. Violence of Reaction I Uncertain (1 of 3)

For a single test, the uncertainty range for reaction of a typical HD 1.3 solid propellant to an insult (impact or heating hazard) is illustrated in **Figure 3**. "Applied energy" is the actual impact or heating hazard insult that is applied to the confinement (e.g., the missile all-up-round (AUR) canister and the rocket motor case). "Delivered energy" is transferred through confinement layers to the propellant via mechanical coupling for impact insults.

For heating insults, applied energy is translated to delivered energy via conductive, convective or radiative heat transfer. <u>Note that "delivered energy," along the horizontal axis, is a complex function</u>

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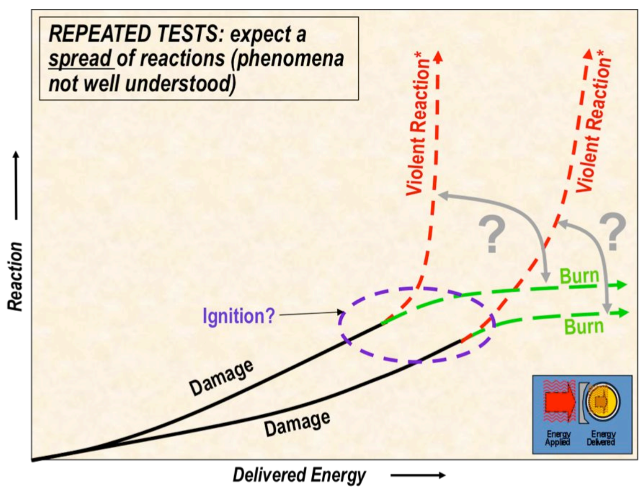
of time and not just time itself. Delivered energy at a particular point along the axis can be associated with the temperature of the propellant at a given time after the insult. Time representation along the axis is non-linear, stretching to seconds, minutes, or even hours during the early temperature rise (damage phase). At and beyond ignition, time is extremely compressed to milliseconds or even microseconds.

Ignition may or may not occur as a result of damaging the propellant. (Absent ignition, the heat could cause pyrolysis, possibly creating a toxicity hazard.) Occurrence of ignition is dependent on the extent and severity of the damage and whether the material is "pristine" (no prior damage) or "damaged" (i.e., prior to the current insult). Given ignition, the reaction could be partial or complete burning in a variety of ways (including smoldering, non-propulsive burn, or propulsive burn). Obviously none of the above are desirable effects. Lacking sufficient venting (unintentional or intentional), the reaction could grow rapidly to an violent reaction with collateral effects.



* Hazard Division 1.3 Propellant

Figure 4. Violence of Reaction I Uncertain (2 of 3)

As illustrated in **Figure 4**, repeated testing (hardware configuration and test conditions remain as identical as possible) might exhibit wide variation due to currently unpredictable stochastic behavior (at the molecular or atomic level) as well as statistically predictable variation (if the probability distributions of variations in hardware configuration and test conditions are determinate).

Although M&S lacks maturity for predicting violence of reaction, it has much potential for quantification of uncertainty associated with damage and ignition. The entire unmitigated response region (cross-hatch) depicted in **Figure 5** is the focus for mitigation after ignition occurs, and the minimum delivered energy threshold (left edge of ellipse) is the focus for avoidance of ignition.

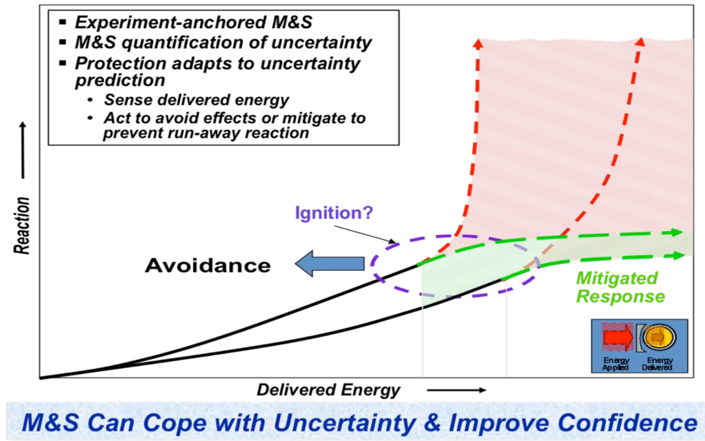


Figure 5. Violence of Reaction I Uncertain (3 of 3)

The Vision & Utility of M&S for Propulsion Systems

Similarity and scaling laws are traditionally used in propulsion system design to define conceptual design for performance and many other aspects of the propulsion environment. Our vision is to employ M&S to extend this capability to the prediction of safety margins throughout the logistic and operational environments of the stockpile-to-target sequence (STS). Further, our vision extends to prediction of safety and IM performance, and facilitates design and development of mitigation concepts for the avoidance of catastrophic events if required.

The STTR envisions materials testing at small scale to provide insight into the behavior of the materials in a full-scale system under conditions that can't be tested until the design has been converted to hardware. To learn of flaws late in the safety and IM design cycle is costly. Redesign, refabrication, and retesting results in cost and schedule growth that may be intolerable. Although cost and schedule growth can lead to program cancellation, more often it leads to waivers and the acceptance of unnecessary risks by military personnel and the public. The M&S toolset approach we envision will provide confidence in the designs, limit cost and schedule growth, and provide an understanding of how the system will behave under standard tests as well as specific design scenarios.

The toolset can be used to extract the most meaningful information from limited full-scale tests and allow extrapolation to real-world conditions. This capability would allow, for the first time, the ability to confidently evaluate new threats, new conditions, new launcher and magazine configurations, and new damage control tools, tactics, and procedures.

M&S is an important component in the weapon development process, especially when applied to propulsion system development. It can help to quantify the region of uncertainty associated with single or multiple trials to establish the weapon level of response to the IM stimuli. This is a cornerstone approach in MDA's STTR process, where a M&S toolset is evolving for industry use in propulsion system development.

Summary

DoD is engaged in a phased development of M&S tools to assist IM design and evaluation efforts for propulsion systems. Strategic Insight, Ltd.'s technical integration (knowledge structure and future model demonstrations) supports the DoD initiative. Benefits of this M&S capability include earlier evaluation of performance-safety tradeoffs, safer designs without sacrificing performance (avoidance and mitigation strategies are key), and better knowledge of design boundaries and margins.

Rapid growth of energetic material reaction vs. delivered energy (impact/heating hazard insults) is a fundamental IM consideration. Uncertainty quantification (using M&S) is a promising technique for establishing available margins for IM hazard avoidance or mitigation. A knowledge structure that captures safety and IM hazard requirements and M&S state-of-the-art capabilities including treatment of mitigations integral to the weapon design or to the fielded system implementation (material and/or non-material protection solutions) is a complimentary enhancement for industry. The envisioned win-win outcome is assured safety and knowledge of the safe operating boundaries/margins over the entire logistic and operational envelopes of weapons systems and their platforms, warfighters, infrastructure, and first responders.

There are other M&S related STTR activities planned for the months ahead. Two additional Phase I topics have been issued this year and offer the potential for increased use of M&S tools for the DoD acquisition community. M&S tools are key components for the weapon development process and will continue to aid the IM and weapon system safety communities.

REFERENCES

1. DEPARTMENT OF DEFENSE TEST METHOD STANDARD, MIL-STD-2105C, "Hazard Assessment Tests For Non-Nuclear Munitions," 14 July 2003.

2. DEPARTMENT OF DEFENSE AMMUNITION AND EXPLOSIVES HAZARD CLASSIFICATION PROCEDURES (Joint Technical Bulletin (TB 700–2 / NAVSEAINST 8020.8B / TO 11A-1-47 / DLAR 8220.1), 5 January 1998.

3. Technical materials and interchanges with STTR technical partners Lawrence Livermore National Laboratory and Sandia National Laboratories.

Co-author biography: As a Strategic Insight senior staff member, Mr. Jones has supported strategic planning and concept development for government and private industry clients. This has included efforts to determine

the strategy and investment plan for development of next generation surface-to-air missiles. He has worked with the Naval Surface Weapons Center Dahlgren Division on several strategic thrusts, including a leadership role for the Office of Undersecretary of Defense Weapon Systems Modeling and Simulation Initiative (MSI). He is familiar with the MSI goals, strategy and management structure, including the DoD/DoE Joint Munitions Program. He is knowledgeable of the multi-layered, multi-dimensional technical issues that must be resolved to transition a validated safety and IM related M&S capability for propulsion design and integration. Mr. Jones has extensive prior experience in acquisition, project management and engineering.

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