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Insensitive Munitions Modeling Improvement Efforts

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Mil-STD 2105C and numerous standardization agreements (STANAGs) outline the various Insensitive Munitions (IM) threats that are designed to simulate the hazards munitions are commonly exposed to on the modern battlefield. These threats include sympathetic detonation, shaped charge jet impact, bullet and fragment impact, and slow and fast cook-off. The asymmetric nature of current and likely future conflicts dictates that ordnance designers attempt to incorporate improvements in IM development as early as possible not only to increase the safety and value offered to the war fighter but also to minimize the expense and time that it takes to deliver these solutions to the field. One of the most promising techniques that engineers and scientists within the U.S. Department of Defense (DoD) are employing to help to achieve IM performance enhancement is the application of advanced multi-physics modeling programs. These programs account for key aspects of the relevant phenomena, including but not limited to shock physics, heat transfer, chemistry, and detonation. Designers use these programs to model scenarios involving the response of confined high explosive warheads or energetic devices to the various external stimuli outlined in the aforementioned standards. Modeling these scenarios is highly desirable as it allows the designer to iteratively interrogate many what if scenarios before ever having to produce test hardware, with obvious beneficial impacts on cost, schedule, and performance. The technique is limited however, by incomplete understanding in some instances, but more commonly by the fidelity of the models which populate the codes and their original intended range of applicability. This paper outlines out a purely computational based effort funded by the High Performance Computing Modernization Office (HPCMO) and managed by the U.S. Army Armament Research and Development Engineering Center (ARDEC) wherein a team of DoD participants, working in conjunction with developers in the U.S. Department of Energy (DOE), are enhancing the two codes used by DoD developers to model IM scenarios. Due to a variety of reasons, including the intractability of attempting to solve the problems associated with all relevant IM hazards, the likelihood of exposure, and the possibility of high payoff, only the specific threats of bullet and fragment impact are addressed and only within two of the codes most commonly used by DoD developers, namely Sandia National Labs (SNL) CTH/SIERRA suite and Lawrence Livermore National Labs (LLNL) ALE3D.

INTRODUCTION

In the past several decades numerous accidents have occurred during war and peacetime, across all services, in numerous countries, and throughout all applications ranging from loading, shipping, up to and including the point of use [1]. Because of these accidents, and the subsequent loss of human life, cost of repair and replacement of materiel, and the toll taken on operational readiness and capability, Insensitive Munitions (IM) improvements are mandated by law in the U.S.. Reducing the response of munitions subjected to certain external stimuli while still maintaining performance is however, a difficult goal to achieve. In part this is the result of the wide variety of hazards and varied methods which are often successfully used to mitigate response levels. Sympathetic detonation (SD) for example, perhaps the most damaging of the hazards outlined and discussed in Mil-STD 2105C and STANAG 4396, has been successfully mitigated through the use of barriers, spacing, and orientation [2]. Slow cook-off has been shown to have reduced response levels when munitions incorporate vents and/or melt out liners which are scaled in accordance with various sub-scale test methodologies [3]. A solution which improves the performance of a system subjected to one threat might hinder the performance of that same system when it is exposed to a different threat. Barrier materials used to mitigate SD for example, may on occasion, function to thermally insulate a system, delaying the onset of reaction and increasing the severity when a system design to have a reduced SD response level is exposed to a thermal hazard.

Other hurdles to universally improving IM performance exist and include volumetric and weight constraints which occur as a result of the number of rounds required to ship on each strategic configurable load. The total number and type of rounds of each type that can loaded into a number of conex boxes that an ammunition ship carries to support a unit in theater has a very real logistic impact not only on the war fighter but on the strategic prosecution of the conflict as well. Weight constraints are often difficult to overcome, particularly for Army systems, most of which are either stowed on a ground vehicles or carried by soldiers. Consequently, threats such as bullet and fragment impact cannot be simply solved by the addition of ballistic protection due to the heavy loads and their negative impact on maneuverability.

In addition to limitations imposed on IM performance from external factors, internal factors also complicate the ability of designers to improve overall system level IM performance. Non-shock and non-prompt shock initiated phenomena for example, are not only much more difficult to experimentally interrogate but they are also much less understood. This is particularly true of bullet and fragment impact scenarios, some of which have been shown in the past to have what is speculated to be a highly localized initiation mechanism. Furthermore the responses that some munitions have exhibited upon being subjected to bullet and fragment impact have been erratic and varied from no reaction, to delayed reaction, to more violent reactions for only slight variations in impact velocity. One possible cause and complicating factor to determining the response level is the fact that it occurs in what is ultimately a damaged energetic media. Burning, and the resultant pressurization, is just one behavior that is exacerbated when it occurs in a material that has opened a number of new surfaces as a result of cracking. In certain scenarios, burn rates that vary between laminar burn rates and detonation velocities have been observed to occur and may occur, albeit indirectly, as a result of physical penetration and damage.

There are also a number of non-technical but ultimately equally important managerial constraints. The old method of creating more IM compliant designs has been through the exclusive application of testing. While this technique has yielded valuable and promising results, it is also a timely and expensive process. Fewer organizations and locations where explosive work can be done, combined with a host of other economic and technical factors, means that it would be prohibitively expensive to attempt to increase IM performance merely by fabricating and testing a number of different designs. For these reasons, and the fact that computational power and the capabilities of the relevant codes have increased so tremendously over the last decade, many DoD munition developers have begun to use the same tools they ordinarily use for performance modeling for modeling IM scenarios as well.

MODELING BACKGROUND

Computationally modeling the performance of explosive munitions and penetrators is not a new undertaking. Hydrocodes, which are based primarily upon deterministic continuum mechanics methods, have been used for several decades by thousands of munition and armor developers to study and improve the performance of systems undergoing a variety of hydrodynamic events [4-5]. Historically these types of simulations have exclusively involved explicit numerical schemes to account for extremely short duration time frames that accompany high velocity, high strain, high strain rate events. These types of scenarios require solution of the conservation equations, mass, momentum, and energy, and that some type of constitutive and failure models exist. They are the most relevant types of codes to use when attempting to model shock wave dominated events as their numerical schemes use an explicit formulation that is suitable for problems spanning the range of tens or even hundreds of microseconds. Typical modeled scenarios include penetrator-target and explosive-metal interactions with many types of armor and warheads performance scenarios still being modeled today.

But as the traditional game between armor and warhead designers has continued, so has the necessity to model nontraditional scenarios involving explosive ordnance. Scenarios where munitions are subjected to fires, or impacted or penetrated by relatively low velocity projectiles which may become embedded in the material and subsequently cause a cook-off are just two examples. The problem with attempting to use a hydrocode to model these and other types of events is that these problems are many times outside the codes' traditional ranges of applicability. As long as the strength of all relevant materials has been overcome by orders of magnitude and the time frames of the events are on the order of no more than a few hundred microseconds and it is not necessary to model in any detail either the reaction chemistry or the damage below the continuum, the results in general tended to remain within an acceptable range of validity. For a scenario where a bullet or fragment embeds itself into an energetic material and stops in what is likely a damaged energetic medium then it is often impossible to obtain an accurate solution. Explicit formulation codes simply don't handle implicit phenomena that may take anywhere from milliseconds up to seconds to react in a computationally efficient manner. As a result the designer's ability to successfully apply these codes in such cases decreases significantly. Reaction chemistry, heat transfer, and damage are just a few examples of factors that hinder a designer's ability to improve the final design's IM performance.

A number of advanced multi-domain multi-physics codes have been developed to model a broad set of coupled physics mechanics problems. These codes account for phenomena which are not typically handled by hydrocodes but which are of acute interest to engineers engaged in improving IM performance, a number of more advanced multi-domain, multi-physics codes have sprung up. Two of the codes most commonly used by munition designers are CTH and the SIERRA suite of codes produced by Sandia National Labs (SNL) and ALE3D produced by Lawrence Livermore National Labs (LLNL). Both of these codes are massively parallel, a feature which is critically important given the ever increasing size, complexity, and fidelity of the scenarios that designers are typically called on to model.

CTH is SNL's explicit Eulerian finite-volume formulation hydrocode that has been in use for years in the warhead community, typically to simulate structural penetration or warhead detonation. It has many attractive features that make it desirable for this type of employment, such as Adaptive Mesh Refinement (AMR), which allows more accurate computational speed by increasing mesh resolution, but only in important regions of the domain. It is an explicit hydrocode however, so it cannot efficiently solve problems that must be solved over a much longer time frame. SNL also develops SIERRA, which is a suite of codes for modeling various physics that are all built on a common framework. SIERRA provides a common database and other essential capabilities and facilitates communication between the physics codes built on the SIERRA framework. Heat transfer, porous flow, and global structural response are all areas that are handled separately by distinct codes. Since the codes are distinct, they rely on code-to-code coupling to solve true multi-physics and multi-timeframe (explicit-implicit) types of problems. SIERRA codes are available for implicit and explicit time integration, so they can efficiently model phenomena occurring over long time frames. SIERRA also provides a means for SIERRA codes to couple with CTH, just as they would couple with each other.

ALE3D, a LLNL developed code, is also used by various DoD participants. It was however, designed differently than either CTH or Sierra. ALE3D is a single entity in that it incorporates a variety of multi-physics and multi-time capabilities that all reside under a single program. In this scenario there is no need to couple separate codes together but a modeler still has the ability to account for other relevant areas of analysis such as chemistry, heat flow, or mechanical response.

There are pros and cons to each approach, which are due in no small part to differing opinions about how these extremely complex, coupled technical problems should be solved. SNL's approach was that many of the individual areas are so complex and potentially difficult to solve on their own, that they warrant a dedicated code to handle each specific type of problem. This is similar to how some commercial codes operate. A designer needing to model fluid flow problems involving turbulence and mixing would turn to a computational fluid dynamics (CFD) code as opposed to standard implicit quasi-static structural code. But if the interaction between the two is important then he must appeal to some type of fluid structural interaction (FSI) software. As a result, SNL developed a central framework under the Sierra umbrella to handle basic, but required, capabilities such as data base management, input parsing, contact, and overhead management to name a few. The various codes could also then be directed coupled to each other through services provided by the SIERRA framework. ALE3D developers on the other hand, felt that both the developers and users would be better served by incorporating the ability to handle all various phenomena under a single framework. Regardless of the code used, there are a large number of factors relevant to solving the numerous complexities of IM hazards. But given finite budgets and time constraints all of these factors could all not be fully addressed. In light of this fact and other technical considerations, it was determined that bullet and fragment impact (BFI) would be the two key hazards to be addressed. The specific threats of bullet and fragment impact were broad enough that they also warranted further focus. These areas warranting further focus include multi-phase flow, code coupling, and particle methods including fragmentation and transport improvement. These technical areas were initially addressed in a prior successful HPCMO Multiphase Flow Target (MFT) Response portfolio that occurred from 2004-2007 [6]. This work further advanced and expanded many of these previously developed capabilities to produce both of these two IM analysis frameworks with enhanced BFI modeling capability.

Multiphase flow modeling is particularly relevant for accurately modeling BFI impacts against energetic media. When a foreign object becomes lodged in an energetic material which has been damaged, then it is possible for localized thermal effects to occur. These thermal effects can result in gaseous products containing combustible reactive debris which behave in a much more complicated manner than either gaseous or particulate phase would alone. The coupling of time scales is also quite relevant for these codes since the ability to move from implicit to explicit analysis as well as implicit to explicit are both required. Finally particle methods, fragmentation, and transport are important to capture damage. The ability to better model fracture and fragmentation for a variety of relatively brittle energetic materials in a non mesh dependent fashion is crucial in order to accurately model localized response. Without accurately accounting for changes in local behavior, which may be the result of spall or the extent to which the surrounding energetic media fractures and the subsequent increase in surface area, the prediction of an accurate overall system level response is highly unlikely.

The problem of modeling BFI against confined energetic warheads is a complicated one. As the image in figure #1 shows, in a typical BFI scenario there are a variety of relevant time scales and physical considerations that occur, sometimes with competing requirements.

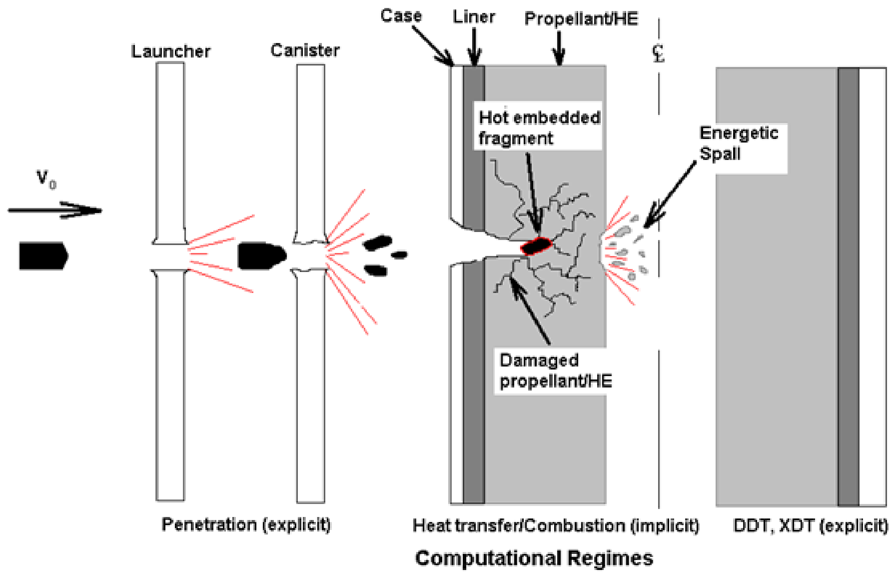

Figure #1 Notional cross section of a BFI scenario

The figure shows a local cross section of generic scenario that may either contain either a warhead or a rocket motor. It is greatly complicated by a number of both physical and numerical factors. Physical factors include complex geometry, a variety of possibly unusual intervening materials, energetic but non-detonable fills, and damage to name but a few. Numerical complications include how can element failure be handled in a physically realistic manner so that the debris that results from the fragment penetrating the canister layer is free to react with the confined energetic and possibly contribute to a response (which must occur in a computationally efficient manner). In addition the ability to adequately model a penetration event taking only milliseconds, followed by an extended duration of time in which the embedded hot fragment embedded causes a cook-off, which takes seconds or longer, to occur requires extensive improvement to the basic physics capabilities and coupling.

Due to the initial differences of both codes, as well as differing opinions on the most appropriate methods that should be used to enhance the three previously specified areas, the exact manner in which the improvements were to be made were code dependent but the major technical areas and overall goals were the same.

CTH AND SIERRA IMPROVEMENTS

CTH is a code employed by large numbers DoD analysts for modeling performance and penetration scenarios. It is however, a traditional hydrocode which as previously pointed out, does not handle events requiring a longer time frame and implicit integration scheme. When linked to the SIERRA code Presto, SNL's explicit structural modeling code, it is capable of a much wider range of predictive modeling such as global structural response due to weapons effects for example.

The ability to model a multiphase flow is particularly important in bullet and fragment impact scenarios where a mix of solid and gaseous products may be participating in the overall response. Under the MFT portfolio, two phase multiphase flow was initially incorporated into CTH. To account for more than two phases with CTH requires the homogenization of the two phase flow. This was one of the reasons that novel equations of state (EOS) were needed. These new EOSs would be required to account for multiple solids and gaseous species and include both inert and reactive materials. The multiphase reaction must be able to accurately account for both grain burning and gas generation in a numerically efficient manner in order for the code to be more predictive in nature. This relates closely to the coupled relationship that damage shares with reaction.

Damage is an obvious phenomenon that results not only from penetration events but also from a much wide variety of physical insults as well. As figure #3 indicates, when a sample, in this case a cylindrical sample of energetic material, impacts a solid target, damage, and often reaction, ensue.

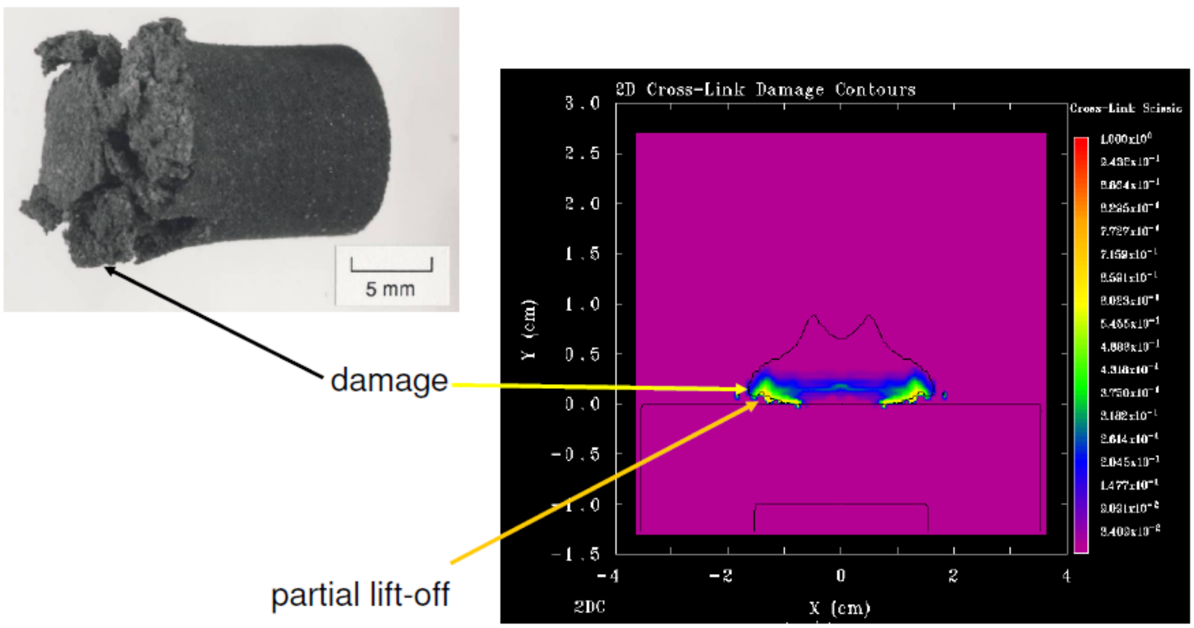

Figure #3 Taylor rod test damaged energetic material and simulation

What is most promising is that the actual damage algorithms used in the new model predict not only the stress history that results from cyclic stress testing but also matches the degree of damage shown in the Taylor rod test. The new damage enabled code predicts this without any changes to the damage parameters from one scenario to the next. This should offer munition designers a much greater opportunity to begin to apply damage, and model its participation in system response, to other scenarios such as physical penetration into encased munitions.

The CTH/ SIERRA suite of codes employs two different coupling schemes. The first approach couples two different physics codes via a common boundary, while the second approach hands-off or transfers a mesh and the results at a point in time from one code to another to continue an analysis. This second method also called code transfer, can transfer results from a code (at a point in time) operating in one time domain to another program operating in either the same time domain (explicit to explicit or implicit to implicit) or in a different time domain (explicit to implicit or implicit to explicit).

The SIERRA program Fortissimo is an example of the first type of coupling. Fortissimo is actually a coupling program between the explicit, Eulerian program CTH and the explicit, Lagrangian, structural program Presto at a common boundary. An example where this type of coupling is most suitable is when a designer wants to model a warhead detonating in a structure and needs to be able to predict the larger structural response, both local and global. The analysis employed needs to be able to couple the blast field to the structural elements and then feed the participation and strength of the structural elements back to the expanding flow field of gaseous products. When used in this manner the coupled codes are, in effect, running in parallel, communicating back and forth in synchronized time steps to modify relevant phenomena that are effected, but can only be modeled by, the other participating code. With this approach the coupled codes can be quite accurate in predicting the overall behavior.

This first coupling technique, though very powerful, is insufficient to model all of the types of behavior that result from full BFI scenarios. Thus, the second form of coupling via code transfer has been employed with CTH/SIERRA under this effort. Examples of these types of transfers include Presto (explicit) to CTH (explicit); Presto to structural code Adagio (implicit); and the fluid flow, heat transfer SIERRA program Aria (implicit) to CTH.

ALE3D IMPROVEMENTS

Within the ALE3D framework there are also a number of improvements that have been made. Under the area of multi-phase flow effort improvements have been made to both prompt and non-prompt ignition models as well as in damage dependent burn models. Prompt ignition work has centered around the use of the models originally developed based on the ignition and growth model which was a relatively successful attempt to account for the coalescence of hot spots into a self sustaining detonation front. In addition non-prompt developments have also been undertaken and implemented. This portion of the effort centers around the use of the Steven test as shown in figure #4.

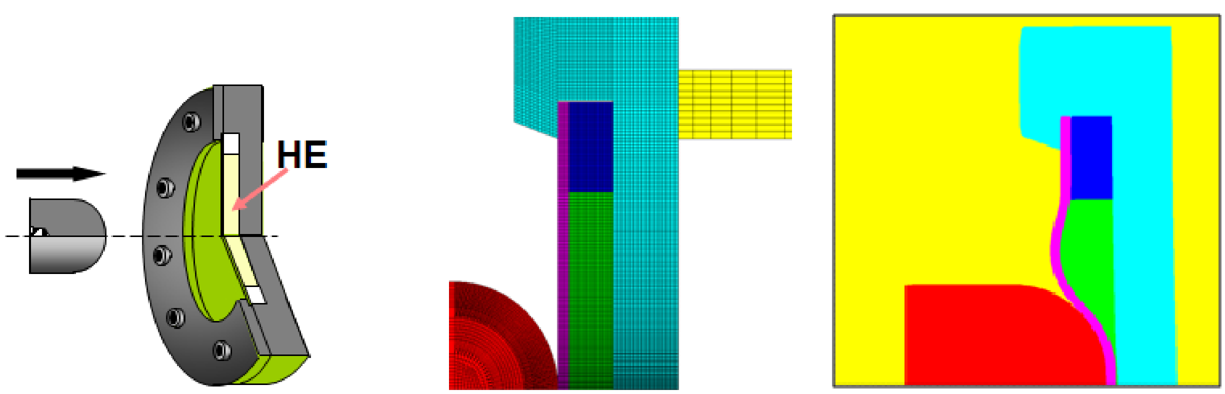

Figure #4 Steven test apparatus

In the Steven test a large blunt nosed penetrator moving at relatively slow velocity, in the range of only a few hundred meters per second, impacts a thin disc of highly confined explosive. The system demonstrates a velocity dependant response but one which is significantly less violent than what would occur if a detonation were to have occurred and correlates well with experimental data. It is not however, a typical shock activation mechanism as the velocities involved are too low. Barrier materials and armor which decelerate penetrators before they penetrate an actual munition make this an obviously relevant scenario.

Finally damage influenced burn rates were improved due to the hypothesis that thermal initiation is somehow at the heart of many if not all, impact scenarios. It is not hard to imagine that a damaged energetic media could cause a much more violent reaction due to the dependence of burn rate on surface area. The more a material burns the more the local pressure increases. As the local pressure increases, the burn rate then increases further. This forms a feedback loop that can cause a violent response when confined. Figure #5 shows one notion of what the "burn" front may look like at only a very small portion of a cracked explosive.

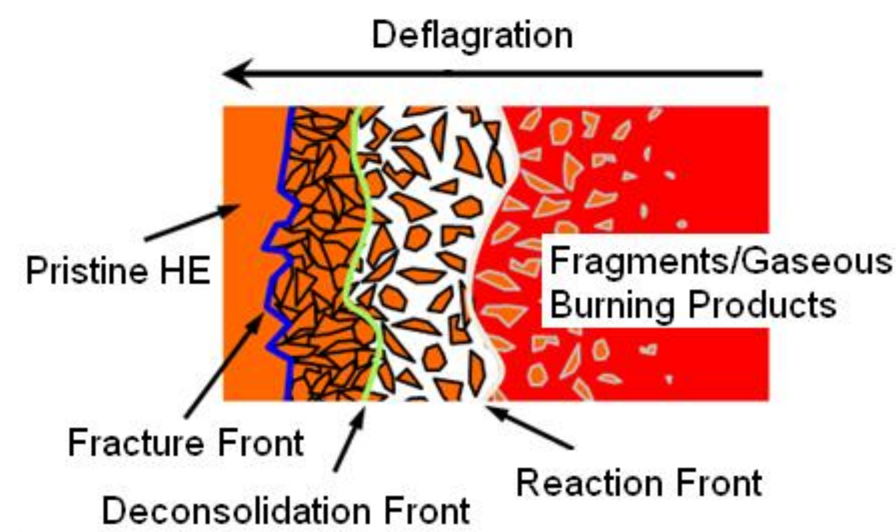

Figure #5 - Damaged reaction zone burning

SUMMARY AND CONCLUSIONS

IM modeling represents a significant improvement to the older technique of improving IM performance through the exclusive application of testing. As modeling capabilities improve, computational costs come down, and expenses and difficulties associated with conducting explosive testing increase, the use of IM modeling will continue to grow. An IM designer might say that the holy grail of IM modeling would be the ability to model a BFI scenario and predict level of violence, from type I detonation up to type V burning reaction, as the velocity of the fragment varies and the geometry changes. We are currently far from achieving such a goal as modeling IM scenarios is not a trivial exercise. It requires a detailed understanding of a variety of complex physical scenarios as well as an intimate familiarity with the numerical framework in which such scenarios are modeled. Much more work is needed to improve the fidelity of the modeling scenarios and the predictive capability they offer designers.

The effort outlined in this paper shows that several real improvements have been made in the areas of multiphase flow, code coupling, and fracture and fragmentation generation and transport within the two codes most commonly used by U.S. DoD munition designers. These improvements, implemented by DOE developers and exercised by DoD ordnance engineers, have incorporated the current state of the art understanding of just a few of the phenomena believed to be of importance for accurately modeling BFI scenarios and should lead to not only a much wider use of these BFI modeling tools, but should provide much a much higher level of fidelity and predictive capability as well.

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