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Tools and Technology for Physics Based Simulations of Hypervelocity Target-Interceptor Impacts for Missile Defense

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Abstract

The simulation of hypervelocity intercept-target impacts by first-principles codes can provide significant value to missile defense programs. First-principles codes for this application must include a range of complex physical processes including shock response of materials, phase changes, mechanical fragmentation, and chemical/explosive reactions. This permits prediction and characterization of impact events and the resulting post-intercept debris cloud, which can be used in support of hit and kill assessment and target typing. Furthermore, simulations are orders of magnitude lower in cost than flight tests and can contain much higher fidelity, enabling more complete exploration of the anticipated engagement space.

This presentation will summarize the computational tools that Sandia National Laboratories has employed to simulate target-interceptor engagements, as well as comparison of simulations with experimental results typical of hyper-velocity impacts. The computational tools include fully Eulerian (CTH), fully Lagrangian (Presto), and coupled Eulerian-Lagrangian (Zapotec) capabilities, all originally developed at Sandia in support of its nuclear weapons mission. Benchmarking or validation of these codes has followed one of two approaches, comparison to test data or to analytic solutions. The availability of analytic solutions is limited but one comparison for shock process will be discussed (Sod's solution to the one dimensional shock tube problem). Many tests have been conducted on high fidelity interceptor-target interactions but, in general, these tests are poor candidates for validation due to uncertainties in engagements and material characterization. We will discuss a series of simpler experimental configurations that demonstrate the utility of the codes to preform full scale simulations. We will discuss comparisons for high explosive induced fragmentation using CTH and Zapotec; fluid/structure interaction using Zapotec and Presto; high explosive initiation using CTH; and an optical and radar signature simulation of a typical target-interceptor engagement.

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Introduction

Over the past two decades, Sandia National Laboratories (SNL) has developed a mature capability for simulating hypervelocity impacts, assessing the lethality of kinetic energy kill vehicles (KV) against various targets, and predicting and enabling characterization of the resulting post intercept debris in both the optical and radio frequency (RF) regimes. This capability is based on an extensive set of engineering analysis tools developed for the United States Department of Energy (DOE) Nuclear Weapons Complex (NWC) under the Advanced Simulation and Computing Program. The centerpiece of these engineering analysis capabilities is the Sierra Mechanics Suite which is constantly being upgraded with new features to address the latest challenges in engineering analysis.

Sandia has also developed tools to appropriately assess lethality and predict post-intercept signatures to aid in target typing and kill assessment. Due to the high cost associated with flight tests, it is desirable to extract as much information as possible from modeling and simulation. These simulations permit exploration of a greater engagement and target space than is available using flight tests. With this increased dependence on modeling and simulation, confidence in these simulations is paramount.

The goal of this paper is to provide an overview of the tools used at SNL to perform performance assessments and predict post engagement debris and their associated signatures. A range of experimental events are presented and their results compared to corresponding simulations. The desire is to increase confidence in the computational code's ability to adequately represent the physics present within a missile defense engagement to the level where the models can confidently be used to make predictions of lethality and post engagement debris. This report presents an overview of the computational codes used for each type of analysis, the specific analysis workflow, and then the associated benchmarking comparisons are presented.

SNL has been designated by the DOE Nuclear National Security Administration (NNSA) as the lead laboratory to develop and provide engineering analysis tools to the NWC under the ASC Program. SNL is developing these capabilities to address multiple challenges in engineering analysis.

This suite of tools includes codes capable of describing shock physics in both Eulerian and Lagrangian discretization's along with the typical finite element based (Lagrangian) solid mechanics, structural dynamics, and thermal/fluids tools. The principle product of these efforts is the SIERRA framework (Sandia's Suite of solid mechanics codes/structural dynamics modules), and CTH (Sandia's Shock Physics Analysis Package).

The Sierra Suite of tools is a general purpose package and can be applied to a broad range of design, qualification, and certification questions as they arise in the system development process. The suite is a massively parallel finite element code comprised of different modules, each describing a specific type and range of physical processes. Flexible coupling capabilities between the modules permit solution of complex multi-physics problems. The three Sierra Mechanics modules are commonly referred to as 1) Presto, 2) Adagio and 3) Salinas. Each provides a solution of structural finite element problems over a span of time regimes (i.e., microseconds to hours and hours to days) and also complexity regimes (i.e., linear/small deformation/shock and vibration applications to large deformation/large strains problems) with complex material behavior and material failure and fragmentation.

In hypervelocity missile defense impacts, the early time response is largely hydrodynamic, driven primarily by the material shock response and equation of state (EOS) effects. For these phenomena, the most appropriate code in the Sandia Suite is the CTH shock physics analysis package. CTH excels at modeling complex multi-dimensional, multi-material problems characterized by large deformations and/or strong shocks. CTH is the most widely used hydrocode in the U.S. defense research industry and the number one requested code in the Department of Defense (DoD) High Performance Computing Centers. CTH has been used extensively in the DoD for a variety of munitions development projects.

The late time structural response of a hypervelocity missile defense intercept is determined primarily by material strength and failure/fragmentation properties in addition to the response of the various engineering fasteners incorporated within the target. The most appropriate description of these phenomena in the Sandia Suite is the explicit transient dynamics mode of Sierra (i.e., Presto). Presto is designed to solve problems where inertia is important and with time durations up to a few seconds. As part of the ASC Program, both CTH and Sierra/Presto have undergone an extensive formal software quality assurance process. As part of the build process, regression and benchmark suite problems and expected solutions are required. These benchmarks are run nightly to ensure code consistency, capability, and quality. Numerous validation studies and activities have demonstrated the ability of the code to match experiments in a range of environments. Additionally, these codes are also subject to formal verification and validation (V&V) processes for DOE specific activities.

Some missile defense applications require a coupled approach (i.e., shock physics to structural dynamics) for suitably describing the range of physics present within a hypervelocity engagement. In these situations, the early shock loading of a target is most appropriately described using a shock physics code to capture the EOS and associated phase change effects of the KV impact on the loading of an assembly or structure. The late time response of the system (i.e., which is dominated by the strength of materials and the various fabrication details making up the target assembly) was modeled using an explicit structural dynamics code.

The current hydro-structural computational tool providing this capability at Sandia is Zapotec. The Pronto code was developed in the early 1990s using internal SNL funding. It utilizes a unique mesh overlap formulation that couples CTH to its explicit structural dynamics code at each time step. There is very limited distribution and use of this tool outside of Sandia. This tool and technique allows for the analysis of complex hydro-structural problems where a high speed impact gives rise to structural breakup. Zapotec incorporates a limited regression suite as part of the build process.

The Zapotec framework is very general and allows the coupling of CTH with alternative structural codes. Recently, activities have commenced to couple the Presto structural dynamics code with CTH using the Zapotec architecture. Other couplings between CTH and Presto also exist but don't have the flexibility of Zapotec.

Confidence in a technical basis for high-consequence decisions does not depend only on simulation results. Confidence in an analysis cannot be guaranteed merely by a quality stamp on a version of the code. The basis of confidence depends on the eco-system in which the code lives. An analogy of the relation between a race car driver and the race car is appropriate for understanding how the role of analyst and a computer simulation code. Having the best race car does not guarantee victory. The combination of the race car and the driver gives a higher probability of victory. Often, the better driver is mature and has experience which can win the race regardless of the car. Likewise, the analyst must drive the mature code properly for confidence in the results. As a well maintained car is essential in any race, a well maintained mature code is essential for quality results. Sandia's analysis philosophy is based on the concept that, "*an experiment is the full truth partially revealed and a simulation is the partial truth fully revealed*." Thus, the key in exploiting computational simulations is to understand how good the "*partial truth*" is for the question at hand. Sandia's view is that a hierarchal validation process is the key to assessing the "*goodness*" of that "*partial truth*." In this manner, confidence in the codes is gained by first isolating and successfully predicting the relevant physical processes that comprise complex missile intercept engagements. For example, predicting debris resulting from simple projectiles impacting metal plates provides confidence that the predicted debris generated by an impact on a RV shell by an interceptor is accurate. The same can be said for the prediction of debris generated by a pipe bomb explosion which increases the confidence that the debris generated by the detonation of an RV warhead on impact is accurate. The demonstration of accurate predictions of simple examples of physical processes increases confidence in predictions of complex interactions composed of the same processes, within an applicable range of conditions, without extensive simultaneous testing of all those conditions.

Once confidence is gained in the process, the simulations can be exploited in many ways. First, a simulation can be used to replicate an experiment (pre-test) before it occurs. This gives the experimenter an idea of what to expect in the experiment and allows the experimental design and approach to be tweaked before the actual experiment is conducted. A second use of simulations is for trend analysis. If the trend analysis absolute differences are large, the local gradients can be accurate. Next, simulations provide the ability to investigate the sensitivity of a physical system to various experimental or test inputs. Finally, computational simulations can provide virtual data for experiments that are too costly or too dangerous to perform.

Tools for Missile Defense Analysis

CTH: Eulerian Shock-Physics Code

CTH is a multi-dimensional shock physics Eulerian code, developed and maintained at SNL. It has the capability to model transient, dynamic events and the Eulerian structure of the code permits large deformation associated with explosive detonation or hypervelocity impact events to be accurately modeled. CTH utilizes a two-step approach for the solution of the mass, momentum, and energy conservation (McGlaun, et al., 1990, Hertel, et al., 1993). The two-step solution approach first involves a Lagrangian step, where the Eulerian mesh is allowed to deform. The Lagrangian step is followed by a remap step. The remap algorithm advects material quantities (e.g., mass, momentum, and energy) from the deformed Lagrangian configuration back into the fixed Eulerian configuration.

The code contains models suitable to describe material response under most conditions encountered in shock physics including material strength, fracture, distended materials, HEs, and a variety of boundary conditions. In addition, several methods are available for computationally describing object geometry including the specification by geometric primitives and the importing of geometry from standard Computer-Aided Design (CAD) file formats [e.g., stereo-lithography file (STL) format]. The intercept conditions (i.e., velocity, orientation and location) are included by geometric translations and rotations about the principle axes and imposing velocities on the materials of the objects. Within CTH, the constitutive behavior is decoupled into the dilatational response, described by an EOS, and the deviatoric response, described using a material strength model. An EOS expresses a relationship between the material thermodynamic pressure, density, and internal energy in a state of equilibrium. The strength model is often a plasticity model, designed to capture the shear-induced response of the material. The code contains the ability to use very accurate tabular EOS (i.e., derived from material testing and theory) and includes a large number of constitutive strength and fragmentation models including the Johnson Cook Fracture Model and the Grady-Kipp Subgrid Fragmentation Model. The reader is directed to McGlaun, et al. (1990) and Hertel, et al. (1993) for a more thorough discussion of the CTH methodology

Most CTH analyses of missile defense hypervelocity impact utilize a dynamic mesh algorithm known as AMR (Crawford, et al., 2010). The adaptive mesh refinement strategy used in CTH is block-based where each block is zoned uniformly into logically identical cells. Blocks are connected in a hierarchal manner with adjacent blocks guaranteed never to exceed a difference of 2:1 in cell size. The lowest resolution mesh (Level 0) is defined by an array of blocks. The Level 0 mesh is intended to provide the proper aspect ratio of the calculation and spans the entire problem domain. Actual calculations use higher level mesh (typically Level 3 or greater) to provide adequate resolution for regions of interest. Higher resolution regions of mesh are created by splitting a block midway along each of the coordinate directions. This produces four child blocks per parent in two dimensional (2D) and eight child blocks per parent in three dimensional (3D). Control of refinement and un-refinement of the problem mesh as the problem progresses is specified by the analyst in the input deck. The total number of blocks available to the calculation (i.e., per processor, if running in parallel) is also defined by the user. The maximum resolution is defined by the maximum allowed refinement level. Since each additional level of refinement provides a factor of two increase in resolution, it is very easy to define a very fine-scale grid with relatively modest values of the maximum refinement level.

Explosives are a material set with unique properties and governing principals. The most accurate and suitable method of predicting High Explosive Initiation in CTH for most missile defense simulations is the History Variable Reactive Burn (HVRB) model. The HVRB model describes shock-induced initiation and detonation wave propagation in heterogeneous explosives, using a pressure-dependent rate law and a delay time to rapid reaction.

In this study, primary EOS models are used to describe the un-reacted explosive and reaction products and the rate equation is used to describe evolution of the reaction or transition in time. Thus, the model does not describe the fundamental chemistry involved, but introduces empirical relationships based on bulk phenomenology of the explosive. Parameters in the empirical model such as the pressure of initiation, the run distance to detonation, and burn rate are determined by lab scale experiments on the material and the model predictions are compared to the experiments. When the model parameters have been determined, the model can be then used in a wide range of environments as long as the assumptions under which the model was developed are met.

Zapotec: Coupled Hydro-structural Code

Zapotec is a coupled Eulerian/Lagrangian code developed for modeling applications involving penetration and blast/structure interaction (Bessette et al., 2003). It was developed at SNL using internal funding and has been used since the mid-1990s to solve a class of problems not readily handled by either Eulerian or Lagrangian methods alone. In these problems, the materials involved exhibit vastly differing degrees of deformation over the time scale of interest. The hydro-structural response encountered in missile defense intercepts is one such application.

Zapotec is fundamentally different from pure finite element codes in that it uses a loosely coupled overset grid technique. The benefits are that it uses the best numerical technique for each of the two domains (i.e., hydro and structural) in the problem. This implies a structured discretization for the hydrodynamic domain and unstructured mesh for the structural domain. These benefits come at the cost of added complexity in setting up and executing the problem. The user and code must deal and interact with different data structures. The code is massively parallel and scales efficiently to hundreds of processors.

In our production environment, Zapotec links the CTH and Pronto3D (i.e., a precursor to Presto) codes (Taylor and Flanagan, 1989, Attaway, et al., 1998). CTH, described earlier, handles the Eulerian portion of the analysis, while Pronto3D, an explicit finite element code, performs the Lagrangian analysis. Pronto3D was developed for modeling transient solid mechanics problems involving large deformations and contact. The numerical formulation utilizes an updated Lagrangian approach whereby the reference state at each time step is updated to coincide with the current configuration. The reader is directed to Taylor and Flanagan (1989) for a thorough discussion of the Pronto3D methodology. The replacement of Pronto3D with Presto is in testing and will be used for future simulations

Throughout the simulation, both CTH and Pronto3D are run concurrently with the appropriate portions of a problem solved on their respective computation domains. Zapotec handles the boundary and time coupling between domains. For a given time step, Zapotec maps the current configuration of a Lagrangian body and its state onto the fixed Eulerian mesh. Any overlapping Lagrangian material is inserted into the Eulerian mesh with the updated mesh data passed back to CTH. Once the material insertion is complete, the external loading on the Lagrangian material surfaces is then determined from the stress state in the Eulerian mesh. These loads are passed back to Pronto3D as a set of external nodal forces. Once the coupled treatment is complete, both CTH and Pronto3D are run independently over the next time step. The reader is directed to Bessette et al. (2003) for a detailed discussion of Zapotec methodology. Figure 4 shows an example of a Lagrangian finite element simulation.

The major weakness of a Lagrangian method lies with mesh deformation, where severe element distortion degrades accuracy and can potentially lead to failure of the calculation due to mesh entanglement. The Pronto3D code provides an element death capability where highly distorted elements are removed from the calculation once a user-prescribed death criterion is met. In most Lagrangian Finite Element Method (FEM) codes, the mass associated with the dead elements is simply discarded from the problem. This can be unfortunate for problems where exact mass accounting is important.

Zapotec, however, allows for a unique capability known as “donation” where the newly dead Lagrangian elements are transferred to the Eulerian problem domain. The algorithm used is the same algorithm that is used for material insertion with the added modification where internal energy is passed back to the CTH and is actually used in the EOS calculations. As such, it is important to ensure consistency of the material state computed by Pronto3D and that the consistency of the material state is passed into CTH for future calculations. The donation algorithm ensures consistency of the pressure-energy state by iterating on the internal energy. This is done by successive calls to the CTH EOS routine, whereby a bisection method is used to iterate on the internal energy until the pressures computed by CTH and Pronto3D are consistent.

The individual codes comprising Zapotec are well verified and validated for particular problem classes described within the literature. However, there has only been limited verification and validation of the coupling algorithm performed even though Zapotec has been used successfully in a wide range of problems where it is applicable. Ultimately, Zapotec provides a substantial and unique capability in the hydro-structural domain.

PREDICTING POST ENGAGEMENT SIGNATURES

A second category of analysis performed in support of missile defense involves the prediction of post engagement debris resulting from hypervelocity hit-to-kill intercepts. These predictions are often used to estimate both optical and RF signals associated with the intercept as well as to develop the consequences of intercept with structures on the ground or nearby objects.

In general, the engagements produce a large debris cloud composed of a variety of materials such as metals, polymers, and explosives, with masses ranging from sub-gram to many kilograms and sizes ranging from microns to meters. These materials produce emissions that can be observed by optical sensors or can be viewed with radar to provide critical information used to perform real time hit assessment/kill assessment and target typing from ground, airborne, and/or space-based platforms.

Successful interpretation of the data requires an understanding of the distinguishing target intercept features and of the transformation of those features into observation. However, sensors have a complicated set of capabilities, limitations, and response characteristics that influence what they observe. The complexity of these observations are further convoluted when viewing post engagement debris clouds which themselves are functions of the exact intercept engagement (i.e., relative velocity, impact angle, pitch and yaw) and structural details (i.e., assembly methods, and material properties) of both the KV and RV. It is also believed that these observations are not unique, that is, multiple different debris clouds can give rise to the same observable signature.

In general, the observed optical and radar signals are sensitive to different phenomena. The optical sensors are often passive and are most sensitive to objects giving off electro-magnetic emissions. For the current class of problems, the largest emissions originate from the small debris that is generated and heated from the hypervelocity impact. These tend to originate in regions closest to the impact. Other physical processes, such as optical scattering, may become important if the debris is near the size of the emission wavelength. At Sandia, the CTH Eulerian Shock Physics Code is used to provide the thermal source term for optical predictions since it incorporates EOS effects and permits estimation of material failure and fragmentation at both the mesh scale and sub-mesh scale.

Radar (i.e., RF) sensors are most sensitive to large objects having a high radar cross section. The material comprising the debris plays a role as well with metals returning a higher reflection than similarly sized non-metals. Typically for the standard X-band radars, the smaller debris, unless clustered into larger zones of agglomerated material, do not exhibit a prominent signal.

While these codes form the core of the current Sandia capability, they themselves do not directly yield optical and RF sensor output. Instead they predict material states as a function of time and space including estimates of velocity, stress, strain, pressure, temperature, mass, density, energies, and sub-grid fragmentation size. These results must be post-processed using an additional set of codes which facilitate predictions of sensor observables.

Post Engagement Analysis Toolkit (PEAT)

At SNL, a set of tools, known collectively as the PEAT, has been developed that makes use of the voluminous results of shock physics and hydro-structural simulations. These tools extract and characterize debris data from simulations of hypervelocity impacts of KVs onto RVs and produces output that allows predictions of both optical and RF observables. An overview of the relationship between the first principle codes and the post-processing tools is shown in Figure 1.

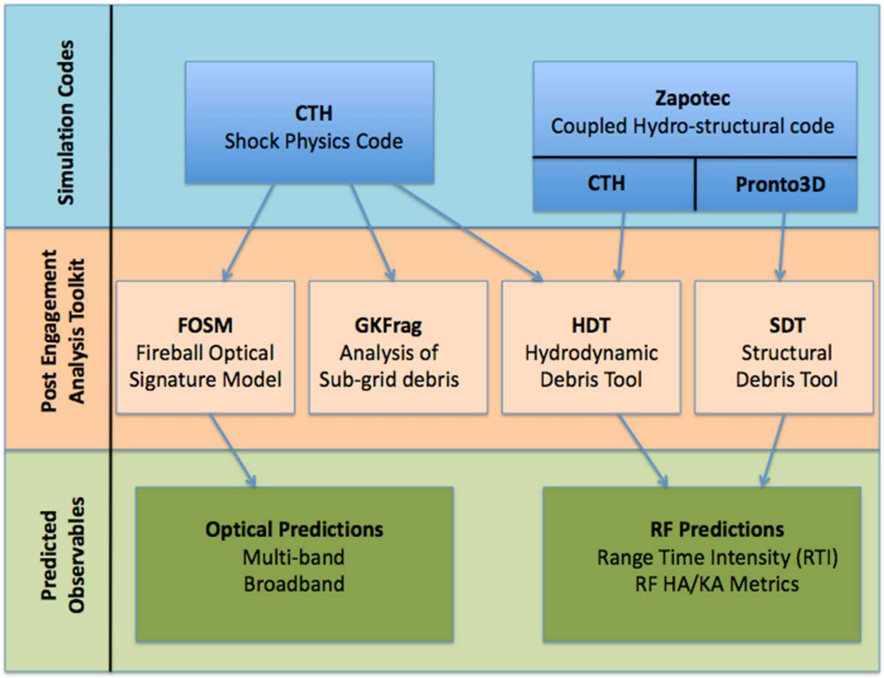


Figure 1: Post Engagement Analysis Toolkit Overview

The top portion of the figure, which indicates the first steps of the overall analysis, illustrates that CTH and Zapotec provide the debris source terms used by the post-processors. The applicable portions of the PEAT are shown in the middle portion of the figure. These tools take the post-impact debris outputs and either calculate the observables directly in the case of optical predictions or create the source information required by third parties to develop the RF radar signatures. The remainder of this section consists of a brief overview of the tools used and contained within PEAT.

Fireball Optical Signature Model (FOSM)

The first post-processing tool, the FOSM, is used to estimate optical thermal emission from CTH and Zapotec simulations of hypervelocity impacts of KVs onto RVs, see Figure 2.

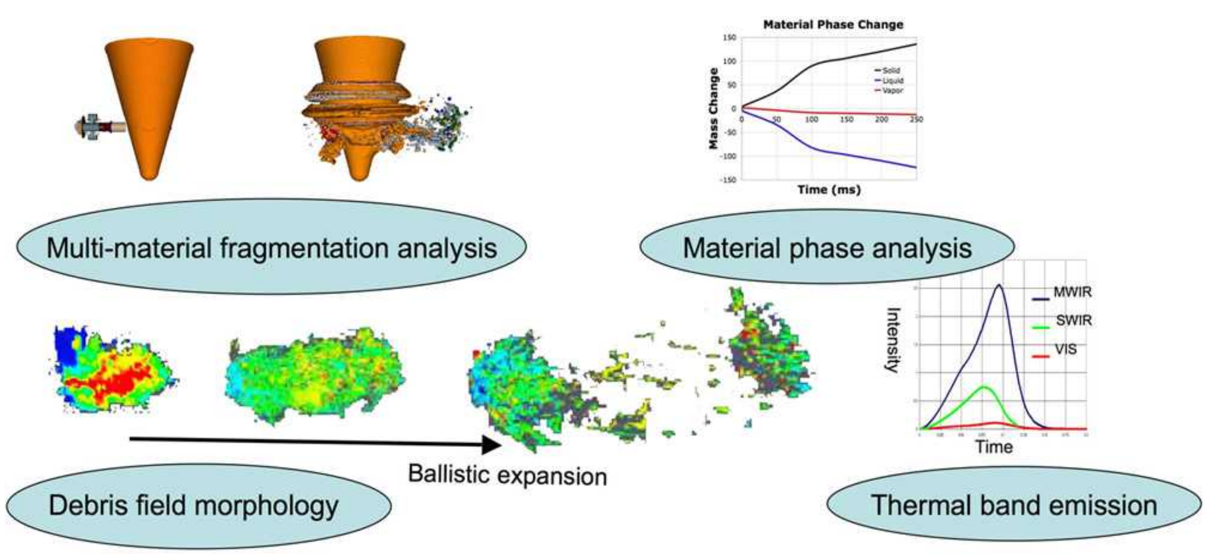


Figure 2: Overview of Sandia's FOSM

FOSM was designed to aid in the identification of exploitable emission features and optimal sensor requirements. It has been designed to describe the entire engagement and data collection process from intercept to sensor response as quickly and accurately as required to produce comparisons between predictions and experimentally observed data.

The physics involved in these impacts encompass a broad range of temporal and spatial scales in addition to a variety of energetic drivers. Because of this, FOSM utilizes two computational phases to describe the fireball over its lifetime: hydrodynamic and ballistic. The Hydrodynamic Phase is simulated using CTH or Zapotec which contains models to accurately describe the intercept impact and early debris cloud expansion where hydrodynamic forces (e.g., EOS, phase change, and HE initiation effects) dominate the physics. The use of CTH allows the incorporation of precise intercept conditions and detailed 3D descriptions of target and KV structures and materials to be utilized. Virtually all of the development for FOSM has been done with CTH as the driver but output from any code that can adequately estimate temperature could be used.

Eventually, a transition point can be identified where the shocks and hydrodynamic effects diminish and the system takes on more ballistic characteristics. At this time, a snapshot of material properties and the thermodynamic state within CTH is taken as the thermal source term for the ballistic cooling phase of the calculation. Then, the relevant physics can be solved using a computationally simpler approach where the debris is expanded assuming constant velocities and no physical interaction between fragments. As the debris expands within FOSM, it is allowed to simultaneously transfer energy throughout the field assuming thermal radiation to be the dominant form of energy transfer. Phase transition effects are explicitly included. FOSM therefore simulates both the short-duration events surrounding the impact of the vehicles and the longer-term dispersion of the fireball with its accompanying thermal emissions.

Structural Debris Tool (SDT) and Hydrodynamic Debris Tool (HDT)

SDT is the first of two tools used to process the results of the Zapotec Hydro-Structural simulations. SDT characterizes the Lagrangian (i.e., Pronto3D and Presto) output and typically identifies and characterizes the larger debris. The Lagrangian data is contained within the Exodus file format. This is a binary format that contains complete details of the computational mesh, including element arrangements and nodal positions. Requested element and nodal data is also saved in this type of file. Typical outputs include: element status, nodal and element masses, nodal velocities and displacements, and element volumes and densities.

HDT provides a similar capability for Eulerian CTH data as SDT provides for Lagrangian data. HDT allows for the extraction of kinematic, spatial, and geometric information from CTH data files at user-selected times. Typically, HDT is used to process the Zapotec Eulerian output from CTH, although it is possible to characterize data from CTH-only simulations. Tabulated descriptions of individual particle states that include mass, size, temperature, location, and velocity vector can be generated. The use of HDT for hydro-structural simulations allows for the characterization of donated materials and structural components represented in the Eulerian mesh that are expected to undergo large deformations, such as the KV.

CTH Benchmarks

Successful comparison of CTH with the physical properties observed during an event increases confidence in CTH for a particular experimental regime of interest. The following comparisons evaluate CTH at several levels of complexity in regimes that exist in missile defense engagements. These include fundamental behavior of material, explosive reaction, and system level engagements. These experiments and events help serve as benchmarks to increase confidence when assessing missile defense engagements.

The approach taken is to start with simple experiments that isolate and explore fundamental material behaviors. Success in these steps builds confidence in CTH and its ability to simulate the behavior of more complex experiments which can be thought of as a collection of simple experiments interacting simultaneously.

CTH is an Eulerian Shock-Physics code and as such is limited to simulation of high speed penetration and the subsequent impact hole sizes, spray debris and subsequent interaction of that spray debris on other target components, including High Explosive response.

One-Dimensional Shock Tube

Sod (1978) introduced the use of an analytic solution for the time-dependent response of a one-dimensional shock tube as a test for finite difference schemes for integration of systems of nonlinear hyperbolic conservation laws. Such schemes are the basis for most shock physics codes, so that this approach is a useful analysis for evaluating code predictions. The Sod problem presents the *only* known analytical solution to a shock problem.

In this case, a one-dimensional shock tube initially has one half-space filled with an inviscid, non-heat-conducting fluid, while the adjoining half space contains a lower density fluid or vacuum. The half-spaces are separated by a diaphragm, which is removed at t=0. The result is an essentially one-dimensional flow discontinuity problem which provides a good test of any compressible code's ability to capture shocks and contact discontinuities and to produce the correct density profile in a rarefaction. It also tests a code's ability to correctly satisfy the Rankine-Hugoniot shock jump conditions. Sod found that many seemingly reasonable integration schemes would fail to capture the basic structure of the shock tube solution or would introduce additional nonphysical behaviors.

Hertel *et al.* (1993) reports the application of Sod's problem to the assessment of the implementation of finite volume integration schemes within CTH. They considered the problem of a one meter long shock tube in which the first 50 cm are initially filled with an inert gas with density=10^{-3} g/cc, and the remainder with an inert gas with density=10^{-5} g/cc. The analytic solution of this version of the shock tube problem includes three common structures: 1) a rarefaction fan, 2) a contact discontinuity, and 3) a shock wave. This represents a particularly good test for various integration schemes. This particular combination of parameters is a very stringent test of a code and would probably not be seen in typical simulations for Missile Defense.

Figure 3 shows the density profile for the above problem when the shock wave has traveled about 35 cm from the initial dislocation.

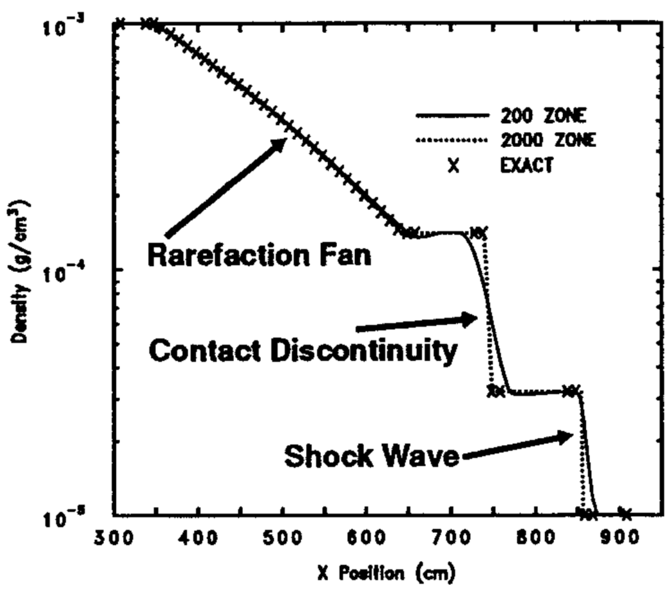


Figure 3: Sod Problem Density Profile Comparison with CTH

Two CTH simulations were compared to the analytic results, a 200 zone calculation with 0.5 cm zones, and a 2,000 zone calculation with 0.05 cm zones. At the time of the original publication (circa 1993), the number of zones was significant, as a 2D problem with $4x10^6$ computational zones was relatively compute-intensive, as was a 3D problem with $8x10^6$ zones. In the intervening 20 years, Sandia's computational capabilities have increased substantially and neither simulation noted above would be considered large. It is still of interest to see how the simulation accuracy varies with the number of zones over which the relevant physics takes place.

Both CTH simulations accurately reproduce the structure of the analytic solution, although it is clear that the 200 zone calculation displays more variation from it than does the 2,000 zone simulation. In fact, the 2,000 zone calculation can barely be distinguished from the exact solution. In the 200 zone calculation, the shock wave is spread out by the effects of artificial viscosity, and the contact discontinuity by diffusion in the advection scheme. Although not apparent in the figure above, there is a small amount of ringing apparent in the particle velocity plots following the contact discontinuity. This examination of Sod's problem shows that the integration scheme used in CTH accurately reproduces the structures encountered in shock wave dynamics. This result, although representing one-dimensional dynamical behavior, underscores the essential accuracy of the CTH simulation code. Figure 4 is the result of more recent work with CTH.

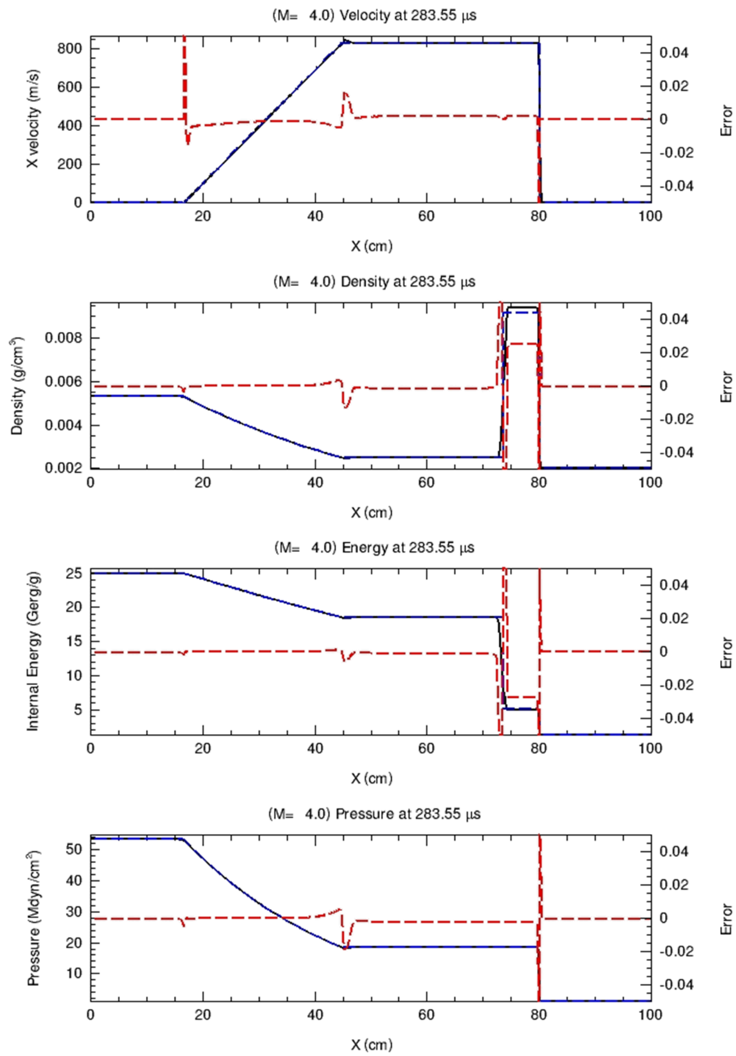


Figure 4: Sod Problem Error Comparison for CTH

Note that the initial pressure-density difference is more typical of real life simulations; and the figure also includes an error measure between the exact solution and CTH. The red dashed line shows that the error is almost zero for all regions except at the shock and rarefaction discontinuities.

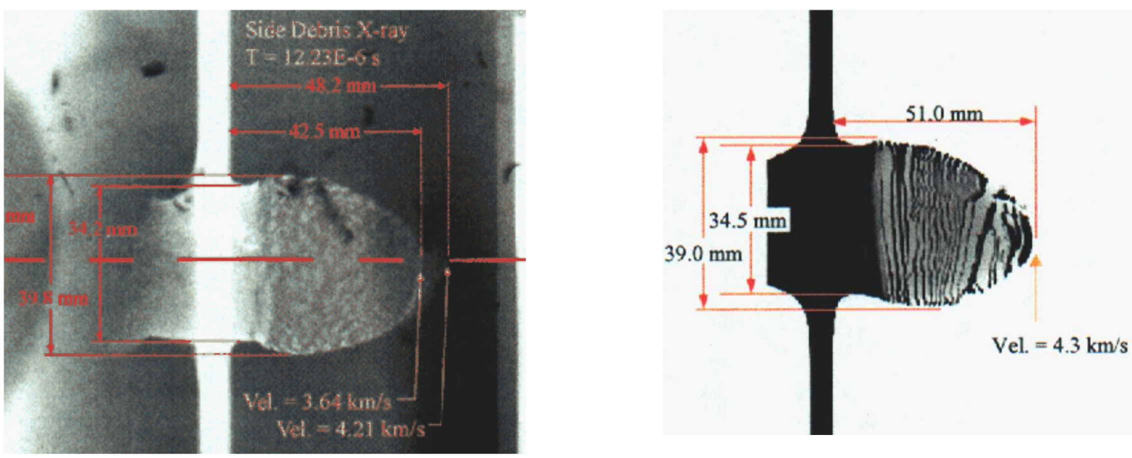
Hypervelocity Thin-Target Penetration

Chhabildas, *et al.* (2003) carried out a combined experimental and CTH simulation study of hypervelocity thin-target impact and penetration. The experimental study involved impact of a hypervelocity Ti-alloy flyer plate on an aluminum (Al) target plate at velocities ranging from 6.5-11 km/sec. Experimental diagnostics included velocity interferometry of a witness plate and x-ray densitometry of the debris plume. The stresses generated range up to some 230 GPa, which accesses both the Al melting transition at ~130 GPa and the Al release vaporization transition which begins at ~230 GPa. This is an extensive study which will not be described in detail in this report, but a summary of relevant results reflects the current state-of-the-art in hypervelocity penetration mechanics.

The Ti-6Al-4V alloy flyer plates are nominally 0.09 cm in thickness, and typically ~1.8 cm in diameter. Nominal impact velocity was chosen to be 6.5, 9.0, and 11.0 km/sec, and the actual value was determined to be ~1% for each experiment. The aluminum targets have nominal thickness of either 0.1 cm or 0.24 cm, and are composed of Al 6061 T-6 alloy. The witness plate is also composed of Al 6061 T-6 alloy and has a nominal thickness of 0.4 cm. Two-dimensional experiments were carried out with nominally normal flyer impact, while in three-dimensional experiments the target surface was tilted at an angle of 20^{o} from the velocity vector. Some of the flyer plates exhibit curvature, in some cases as much as a radius of curvature of 3.26 cm. However, at lower velocities and for short flyer throw distance the observed flyers were nearly flat and parallel to the target surface.

A CTH simulation was made of the various impact initial conditions. The material EOS was described using the SESAME Library Model parameters. The aluminum EOS includes the effects of melting, vaporization, and material tension, and is one of the best understood and documented EOS extant. Strength effects in both materials were described using the SGL Model parameters in the CTH data library. It is believed that the SGL Strength Model underestimates the strength of a material in the lower hypervelocity regime, but this has not yet been firmly established. Fracture was modeled with the void insertion model with fracture strengths of 1.0 GPa for the Ti alloy and 1.1 GPa for the Al alloy. The magnitudes of the fracture strengths are based on agreement with earlier experimental results.

Figure 5 shows an experimental radiograph of a debris cloud generated by 6.49 km/sec impact of a plate tilted 20^{o} relative to the target plate at ~12 μs after impact (left), and a CTH simulation of the debris cloud from a similar impact (right).



Experimental Result CTH Simulation Result

Figure 5: Ti-Alloy Flyer Plate on an Aluminum Target Plate Impact at 6.49 km/s

It is clear that the general features of the debris cloud is clearly shown in the CTH simulation. Quantitative comparisons given in Figure 5 are within a 10% bound.

Figure 6 compares Velocity Interferometer System for Any Reflector (VISAR) measurement (i.e., the blue line) and the CTH simulation (i.e., the red line) of a 10.85 km/sec normal impact of the same flyer/target combination.

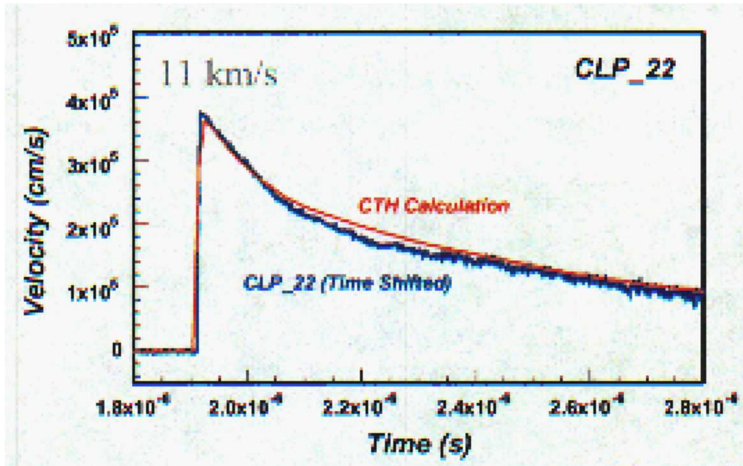


Figure 6: Ti-Alloy Flyer on Al VISAR Comparison

VISAR is a laser interferometer technique which measures the velocity time history of the back side of the target. It was developed by Barker and Hollenbach at SNL in 1972. This technique is done by splitting a laser beam reflected from the mirrored back surface of the target, delaying one portion of the split beam, then recombining the beams and counting the fringes to determine the surface velocity.

Fundamental Zapotec Benchmarks

Spaced Plate Comparison

The prime benchmarking objective with these experiments was to validate the failure modeling of 6061 T-6 aluminum. These initial experiments serve as the first building blocks for additional benchmark studies.

The projectile was a 350 gram generic Nylon/Aluminum Projectile with a length-to-diameter ratio as that shown in Figure 7.

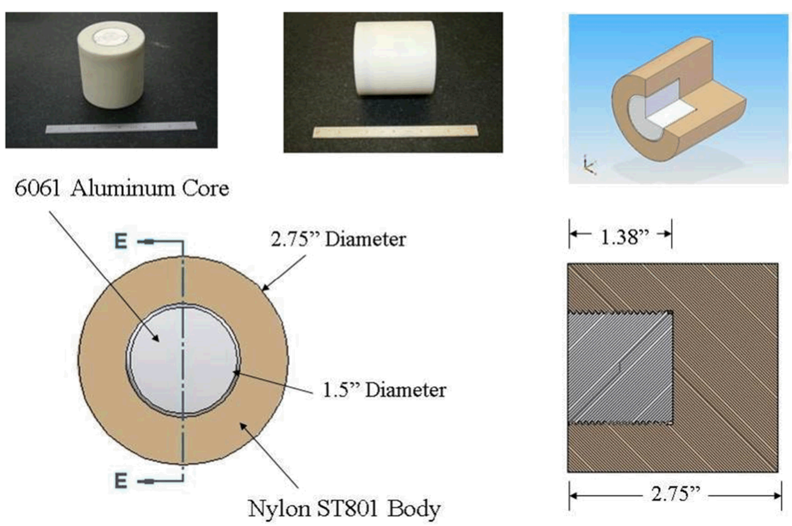


Figure 7: Generic Nylon/Aluminum Cylindrical Projectile

The experimental set up was similar as that shown in Figure 8.

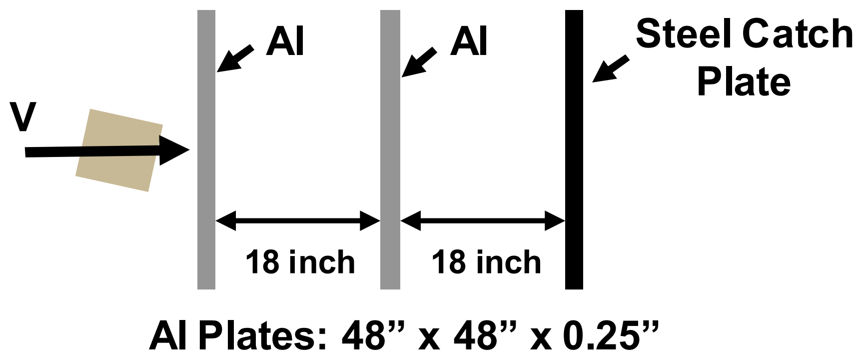


Figure 8: Spaced Plate Experimental Setup

Two aluminum plates (48” x 48” x 0.25”) were hung 18” apart followed by a steel catch plate, 18” from the last plate. The problem was modeled in Zapotec with the two aluminum plates being Lagrangian and the projectile (i.e., which is expected to undergo relatively large deformation), as an Eulerian material. The target plates were meshed at a resolution comparable to that used in full scale simulations with approximately 660K elements per plate.

The main focus of this benchmarking study was to access the Al 6061 T-6 material model. This benchmark helps to ensure that the damage phenomena (i.e., bending and tearing) are captured in a “simplified” setting.

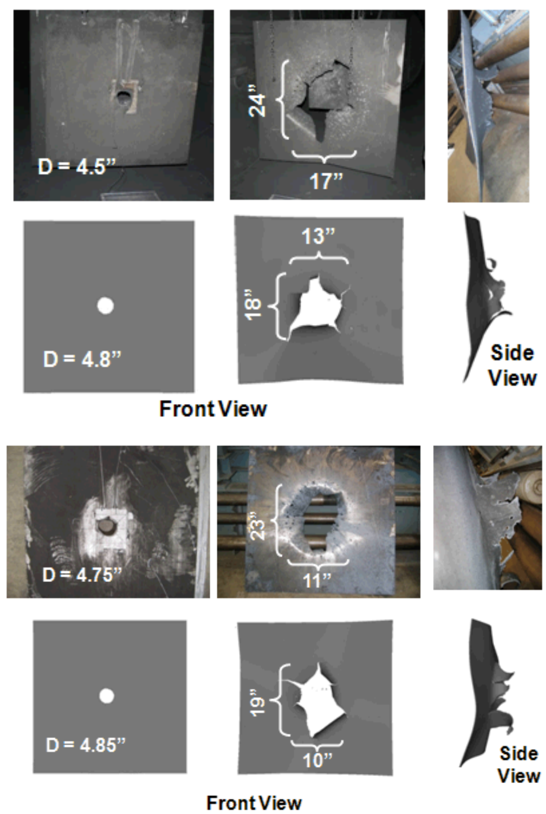


Figure 9: Comparison between Experiment and Prediction for Two Similar Tests

Experimental and simulation results are shown in Figure 9. Again the comparison with experiment is satisfactory. The gross features of bending, tearing, and petalling are captured by Zapotec. Differences are observed however in the under-prediction of the gross hole size in the back plate and the larger region of bending predicted by the calculation. One can get some idea of the experimental variation since the two tests were nominally identical.

Overall the match between experiment and prediction was good with the simulations capturing the gross hole sizes and material failure/petalling that matched the experimental data reasonably well. Such a result helps to give confidence in Zapotec's ability to predict structural failure and the 6061 T-6 Aluminum Material Model.

Pipe Bomb Analysis

A second fundamental analysis explored in this benchmarking test was a pipe bomb experiment. This data was used as a benchmark to assess Zapotec's ability to predict HE driven fragmentation.

The specific test of interest was a pipe bomb experiment. Here a cylindrical casing pipe bomb made from AerMet 100 Steel (i.e., a high strength steel alloy) was set off and the resulting fragments were soft captured and measured. The experimental set up is shown in Figure 10.

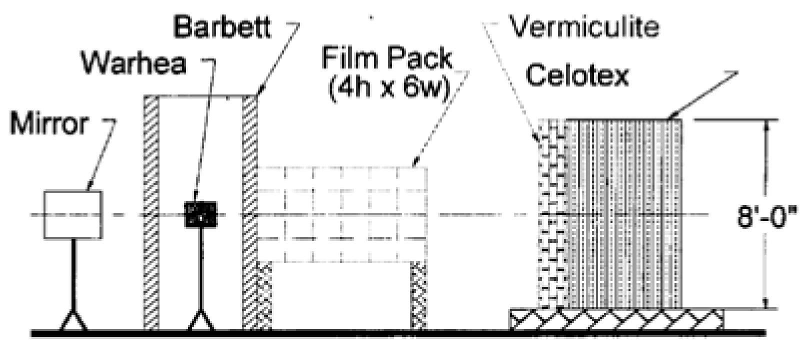


Figure 10: Setup for the Pipe Bomb Experiment

The test utilized high speed cameras to record case expansion and onset of fracture. Flash x-ray provided fragment velocity and polar ejection angle distribution. Fragment soft catch was accomplished using Celotex bundles (i.e., having 25° azimuth coverage).

More comprehensive details on the test and results can be found in Rice et. al (1996) and Wilson et. al (2000). Within the Zapotec simulation, the AerMet Case was modeled as Lagrangian with all other parts modeled as Eulerian. An investigation of the results sensitivity to the number of elements across the thickness of the case was performed with eight elements appearing to be optimal. The final finite element mesh therefore employed eight elements across the AerMet Case thickness and was comprised of more than one million hex elements. A Johnson-Cook Constitutive Model with EOS and fracture was employed to describe the AerMet 100 material. A CTH resolution of 0.25 cm was utilized allowing approximately 30 cells across the HE radial extent. Figure 11 shows the comparisons between the evolutions of the experiment compared with the Zapotec prediction.

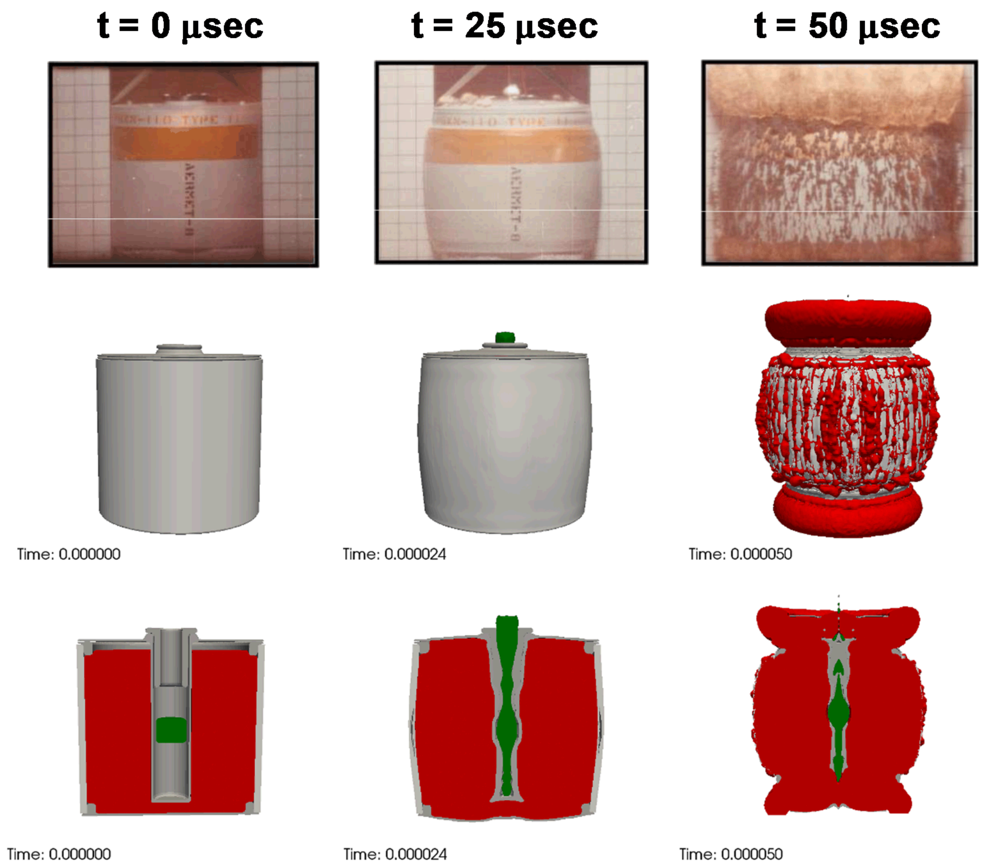


Figure 11: Comparison between Zapotec and the Experiment

A total of 157 fragments were recovered with a case mass recovery (extrapolated to 360°) of approximately 43%. The Zapotec predicted fragment masses compare well with experimental values. Figure 12 shows a qualitative comparison between predicted and experimentally observed fragments.

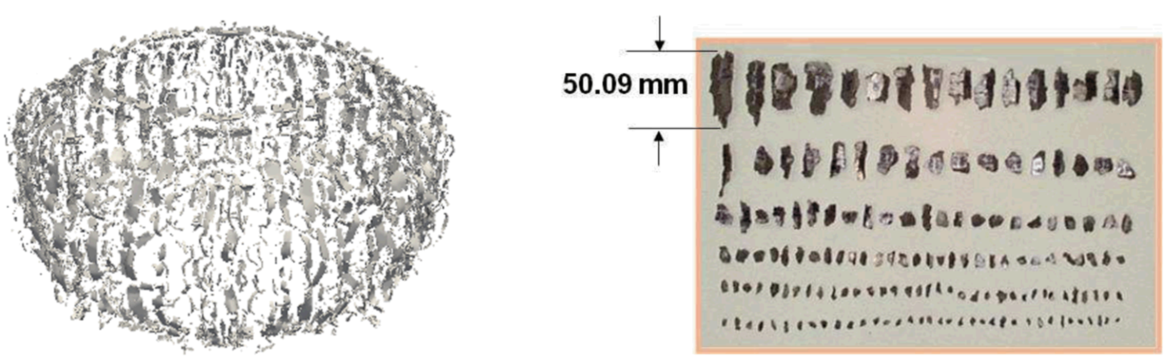


Figure 12: Qualitative Comparison between Predicted and Observed Fragments

Figure 13 shows a quantitative comparison between the experiment and the simulation.

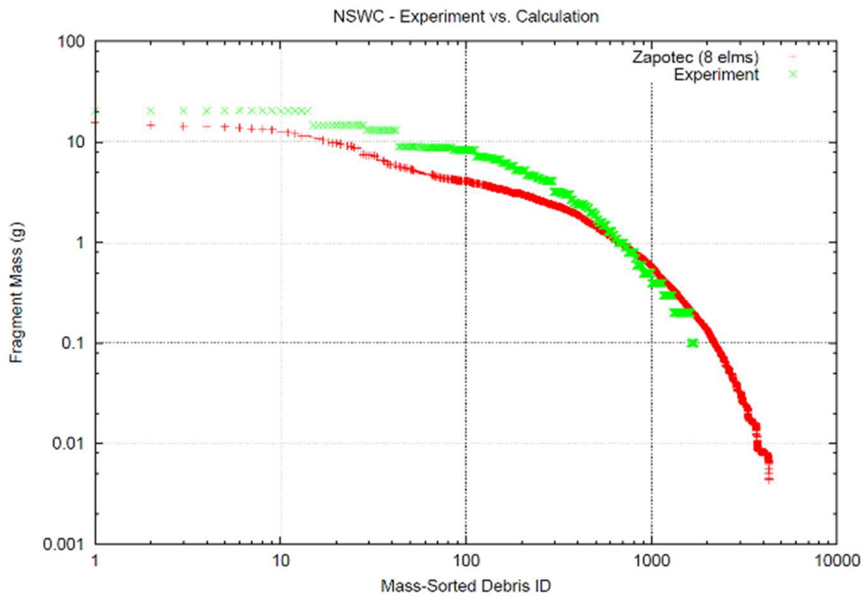


Figure 13: Fragment Mass Comparison between Zapotec and the Experiment

Unfortunately, direct comparison with experiment data was difficult since it is hard to achieve 100% mass recovery (i.e., typically the smallest fragments are not recovered and that data is lost). In this case, 123 sizeable fragments were recovered experimentally with the largest appearing to originate from the end plate (22.9 g). There were 34 additional fragments of 0.1 mg or less with the average mass of the collected fragments being around 2 grams.

Post Intercept RF and Optical Signature Analysis

Sandia's Post Engagement Analysis Toolkit is used to extract and characterize post engagement data from the Zapotec simulations to enable predictions of RF observables. Comparisons are typically limited to qualitative comparisons between observed and predicted Range Time Intensity (RTI) plots. Hypothetical results from this process are given in Figure 14.

Typical Non-Lethal Prediction   Typical Lethal Prediction

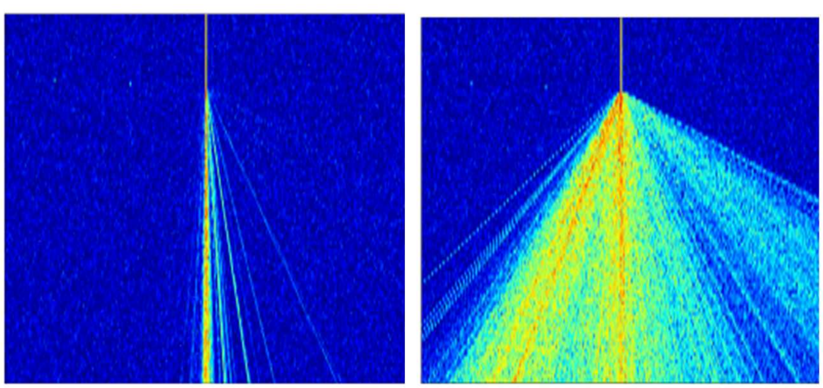


Figure 14: Sample RTI Results from Zapotec/PEAT

Sandia's Fireball Optical Signature Model (FOSM) has been developed to predict the visible and IR signatures associated with exo-atmospheric hypervelocity engagements. The hot debris cloud from a CTH simulation is used as the starting point for FOSM which estimates the expansion of the cloud, does the radiative thermal transport within the cloud, and calculates the signature that an external sensor might experience. Figure 2 shows a hypothetical result along with the workflow for an estimate of the optical signature.

Conclusions

This paper has provided an overview of the phenomenology of hypervelocity impacts associated with missile defense applications, a broad overview of the DOE engineering tools used at Sandia to simulate these impacts, and a general analysis philosophy. In addition, the assessment of missile defense lethality was discussed with an emphasis on the computational tools used to model the engagement. The computational approach used to predict both optical and radar signatures from post engagement debris was also presented.

The motivation for this report was to collect and present documentation in support of the tools and procedures used at Sandia to perform lethality assessments and predict post engagement debris and their associated signatures. Comparisons with experimental data were shown for each computational tool utilized during the analysis process. For each code, a stepwise benchmarking approach was utilized. Here, accurate predictions of simple experiments involving basic physical processes increase confidence in predictions of complex interactions involving the same processes under an applicable range of conditions without extensive testing of the complete range of conditions. Success in describing these basic experiments therefore increases confidence in the codes ability to suitably model the complexities present in full scale missile defense intercepts and provide a benchmarking level for code fidelity. This step-wise process for validation is the cornerstone of the DOE process for support of the Nuclear Weapons Complex.

Finally, the ultimate test of both CTH and Zapotec predictions is the accurate calculation of both RF and optical post intercept signatures. Here the code results are first post-processed using Sandia's Post Engagement Analysis Toolkit and then signatures are generated in-house or at partner sites. Successful comparisons help increase confidence in the predictions of post-intercept debris fields resulting from both flight test engagements and simulated engagements.

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