CHALLENGES IN THE PREDICTIVE CAPABILITIES OF FRAGMENT IMPACT OF ROCKET MOTORS

K. Clotfelter, J. Uschock
NAVSEA Dahlgren, Surface Warfare Center Division, Dahlgren, VA

This paper examines the current and emerging capabilities to address the response of tactical rocket motors to fragment impact. Focus was placed on the areas in need of improvement of current propellant models. Two models, which are being developed by the Department of Energy laboratories, were exercised and the current challenges were identified. A plan was developed to improve these models and to tie them into a larger system model.

INTRODUCTION

Insensitive Munitions (IM) requirements impose significant constraints on the design and fielding of modern munitions. Failure to account for these constraints early in the design phase can lead to serious cost overruns and schedule slips in the latter stages of system development. Hence, predictive tools for estimating the likelihood that a candidate design will pass full-scale IM compliance tests are becoming increasingly necessary. Tools exist to predict the detonation response of an explosive to shock. However, the mass of propellant contained in a tactical missile is much greater than the mass of explosive; therefore, predicting the response of a tactical rocket motor to IM stimuli is of great interest. The Department of Energy (DOE) laboratories are developing computational physics tools which, combined with well instrumented tests, may be able to predict this response acceptably to reduce the number of expensive, full-scale tests required to ensure IM compliance. These tools are described and compared in this paper. Shortfalls are noted and recommendations for future investment are made. This paper contains a subset of the information published in a larger report, coauthored by U. S. Navy and Army personnel[1].

THE BULLET / FRAGMENT IMPACT PROBLEM

A typical fragment impact scenario of a tactical rocket motor in a weapon system can be very complex to model. A tactical rocket motor is deployed from a launch canister that resides inside a launcher. The launcher may be armored. In order for a threat fragment or bullet to reach the rocket motor, first it must perforate the launcher, the armor, and the launch canister. The whole fragment may perforate all of these layers with a relatively high residual velocity, it may break into smaller pieces, or it may stop. If the prediction tool used for this problem does not model the penetration event accurately, the initial conditions of the fragment impact on the rocket motor will be incorrect.

In order to predict whether a munition will pass an IM test, it is necessary to model the entire chain of events starting from fragment impact to case rupture. Relevant phenomena include perforation of the launcher, armor and launch canister;

rocket motor case penetration; propellant penetration; propellant initiation; and propellant burn. Possible reactions are no-reaction, burning and detonation. However, in order to make these reactions pertinent to the IM community, the model must be able to predict fragment size and the distance thrown. In the event of no-reaction, this is easy. In the event of burning or detonation, there are many complicating issues, such as the role of confinement on the reaction.

There are essentially three numerical formulations for the analysis of IM and other weapons related problems: Lagrangian, Eulerian and Arbitrary Lagrangian Eulerian (ALE). In the first method, the media is treated as a structure. In the second method, the media is treated as a fluid with strength. The ALE approach is a mixture of the first two, Lagrangian and Eulerian, offering some improvements over the first two approaches. The Eulerian code used in this effort is CTH from Sandia National Laboratory (SNL), Albuquerque, NM.[2] The ALE code used in this effort is ALE3D from Lawrence Livermore National Laboratory (LLNL), Livermore, CA.[3]

MODELING FRAGMENT IMPACT WITH CTH AND ALE3D

In order to assess the current and emerging capabilities of ALE3D and CTH to model Fragment Impact (FI), the codes were exercised on a common FI scenario. The scenario is a cylindrical fragment with a conical end, impacting a rocket motor surrogate filled with a 1.3 propellant at different velocities. The propellant cylinder, with aluminum case and steel endcaps, is shown in Figure 1. The steel end caps were designed so that the aluminum case would rupture before the end closures would fail. This scenario was run in both CTH and ALE3D, and the results were compared.

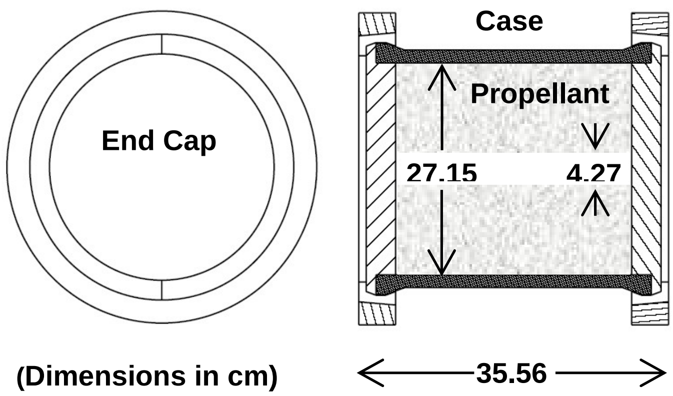


Figure 1. Rocket Motor Surrogate

CTH

CTH contains two propellant models: CDAR[4] and PMOD[5]. CDAR is a physics-based model that is still being researched. It was not available to be evaluated for this project due to model/code improvements under development at SNL. PMOD is a phenomenological model used to predict propellant response to shock loading.

PMOD assumes a linear shock-particle velocity equation-of-state (EOS) for the solid phase of the propellant. The reaction phase gas products of the propellant are modeled as a tabular EOS generated by Cheetah[6] for multiple pressures. Transformation between these two phases is governed by an extent of reaction equation that accounts for both volumetric and surface burning of the propellant (considered as two separate entities). Common to both of the burn models is a combustion model, which is valid over two pressure regimes and is calibrated in part against published burn data. Also common to both of the burn models are damage models. In the case of volumetric burn, damage is accounted for by a strain and strain rate dependent surface-area-to-mass ratio occurring under compression; in other words, under compressive shock loading, the surface-area-to-mass ratio increases, which leads to an effective “rubbleization” of the propellant and higher burn rates. The case of the surface burn is very similar except that it focuses on tensile shock loading conditions. Neither model explicitly models fragmentation. While this is meant to be a short overview of the formulation, more detailed information may be found in the summary report on PMOD.

PMOD is only calibrated for one AP/Al/HTPB propellant. Specifically, multiple series of tests in confined and unconfined environments, across three scales (laboratory, mid-scale, and full-scale) involving cylinders of explosive and propellant were conducted at SNL to calibrate different parameters in the mathematical formulation of PMOD.

The rocket motor surrogate described previously was modeled in CTH with PMOD. The code was run with varying fragment velocities to determine the minimum velocity, termed threshold velocity, required to cause propellant reaction. A threshold velocity of 12,000 feet per second (fps) was predicted via gas volume fraction plots. Figure 2 shows the fragment, case, and unreacted propellant materials at 12,000 fps. Though specific test data for a direct comparison did not exist, the predicted threshold velocity seemed unreasonably high. For comparison, it is fifty-percent higher than the NATO fragment velocity[7]. This result was initially viewed as suspect, but held up, in terms of the model, under the scrutiny of further sub-analyses.

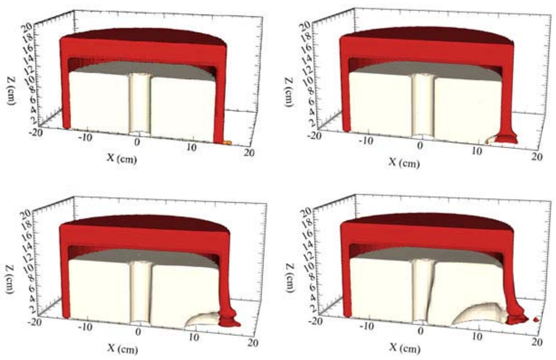


Figure 2. CTH Material Plots for Rocket Motor Surrogate at 12,000 fps

The second of the CTH investigations with PMOD focused on its ability to correctly model propellant reaction for a known problem. Applied Research Laboratory (ARL) conducted small-scale fragment impact tests, varying fragment weight, case material, case thickness, and impact velocity.[8] Since the propellant considered therein had an AP/Al/HTPB composition, these test results were a natural choice to model with PMOD in support of this effort. The worst-case test in the database was modeled in CTH and is shown in Figure 3. The volumetric burn plots showed that PMOD predicts a "no-go" reaction in this case, contrary to the experimental results.

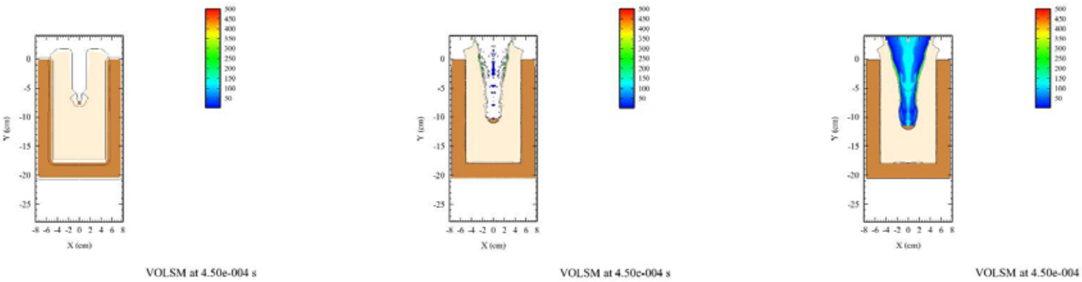
t=0 µs   t=40 µs

Figure 3. 3-D Model of High Velocity Fragment, Thin-Skinned Case

The results suggest that PMOD is predicting a threshold velocity higher than the high end of the ranges considered for testing purposes. Other scenarios involving the highest impact velocities were run for the thicker cases, and they too failed to predict a "go", running counter to experimental findings. The collection of these findings in conjunction with the rocket motor surrogate results begin to suggest that PMOD, as it is currently parameterized, may not be accurate at predicting fragment impact threshold velocities. Given that PMOD was calibrated to more traumatic damage scenarios (specifically, explosive detonations in close proximity), its inability to react to the much lower-energy impact of a single fragment is not surprising.

Given these findings, it became important to consider how values for PMOD parameters corresponding to the calibrated propellant were derived, and ways they could be altered, while ensuring that PMOD continues to be in agreement with the pressure and propellant burn data. Dr. Dave Crawford, the developer of PMOD, suggested a viable procedure to improve agreement with test data for fragment impact studies with only minor modification to the original calibrated parameters. The key was in realizing that the primary driver in accurately predicting velocity thresholds in bullet and fragment impact is the pressure due to the strain-to-failure model which was encapsulated in a user parameter. This reduced the effort of reparameterizing the entire model to changing only two parameters and ensuring that the modified model still accurately replicated the original test suite data. If the new parameter pair continued to provide accurate predictions, then the modified parameter pair could be investigated in other fragment impact scenarios to determine its predictive capabilities. This effort in the model was sufficient to conduct a reparameterization effort, which showed promise in improving PMOD's ignition threshold impact velocity predictions over the baseline predictions made with the original parameters.

Taking this approach, careful analysis showed that a new S_{V_1} and ν_V parameter pair resulted in 96 percent of the baseline in measuring the amount of propellant burned in a laboratory-scale test. The volumetric burn produced by the same model, varying only the S_{V_1} and ν_V parameters and mesh resolution is compared in Figure 4. Figure 4(a) shows the results using the original PMOD parameters and mesh resolution driven by the propellant radius. Figure 4(b) shows the results using the PMOD parameters and mesh resolution driven by the fragment radius. Figure 4(c) shows the results using the new parameter pair. All plots are volumetric burn contour plots at time t = 450 µs.



(a) S_{V_1} as a Function of Propellant Radius Resolution S_{V_1} =150, ν_V = 0.25, resolution = 0.125 cm

(b) S_{V_1} as a Function of Fragment Radius Resolution S_{V_1} =27, ν_V = 0.25 resolution = 0.0635 cm

(c) with the New Pair as a Function of Fragment Radius Resolution S_{V_1} =27, ν_V = 0.10 resolution = 0.0635 cm

Figure 4. Volumetric Burn Corresponding to Fragment Impact into Bare Propellant

Figure 4 shows the new parameter pair had a significant effect in producing volumetric burn as compared to the original calculation where no burn occurred. It is also important to note that the higher resolution in combination with the original PMOD parameters captured burn as well, which was not expected.

At this juncture, it was important to understand whether or not the proposed new parameter pair could be useful in producing more realistic agreement with some of the ARL tests. With original parameters, no burn was predicted which was inconsistent with actual test data. Revisiting the model now accounting for the reparameterization of the AP/Al/HTBP propellant produces some different results as shown in Figure 5.

(a) ARL test with original PMOD Parameters (b) ARL test with Revised PMOD Parameters

Figure 5. Volumetric Burn Corresponding to Known Fragment Impact

First, note that it was not practical to run the two scenarios depicted in Figure 5 as full 3-D cases even with symmetry in a short period of time due to their size. As such, only small 3-D sections with two planes of symmetry were considered. In the case of the higher resolution and original parameters, no burning occurs; whereas in the case of higher resolution and revised parameters, slight burning is clearly present at the boundary. This latter result is now consistent with experimental data. Clearly much more investigation needs to be conducted to better understand how these changes in input affect propellant response to fragment impact. Finally, this last result shows the promise in this approach for beginning to capture realistic bullet and fragment impact events even if the modeler is hobbled by mesh resolution constraints.

In short, PMOD has been exercised in several different fragment impact scenarios with success only occurring within the context of a reparameterization effort. This is not unreasonable given that the attendant test suite was specifically designed for capturing propellant response in explosively driven scenarios. These are scenarios where high strain rates are dominant. Comparison of PMOD predictions with these test results as well as other scenarios of interest showed excellent agreement, which speaks to the quality of the calibration to events involving higher order trauma. Unfortunately, the test suite did not incorporate any tests involving bullet or fragment impact as that was beyond their scope of interest.

Currently PMOD is quite limited in its applicability since it has only been calibrated for one propellant and can only handle a single instance of propellant in a given calculation. Further, PMOD, as is, does not capture all of the necessary physics intrinsic to bullet and fragment impact. For instance, a third damage mechanism corresponding to shear should be incorporated; though developing a constitutive model for each propellant being considered will be costly. Also, within the model, ignition is considered to be purely pressure-driven; this misses the key role that temperature can play in IM hazard scenarios. Another limitation is the treatment of fragmentation of propellant and case. Finally once important additions like these are made to PMOD, the complexity of the model can grow to include deflagration models and the ability to gradate levels of burning. SNL envisions that CDAR will eventually fulfill this capability.

ALE3D

ALE3D contains one propellant model: PERMS[9]. PERMS is a phenomenological model to predict propellant response when a rocket motor falls to earth at speeds on the order of 300 to 600 fps. This differs from PMOD since the response to fallback is not due to a shock reaction but is driven by propellant fragmentation burn.

The PERMS ignition and growth model uses the classic Lee-Tarver explosive SDT approach with a modification for propellant behavior. The Lee-Tarver ignition and growth model[10] has two parts, a pressure threshold for ignition and a pressure based reaction rate to convert all solid explosive-to-explosive products. In a non-detonation event, such as propellant reaction or low order explosive reactions, not all solids are converted to gas and multiple chemical reactions may occur. Therefore, the PERMS model has three parts. Similar to Lee-Tarver, the first part is a pressure threshold for ignition. The next two parts are pressure-based reaction rates for: 1) decomposition of ammonium perchlorate, with the subsequent oxidation of the polymeric binder, and 2) combustion of Al particles in the presence of carbon dioxide and water produced by the first reaction.

The PERMS fragmentation model assumes increased surface area due to mechanical damage is driven by strain and strain-rate. The surface to volume ratio at the onset of chemical decomposition is determined by averaging the equivalent plastic strain. The surface-area enhanced burning parameters in the fragmentation equation are evaluated to match the results of shotgun tests. It should be noted that the bullet / fragment velocity could be on the order of 10 times higher than the impact velocities of the shotgun tests. It should also be noted that the fragmentation model does not explicitly model fragmentation.

For the bullet / fragment impact problem, PERMS is only applicable in the compressed region surrounding the projectile trajectory, which is at most a few times the projectile diameter. This is sufficient to predict whether or not ignition occurs, and if so, the surface-area enhanced burn rate of the damaged propellent. However, the amount of damaged propellant is small compared to the total mass of the propellant in the motor. The subsequent spread of the flame front by thermal ignition, or deflagration, accounts for combustion of the remaining propellant. ALE3D is capable of modeling deflagration. The deflagration model has recently been invoked with PERMS to simulate the results of thermally induced combustion of the undamaged propellant surrounding the impact crater. Further investigations are required for this coupled response.

The rocket motor surrogate was simulated in ALE3D. The core diameter, 8.54 cm, is different from the CTH model, but the area of most interest was the interface between the outside surface of the propellant and the inside of the case. The Eulerian mode was used at the recommendation of LLNL. The propellant parameters for PERMS and the deflagration model were provided by LLNL. The PERMS parameters are also located in Reference 9. Figure 6 shows a sequence of predicted material boundary plots produced from a 6,000 fps impact. The fragment is almost completely eroded after penetrating the case and creating a sizable crater in the propellant. However, the propellant damage does not seem to extend into the bore. Combustion begins almost immediately as the fragment penetrates the case. The surface of the crater expands as the propellant continues to burn, allowing the combustion gases to escape and not further deform the case around the entrance hole. Some bulging of the propellant at the surface of the bore is apparent.

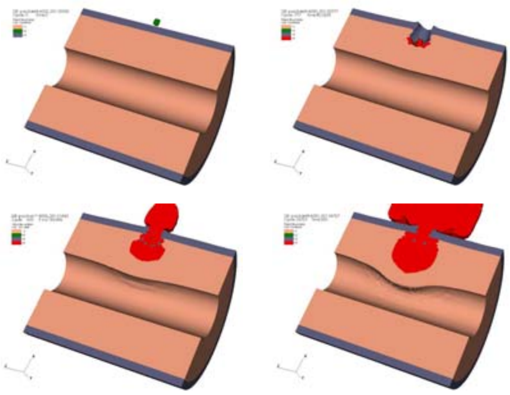


Figure 6. Impact Response at 6,000 fps (Time = 0, 80, 160, 320 μs)

It is important to note that the combustion seen in Figure 6 is due to two models: the PERMS model and a deflagration model. The deflagration model is initiated by temperature produced during the initial PERMS reaction. The deflagration model was previously available in ALE3D, but has recently been connected to the PERMS model as a part of this effort. This is a key capability that will allow the reaction to be modeled long enough to predict case reaction.

Since the reaction predicted for the 6,000 fps fragment impact seemed to be quite violent, the run was repeated with the fragment's initial speed set at 3,280 fps. Based on earlier simulation runs, this speed was near the ballistic limit (i.e., the speed at which the projectile perforates the case) for this surrogate. In runs for which the fragment's initial speed was substantially below the predicted ballistic limit, PERMS did not predict ignition. Figure 7 shows a sequence of predicted material boundary plots produced from the 3,280 fps impact. The fragment penetrates the case, but does not create a crater in the underlying propellant. Combustion begins in a small region immediately adjacent to the entrance hole. Since the combustion gases cannot readily escape, pressure builds, combustion spreads rapidly, and the case wall surrounding the impact site is blown outward. Some bulging of the propellant at the surface of the bore is also apparent as the reaction progresses. Note that PERMS does predict ignition at 3280 fps, while PMOD predicts a threshold velocity of 12000 fps. This is quite a discrepancy between the models.

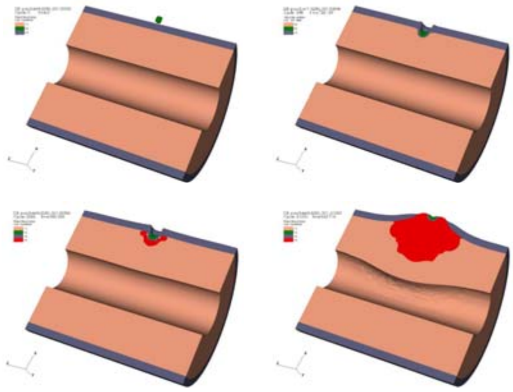


Figure 7. Impact Response at 3,280 fps (Time = 0, 130, 380, 633 µs)

The model results at 3,280 and 6,000 fps are meaningful, qualitatively. The low velocity impact created a smaller hole in the case and less damage in the propellant, but the resulting burning reaction created a large bulge in the case which would result in a large hole in the case. The faster impact created much more damage to the case and propellant on impact, but the resulting case damage was less significant locally. These model results are consistent with actual safety tests where a slow bullet was more damaging than a fast fragment impact.

One shortfall discovered in the PERMS model during this exercise was the lack of a meaningful ignition threshold. PERMS was developed to predict the airblast resulting from fallback occurring as a result of a failed space launch. In these scenarios, ignition would certainly occur, and there was no need to determine an accurate value for the cutoff parameter. Therefore, the cutoff parameter was taken to be a low value making PERMS very conservative in predicting reaction. Contrary to the fallback problem, reaction may or may not occur for the fragment impact problem. Another limitation is that the fragmentation model does not explicitly model fragmentation. Finally, a deflagration capability was linked to PERMS during this project. It shows promise but will require much further evaluation.

SUMMARY AND RECOMMENDATIONS

Two models which are being developed by the DOE, PERMS and PMOD, were exercised on a rocket motor surrogate fragment impact problem. The PERMS model within ALE3D predicted a low threshold ignition for the scenario considered, while PMOD within CTH predicted a high threshold ignition using the original calibrated parameters. The reparameterized version of PMOD showed more realistic sensitivity for the fragment impact scenarios considered, though much groundwork remains to investigate the viability of this option. Likely these results were very different due to the empirical nature of the codes. Several efforts are recommended to improve the predictive capabilities of the current codes for impact.

First, a test series has been designed to explore one of the areas in need of improvement in both propellant models, the ignition threshold criterion. Both ALE3D and CTH assume ignition based on pressure, but neither tool has bounded this pressure value for the fragment impact problem. The tests would provide some data with which to validate or modify the models.

Additional efforts are being pursued to improve our current modeling capability. Existing fluid and structural models are being combined, incorporating FEM particles. Constitutive testing of composites, explosives and propellants continues. Instrumentation is being developed to discern ignition mechanisms. Highly instrumented tests of explosives in impact conditions are being performed to understand the mechanisms involved in ignition. Work is proposed in the areas of physics; numerics; database exploration and development; validation and transition to leverage other funded activities. A testing methodology that includes IM-specific testing, including low speed impacts and plausible thermal hazard scenarios, and that is amenable to calibrating both PERMS and PMOD is recommended. These efforts would allow the DoD to focus on materials and phenomena of DoD interest. They would also allow the DoD to validate the models for real DoD problems and transition the tools to industry where they will be used for acquisition programs.

We believe that the codes and approaches mentioned here do adequately represent the current state-of-the-art which is presently somewhat limited with regard to prediction of response. The tight coupling of appropriate experiments with current numerical modeling capabilities is imperative, and we believe that this is the best path to success in the future for this important class of problem.

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