MODEL PREDICTIONS OF PRESSURIZATION OF ORDNANCE MAGAZINES BY INADVERTENT IGNITION OF ENERGETIC MATERIAL

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ABSTRACT

For this study, high fidelity computations were performed on a simple fortified ordnance magazine with different levels of confinement and energetic material reaction rates. Pressurization rates versus time were calculated for the different confinement/reaction rate combinations. Calculations were then done to determine the effect of the pressurization rate on the magazine structure. For the pressurization calculations, it was assumed that the energetic material came from a mixed system with a small amount of hazard division (HD) 1.1 energetic material and enough HD1.3 energetic material to fill the magazine to capacity. For comparison with the pressurization computations, calculations were also made with the HD1.3 system energetic material detonating and the effect of a detonation on the ordnance magazine was compared with the effect of the pressurization due to deflagration.

Simulations were performed that calculate the pressure rise inside an RC Freloc Stradley 33-15-74 earth-covered magazine (ECM) from the burning of M10 gun propellant. Simulation data argue the potential for the safety standards in DoD 6055.09 to be inadequate in some instances of HD1.3 storage, but this argument cannot be responsibly made until structural simulations can be run to on the simulation data to calculate damage effects. Calculated pressures predict that pressurization occurs for weights of M10 between 100,000 pounds and one million pounds, but to an extent that is dependent on the mass burn rate via the reaction surface area. At surface areas higher than the arbitrarily-defined nominal area, pressurization occurs severely enough that the ECM is likely to rupture due to stresses on ECM surfaces. Structural simulations must be conducted to calculate whether the magazine ruptures. Future studies will investigate lower weights of M10 in the magazine as well as other reaction surface areas. Detonation simulations reveal pressurization due to deflagration to impart a higher impulse to magazine surfaces than detonation, although over a much longer timescale. Ramifications of the higher impulse will be investigated through structural simulations.

INTRODUCTION

Per DoD 6055.09-STD, “DoD Ammunition and Explosives Safety Standards,” current methodologies for siting AE allows mixed storage of HD1.1, 1.2.X, 1.3, 1.4, and 1.6 and follows the equation: D = K(Net Explosive Weight)$^{1/3}$. Generally, if a storage site or an operating building is sited for HD1.1, the only limitations for HD1.3 AE storage is the physical capacity of the facility or 500,000 pounds. HD1.3 systems pose a mass fire hazard and are uniquely different when compared to detonable systems (HD1.1). If an ordnance magazine is fortified to mitigate or reduce the blast pressure from a mishap in an adjacent magazine, it is also possible to build up substantial pressure inside the magazine as large amounts of energetic materials deflagrate instead of detonate, which might pose a greater threat than recognized.

The inhabited building distance (IBD) is based on the propagation of the blast wave and fragments for an HD1.1 system with larger than 45,000 pounds net-explosive weight for quantity distance (NEWQD). Blast propagation is a well studied phenomenon with the strength of the blast-wave decreasing by the cube power of the distance from the blast. This leads to the well-known relationship of the IBD proportional to the cube root of the NEWQD. The IBD for HD1.2 systems and for HD1.1 systems with a NEWQD below 45,000 pounds is determined by fragment throw distance. Neither detonation nor fragment throw are considered to be a threat for HD1.3 systems. The IBD is still proportional to the cube

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14. ABSTRACT
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root of weight, but with a much lower constant than that for HD1.1 systems. Although not considered a detonation threat, HD1.3 systems are considered mass deflagrating and rapid energy release is possible. This energy release can lead to a large fireball with an associated thermal radiation threat (Reference 1). In confined environments, the burning rate of the energetic material can increase substantially as the pressure increases. Pressurization can lead to rupture of the enclosure and long plume generation from the venting areas of the enclosure. There is also theory that predicts that for HD1.3 systems under sufficient enclosure a mass deflagration may transition to a mass explosion/detonation, posing a greater threat than for what the HD1.3 system IBD siting accounts (Reference 2).

Several studies have been performed to investigate the effect of confinement on the reaction of HD1.3 systems. Herrera and Vargas used 1/10th size igloos with various energetic material quantities and vent area sizes in their experiments (Reference 3). They measured plume length and velocity exiting the igloos. They also measured temperatures at various locations inside and outside of the igloo. They observed that much of the unburned energetic material was carried out of the igloo by the plume and burned outside the confined space. The vent plume velocity decreased and the energetic material burned inside the igloo as the quantity of burning propellant increased or as the vent area was decreased. They hypothesized that this occurred as the vent flow became choked and the pressure inside the igloo began to rise. They concluded that the choked conditions could lead to catastrophic failure even though none of their igloo's failed during tests. Allain also performed experiments with the combustion of HD1.3 material in igloos (Reference 4). His focus was on thermal flux measurements. For two of the tests, pressurization of the igloos occurred and the igloos ruptured. Large sections of the igloo were thrown over 15 m for the test with the most violent reaction. Joachim (Reference 2) also performed confined propellant combustion experiments with a various loading densities. Plume lengths from the vent were recorded along with pressure inside and outside the bunker along with thermal flux measured in the vent pipe. The structure failed after 6 seconds in the test with 250 kg of propellant. It failed due to over pressurization. Further studies to investigate the effect of the storage of HD1.3 material to its level of reaction violence can be found in the work of van Wees and Steyerer (Reference 5).

Swisdak and Montanaro recognized the possibility of HD1.3 materials pressurizing a storage structure (Reference 6). They acknowledged the possibility of secondary debris caused by the pressure rupture of the container. They used the computer code BLASTX to investigate the pressure rise inside a chamber from energetic material burning as part of their study. The volume of the chamber was kept constant and the amount of material and venting area were varied. They reported their results in arbitrary units as the parameters selected for their problem did not represent any real situation of propellants. They concluded that the appropriate vent area is related to both the volume of the chamber and the weight of the energetic material involved. They also concluded that if their studies had represented a real-life situation the chamber would probably have failed catastrophically.

A mishap that underscores the importance of understanding the potential for enclosure pressurization due to HD1.3 material reaction is the 2004 Milan Army Ammunition Plant earth-covered magazine (ECM) explosion (Reference 7). In this event, 22,000 pounds (10,206 kg) of energetic materials threw large fragments over 2700 ft (823 m), which is more than twice the IBD for this amount of HD1.1 material. Although the total material load out was rated HD1.1, there were several thousand pounds of HD1.3 material in the magazine. The spillage of the HD1.3 material and its ignition started the energetic event. HD1.3 material typically burns and ignites easier than HD1.1 materials. Also, according to an interview with one of the investigators, witnesses reported two blasts in fairly rapid succession. The size of the crater indicated a detonation had occurred. However, there is no evidence that does not preclude the first audible blast sound as a result of rupture of the magazine through over-pressurization. The combination of a pressure burst followed by a detonation may have lead to the greater than expected throw distances with large fragments that were characteristic of a deflagration.

The object of the present study is to further study the pressurization of storage chambers through inadvertent ignition of energetic materials inside the chamber. A three-dimensional model of a presently used ECM (RC Freloc Stradley, 33-15-74 (Reference 8) was constructed to strive to achieve real-world application. This ECM has a pressure designation of 7 bar (102 psi) and a maximum allowable NEW of 500,000 pounds (226,796 kg). There is a sliding door in the front of the ECM that was not included in the model because it will be blown out with as little internal overpressure of 0.034 bar (0.5 psi). The model was constructed in the computational fluid dynamics (CFD) software FLUENT. It is possible to more accurately capture the plume development through the venting area by constructing the model in a high fidelity fluid dynamics solver.

The propellant burning rate was coupled with the magazine pressure in order to accurately model the pressurization of the ECM. The solid energetic material surface was also allowed to regress as it burned, providing additional volume for the gases in the ECM as would happen in an actual event. The walls were assumed rigid and the predicted pressure gave maximum possible values in the present study. Future work will be done to couple the pressure impulses predicted on the walls with structural dynamic simulations to determine the response of the ECM. It is also recognized that experiments have shown that for un-choked flow much of the propellant can be expelled from the magazine during the energetic event and burn outside of the magazine, this conclusion is not currently included in the model. The focus of this study is to examine when the magazine venting area chokes. Tests show that expulsion of the propellant from the magazine is not prevalent at these conditions. A detonation of a smaller amount of the same propellant was modeled inside of the magazine as a basis of comparison. A three-dimensional model of the ECM was constructed with the computer code SHAMRC to examine the detonation case. SHAMRC is a hydrocode developed by Applied Research Associates, Inc. which uses a second order-accurate finite differencing method, and is an industry standard blast calculation code. The walls were also treated as rigid as the pressures on the walls were recorded during the simulation for comparison with the FLUENT results. This is a first step in the use of high fidelity modeling to understand and predict what will happen with the pressurization of magazines through rapid burning of energetic materials and thus provide safer recommendations for IBDs.

MODEL DEVELOPMENT

PROBLEM ANALYSIS

An analysis of the full physics of confined HD1.3 reaction encompasses the chemistry of energetic reaction, the fluid dynamics of the mass release through energetic reaction and venting from the structure, and the material mechanics of magazine damage caused by pressurization. Solving for all three fully-coupled physics problems requires a prohibitive amount of computational resources. Alternatively, simplifications were made to the problem analysis to improve tractability.

A material's pressure-dependent reaction rate is defined as the combination of its linear burn rate, reacting surface area, and material density. The linear geometric burn rate is dependent only on fluid pressure adjacent to the reaction surface, taking the form of a power equation (e.g. $r = bP^n$, where r is the burn rate in m/s, b and n are material-specific constants and p is the pressure in Pascal). The linear reaction rate equation implicitly accounts for the chemistry of reaction, de-coupling chemistry from the required equation set.

Pressure in the magazine depends on two factors: gas addition from the burning HD1.3 material and gas that exists from any vents or holes in the magazine, either intentionally placed or created through damage. Accurate fragmentation and throw distances require both fluid and structural problems to be calculated. However, this coupling is not required through the entire simulation time. Until initial damage occurs, assumed to be a breach caused by pressurization to around seven bar, only the fluid problem needs to be solved for. Pressure history data from the fluid simulation can be applied to a structural simulation to find the point of initial damage.

The fluid mechanics model was treated as a control volume problem of the magazine and surrounding air, driven by four factors: the magazine volume, the volume of solid energetic material, gas addition to the magazine through energetic reaction, and fluid mass lost from the magazine through flow out of vent areas. The magazine volume and vent area are constant under the prior-to-breach assumption, and only the reaction products mass and solid energetic material volume were allowed to vary.

Model Capabilities and Assumptions:

The CFD software FLUENT was chosen as the framework for the confined reaction model (CRM) due to its high quality of results, accessibility, and familiarity. FLUENT is an industry-standard CFD program that solves the Navier-Stokes equations, including turbulence effects. The CRM is an extension of FLUENT's transient-domain solver. The pressure dependence of energetic volume reduction and reaction products mass addition is controlled through a FLUENT scripting feature called User Defined Functions (UDF).

As with any numerical simulation, the appropriate assignment of boundary conditions is vital to the calculation of accurate results. The addition of fluid mass is accomplished through a mass-inflow boundary condition on the top mesh face of the energetic volume. Added mass is given the properties of the reaction products and enters the computational mesh at the equilibrium temperature of the energetic material products.

Mesh boundaries outside the magazine geometry are assigned a pressure-outlet boundary condition, while all other mesh boundaries are assigned a wall boundary condition. The loss of solid energetic material volume is simulated through FLUENT's sliding dynamic mesh feature. The Spalart-Allmaras turbulence model was used because of its quick calculation speed.

Model Features:

- Both 2D and 3D
- Couples propellant surface pressure to linear (therefore also mass) burn rate
- Accounts for reduction of propellant volume as the energetic material burns
- Multiple, independent energetic volumes

Model Restrictions/Assumptions:

- Ignores heat transfer of magazine walls
- Ignores chemistry in the flow field
- Ignores effects of magazine damage
- Single burning surface on each energetic volume
- Burning surface is averaged
- Simplistic assumption of a time-constant reaction surface (surface area)

Actions taken during the initialization phase:

1. Problem-specific properties are assigned to each energetic volume

Actions taken for each energetic volume during the simulation:

1. Check if the energetic volume is burning, if true continue
2. Read the pressure from the burning surface belonging to the energetic volume
3. Calculate the instantaneous burn rate of the energetic volume, convert to mass burn rate
4. Iterate steps 3 and 4 until the end of the time-step is reached
5. Calculate the mass released during the current time-step
6. Add the current mass release value to the total mass of energetic burned, check if the added value burns out the energetic volume
7. Move the mesh cells representing the energetic volume according to the current mass release value

MODEL VALIDATION

VALIDATION CASE

The CRM was validated using a test case described in the report authored by van Wees and Steyerer (Reference 5) that shares similarities to the current study. A hollow metal cylinder (essentially a "pipe bomb") represented the enclosed "magazine" volume, with one end closed by a metal cap while the other end cap had a circular vent hole (representing the blown-out door). The 100 grams of gun propellant was placed inside the cylinder at the closed end and ignited. Test data took the form of a pressure history interior surface of the cylinder, measured using pressure ports along the cylinder wall and the vented end cap.

The test case was duplicated by creating a computational mesh of the cylinder and outside air. Cylindrical symmetry was utilized to reduce the simulation to two dimensions. The gun propellant was assumed to occupy an idealized cylindrical volume spanning the entire radius of the cylinder, allowing the dynamic mesh to be a circular surface that slid outward axially, like the piston in a reciprocating engine. The propellant weight was distributed among hundreds of millimeter-scale perforated grains in the experiment. Due to the unpredictable nature of the orientations of the grains inside the test pipe the burn propagation, and therefore reaction surface area, could not be predicted. The assumption of a single, idealized propellant volume meant the burn propagation could not be calculated. Since propagation could not be predicted nor calculated, the reaction surface area was assumed to be constant, with a value equal to the total exposed surface area (including perforations) of all the grains before any reaction occurs. The computational mesh is shown in Figure 1.

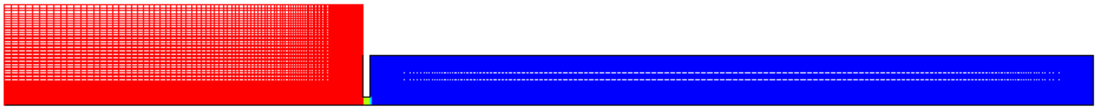

FIGURE 1. Validation Case Mesh, Zone Colored.

Figure 1 shows the computational mesh, with colors added for ease of reference. The blue region is the space inside the cylinder, the red section is the outside space, and the green is the space inside the end cap vent. Black outlines around the mesh are wall boundaries, while the bottom of the mesh is the axi-symmetric boundary. All other boundaries are assigned the pressure-outlet boundary condition. Figure 2 is the same mesh image as Figure 1 but zoomed in around the vent area.

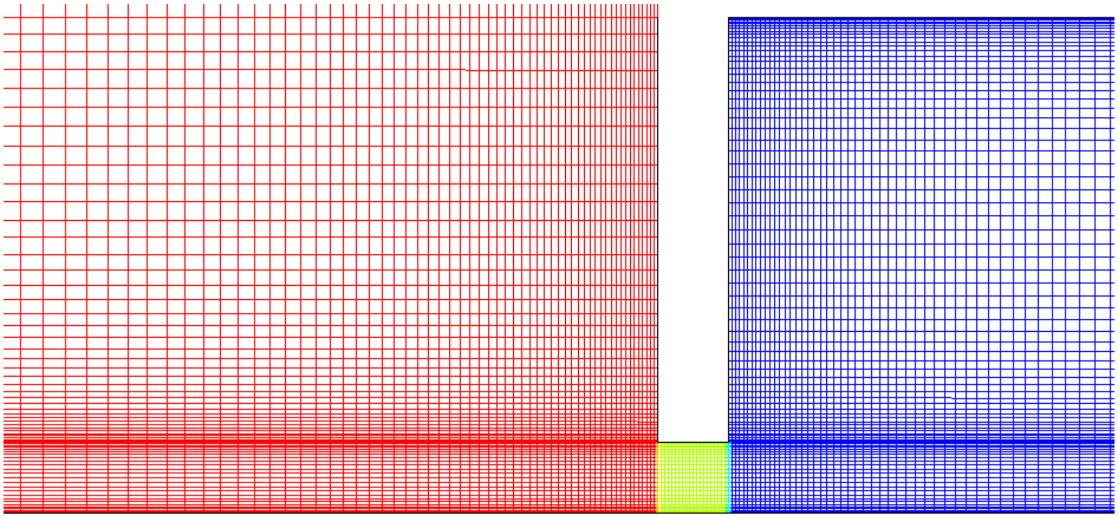

FIGURE 2. Detail View of Validation Case Mesh, Zone Colored.

Figure 2 illustrates the scale of the vent area and also shows better mesh detail. The mesh can be seen to get finer as walls are approached, allowing for more accurate calculation of fluid flow near mesh boundaries.

Figure 3 reveals the CRM's predicted magazine time-pressure history compared to the pressures measured in the experiment.

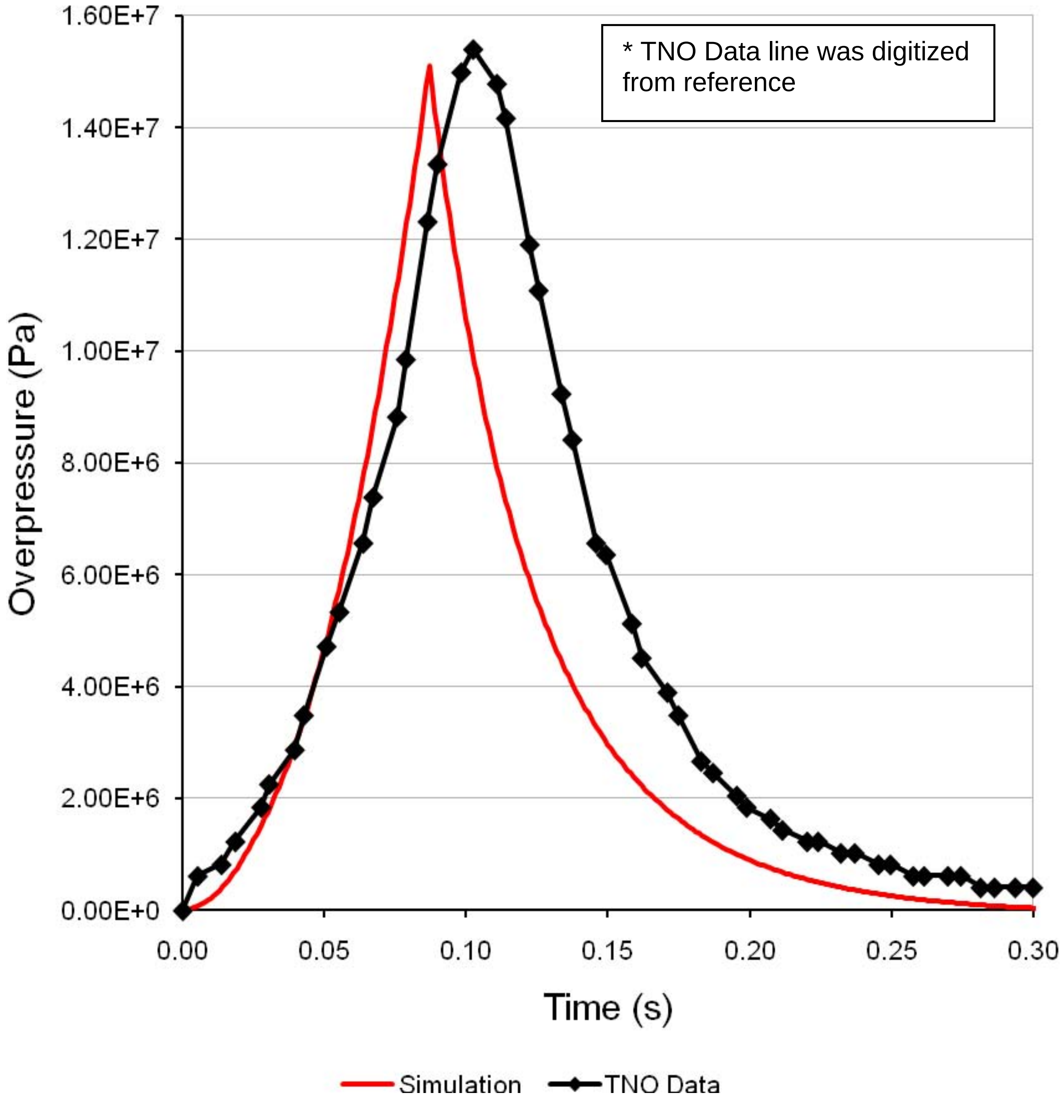

FIGURE 3. Simulated Magazine Pressure Compared to Experiment for Validation Case.

It can be seen in Figure 3 that the calculated pressure history closely follows the shape of the experimental pressures both during pressurization and de-pressurization after the propellant burned out. There is a difference of 2 percent between maximum pressures; such an accuracy is excellent considered the assumptions and limitations present in the CRM. The CRM simulates a faster pressure rise than seen in the experiment, but this is consistent with the assumption of a constant maximum reaction surface area. The reaction surface area would realistically begin near zero, increase to a maximum value and then gradually decrease as the propellant nears burn-out. The CRM is shown to accurately model the test case quantitatively, successfully validating the model and its assumptions.

SENSITIVITY STUDIES

A series of sensitivity studies was performed to analyze how sensitive the simulation is to a given variable to establish the range of suitable input values and the necessary precision of assumed values. The CRM was studied for its sensitivity to the following input variables: mesh grid density, reaction surface area, temperature of released mass, and turbulence model.

After the initial simulation of the validation case several more tests were conducted in which the temperature and surface area were varied to study how much the calculated pressures would change from the data in Figure 3. The initial simulation was considered to have nominal (100 percent) surface area. Simulations were conducted at 50 and 200 percent of the nominal surface area. Simulations were also conducted at reduced reaction product temperatures of 2,924 and 2,417K. Simulations above the initial 3,335K temperature were not conducted because the mass release was too rapid, causing FLUENT to crash. Surface area and temperature variations were combined, for a total of nine studies being included in the sensitivity study. The resultant pressure histories can be seen in Figure 4.

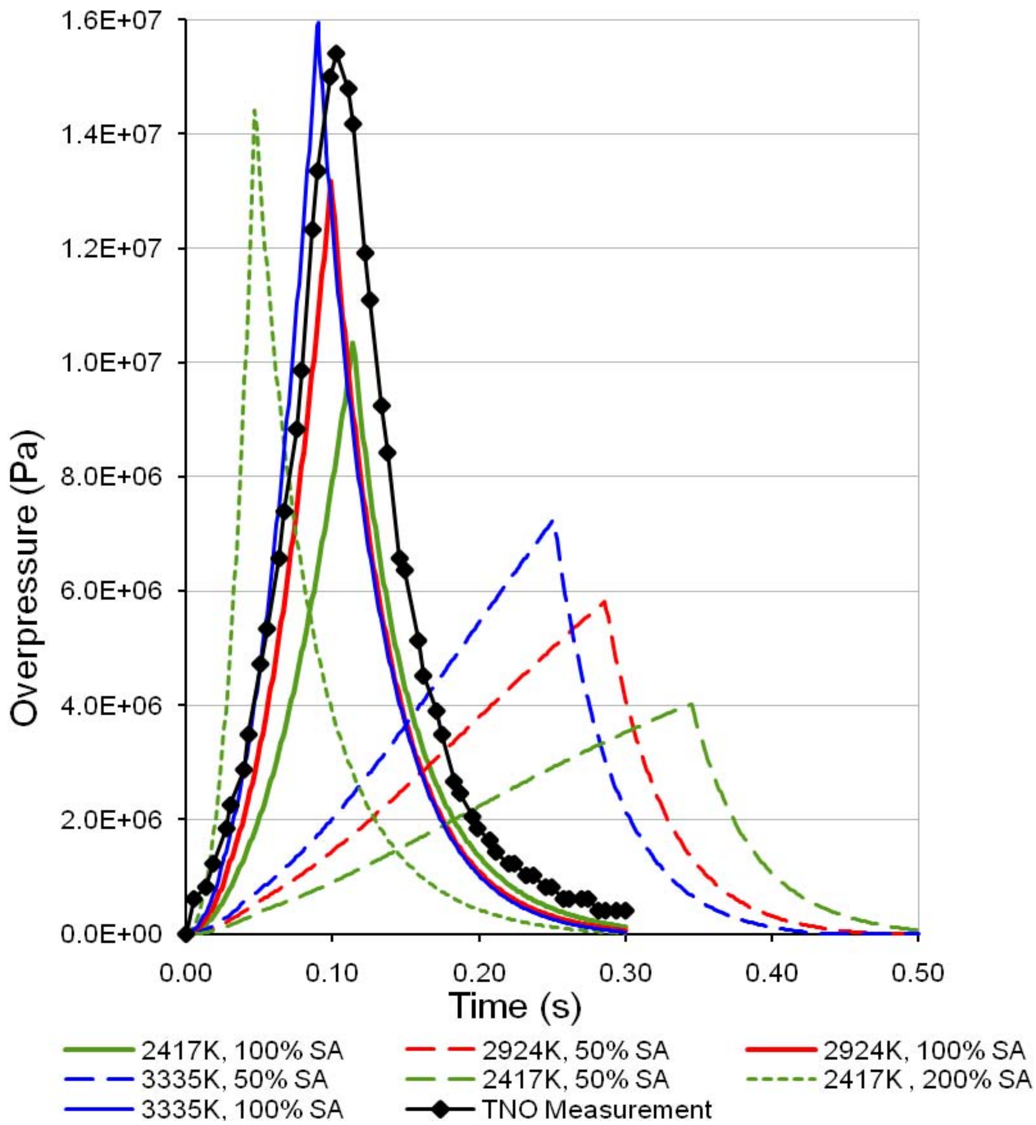

FIGURE 4. Surface Area and Temperature Sensitivities.

As seen in Figure 4, both reaction surface area and reaction products temperature increase the maximum overpressure and reaction rate (indicated by both the time of maximum overpressure and the slope of the pressurization curve). Reaction surface area appears to be the more critical variable, although the CRM shows enough sensitivity to both factors that care needs to be taken in the proper assignment of both inputs to assure accurate results. The simulations at 2924K, 200 percent surface area and 3,335K, 200 percent surface area are not included in the graph because both simulations crashed before the entire 100g of propellant had reacted and when the simulations had crashed the overpressure values were near the detonation pressure for 100g of M10 and thus not representative in deflagration studies.

MODEL APPLICATION

Knowledge needed to apply the CRM to ordnance magazines, such as magazine models and designs, and how items are commonly stored in magazines, was obtained through a literature search including sources such as standard operating procedures, inventory statistics, other technical documents, and general practices of magazine personnel (Reference 9). When information from these sources is combined it creates a general picture of how ordnance is currently stored in magazines allowing knowledge important to the simulation effort to be extracted, such as general configurations of items inside the magazine, common ratios of HD1.1 to HD1.3 materials present in mixed storage conditions, and common ratios of inert volume to energetic volume (e.g., the packaging around ordnance items and the inert portions of hazardous items such as missiles). Another valuable fact is that the doors of ordnance magazines are designed to pop off their hinges at a low overpressure (< 1.0 psi) to act as a vent during a mishap. Additionally, some magazines that store HD1.3 material have an IBD great enough that the magazine cannot physically hold its maximum NEWQD of HD1.3 material as sited in DoD 6055.09-STD.

The RC Freloc Stradley 33-15-74 ECM was chosen to be modeled as a representative 7-bar ECM design after recommendation by the Naval Facilities Engineering Service Center (NAVFAC ESC). A study of energetic materials stored in the US inventory (Reference 10) was conducted, with findings that indicate M10 gun propellant to be a common HD1.3 substance currently stored in magazines. Lacking detailed storage information, the M10 is modeled as a single box-shaped volume inside the magazine. The volume of M10 was modeled to sit on another box-shaped volume of inert material with the same horizontal cross-section. A review of several ordnance containers yielded an estimation of the inert volume as an additional one-third of the M10 volume, an admittedly rough estimate that will be made more accurate with more detailed modeling of item geometry. The reacting surface was assumed to be the top surface of the M10 volume, so the volume burns downward one-dimensionally. Several reaction surface areas were simulated, in multiples of the reacting surface's area, since an accurate reacting surface area was not known. Multiple magazine loading densities were simulated with the purposes of gaining understanding of confinement effects at a range of load densities as well as finding the minimum loading density of confinement (when pressurization occurs). The selected M10 weights were 1.0E5, 2.5E5, 5.0E5, and approximately 1.0E6pounds (4.53E4 kg, 1.13E5 kg, 2.27E5 kg, and 4.65E5 kg). These weights correspond to loading densities for the RC Freloc Stradley 33-15-74 of 3.5 lb/ft^3, 8.7 lb/ft^3, 17.5 lb/ft^3, and 35.8 lb/ft^3 (56.1 kg/m^3, 139 kg/m^3, 280 kg/m^3, and 573 kg/m^3).

Figure 5 displays the initial geometry of the FLUENT model for each of the loading density configurations.

The mesh boundary is shown in Figure 5 as gray surfaces (both magazine walls and outside pressure outlets). The open ECM doorway is outlined in blue. The yellow block is the volume of propellant and inert material, with the top surface colored red to distinguish it as the burning surface. The computational grid for all four loading density configurations is displayed in Figure 6.

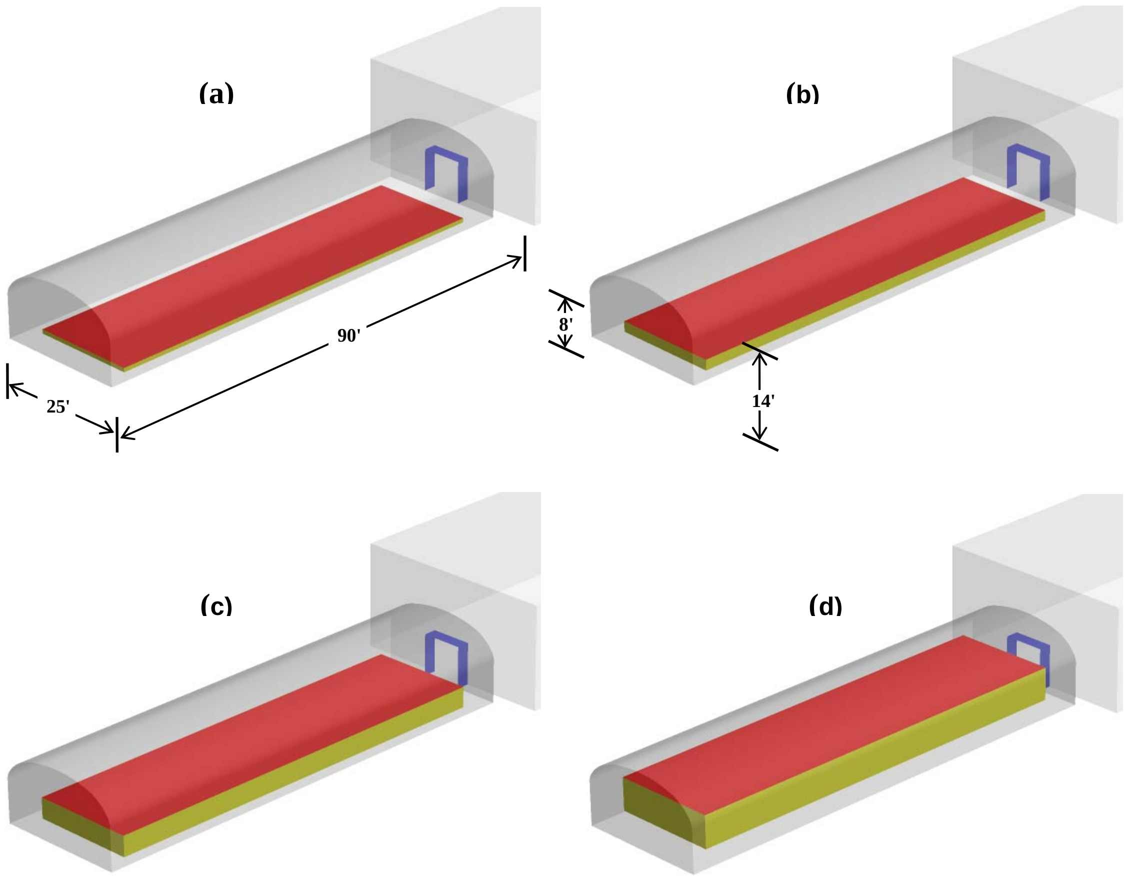

FIGURE 5. 3D Computational Magazine Geometry With Four Weights: (a) 1.0E5 lb (4.53E4 kg), (b) 2.5E5 lb (1.13E5 kg), (c) 5.0E5 lb (2.27E5 kg), (d) 1.024E6 lb (4.65E5 kg).

The top two images in Figure 6 illustrate the outer grid, the right image being a focus on the magazine. Sub-plots (a) through (d) present the surface grids of the solid volume of propellant and inert materials.

Pressure versus time results of the CRM simulations are illustrated in Figures 7 through 9. Each figure shows four of the twelve total configurations. Note that the configurations were not all run to the same simulation time; in the effort to conserve computer resources, some simulations were terminated once the behavior of the pressure history curve was evident. Maximum values of the pressure curves will be compared to 7 bar for two reasons. First, the ECM is rated as a seven bar external pressure designation. While external impulse strength is acknowledged as not being equivalent to internal pressurization strength, it establishes the order-of-magnitude range of the interior pressure limit. Secondly, Joachim and Allain both judged (Joachim through measurement and Allain through calculation) that the test articles in their studies burst at 10 bar (145 psi). An important feature of the data is each simulation's pressurization rate (slope of the curve) during pressure increase. The pressurization rate is a tool that helps further reason the behavior of the simulated event. The pressurization rate is proportional to the M10 mass burn rate due to the simulation assumptions of constant density and burn area. It is important to note, however, that in these results the maximum pressure does not correspond to the point of propellant burn-out, as was seen in the validation study. Figure 7 displays the averaged pressure history over all ECM surfaces (front, back, side, top) for each of the four propellant weights simulated, at 100 percent of the nominal reaction surface area.

None of the four loading configurations in Figure 7 reach a pressure of seven bar. Behavior of the pressure history curves is consistent with expectations. Figure 8 exhibits the averaged ECM pressures for all four loading densities with an assumed 200 percent of the nominal reaction surface area.

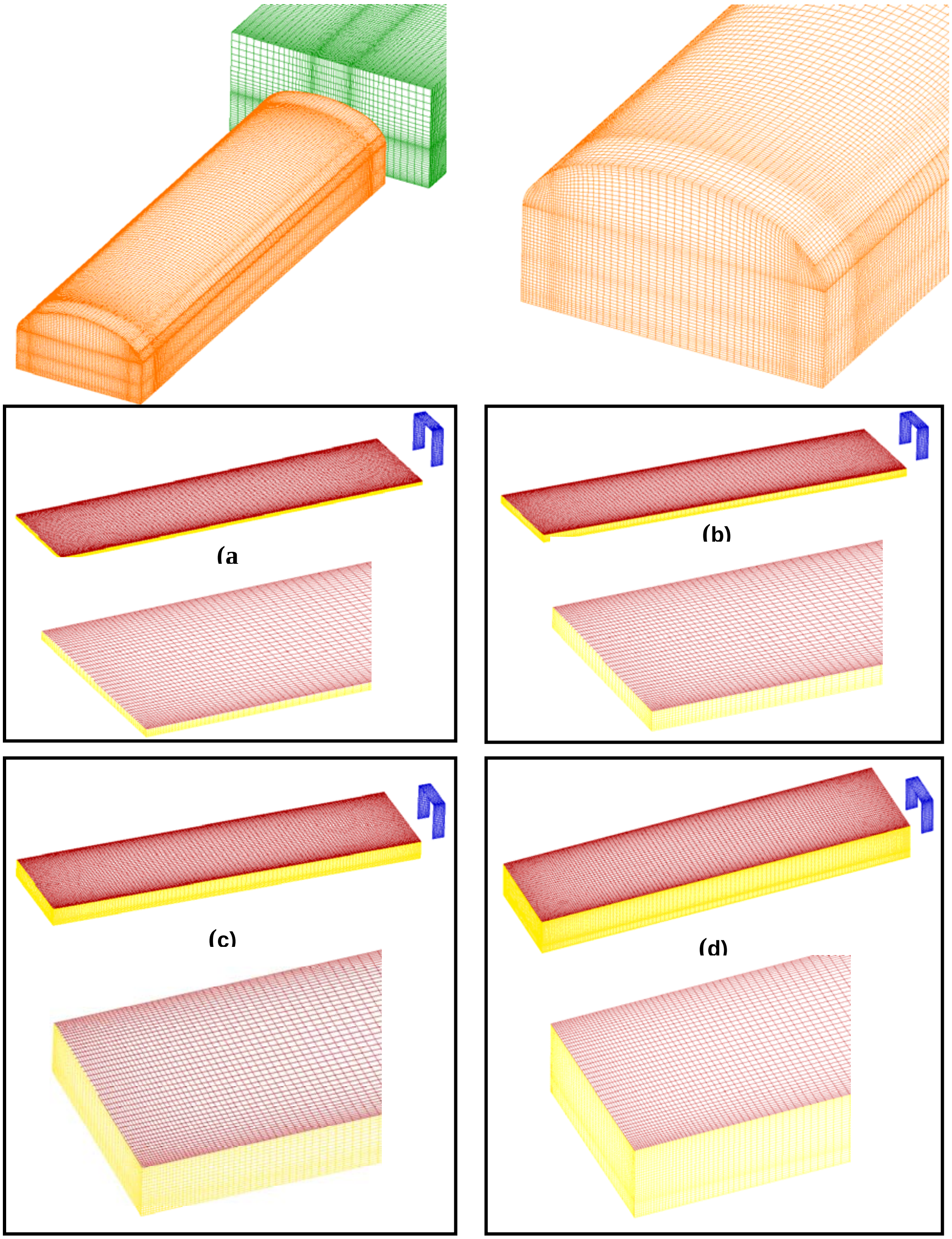

FIGURE 6. 3D Computational Surface Grid with Four Weights: (a) 1.0E5 lb (4.53E4 kg), (b) 2.5E5 lb (1.13E5 kg), (c) 5.0E5 lb (2.27E5 kg), (d) 1.024E6 lb (4.65E5 kg).

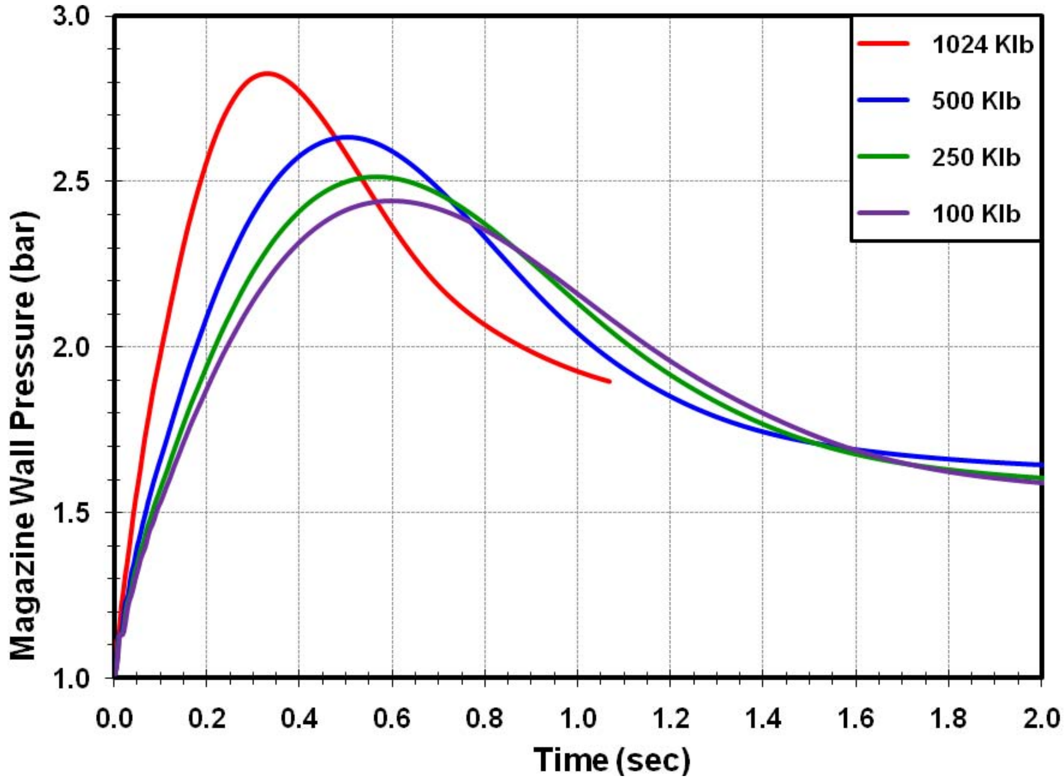

FIGURE 7. Averaged ECM Surface Pressures for Multiple Loading Densities With Nominal Burn Surface Area.

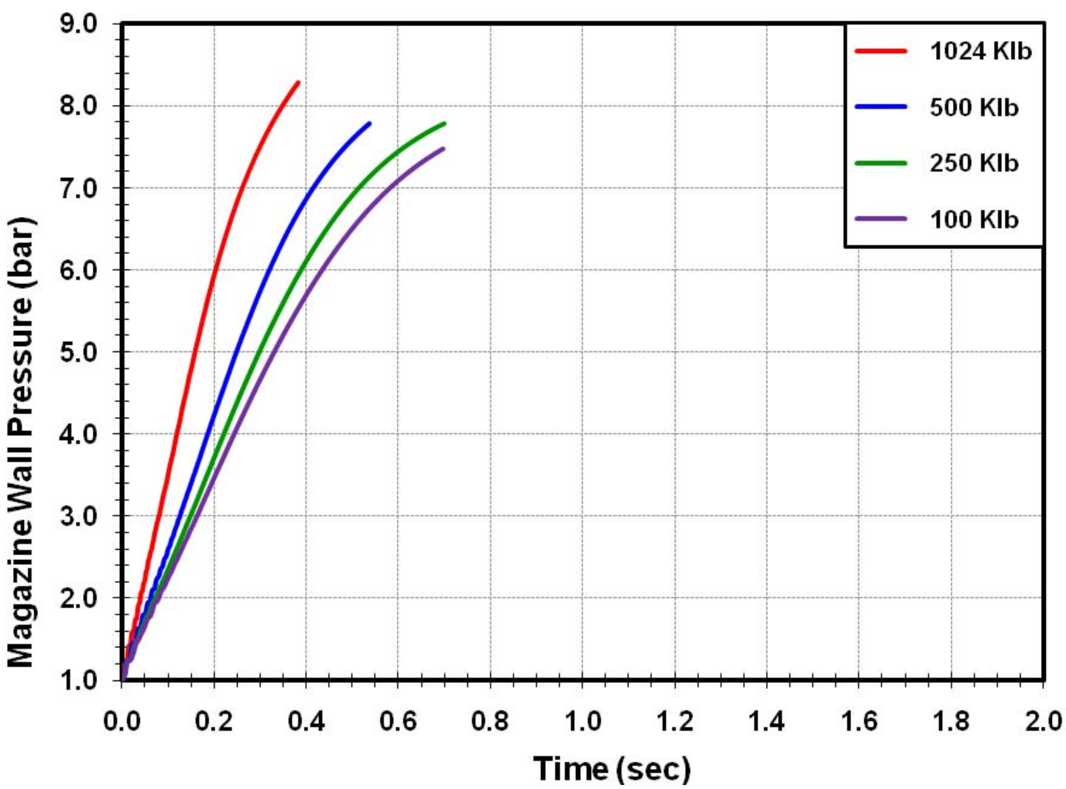

FIGURE 8. Averaged ECM Surface Pressures for Multiple Loading Densities With 200 Percent Nominal Burn Surface Area.

Figure 9 clearly displays the dependence of pressurization to reaction surface area. While none of the configurations at nominal reaction surface area reached seven bar pressurization, all configurations at 200 percent nominal reaction surface area reach the seven bar in less than a second.

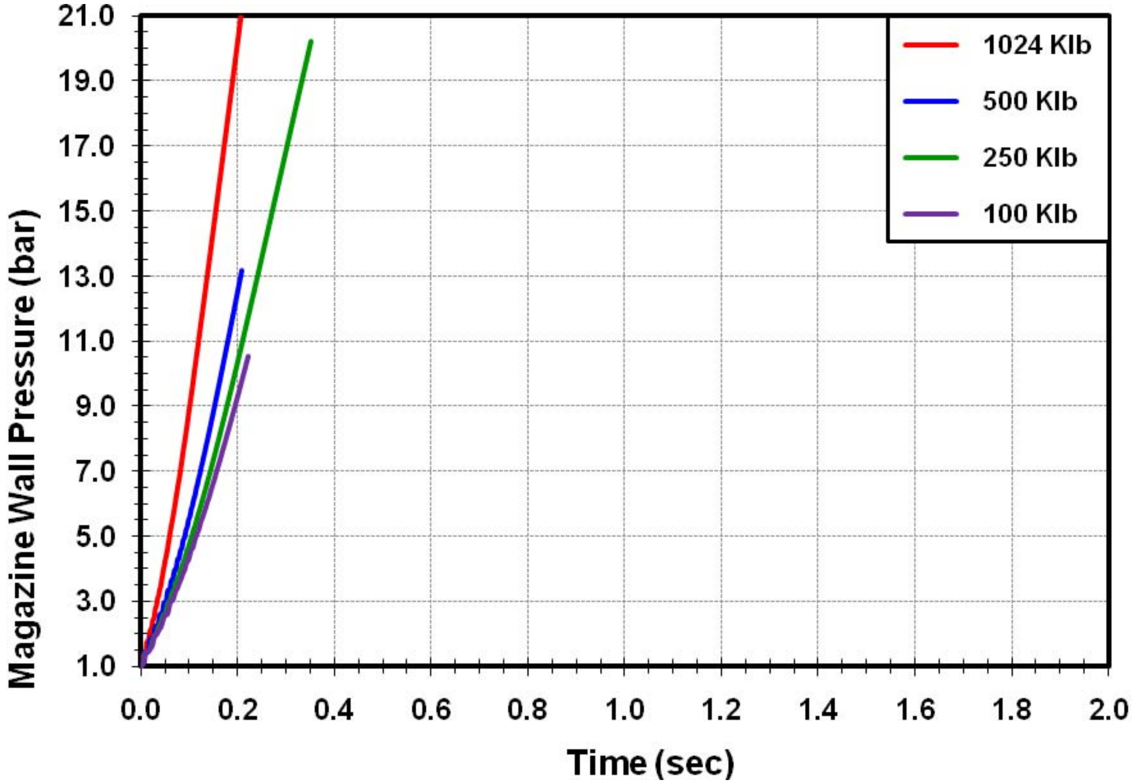

FIGURE 9. Averaged ECM Surface Pressures for Multiple Loading Densities With 400 Percent Nominal Burn Surface Area.

A further increase in pressurization rate is evident in Figure 9. All loading densities pressurize the ECM above seven bar in less than two-tenths of a second. By visual extrapolation it can be seen for all loading densities that breach and fragmentation of the ECM walls before M10 burnout occurs is almost assured.

The flow field inside the ECM is plotted for each loading density configuration with nominal reaction surface area in Figure 10, along planes inside the magazine as well as the vent cross-section. Mach number determines whether flow outside the magazine is choked, with sub-sonic flow being un-choked.

Figure 10 has the expected results. Flow at the closed end of the ECM has a low velocity that gradually increases towards the vented front of the ECM, where gas can escape. The Mach contours at the vent surface reveal that all of the loading density configurations approach Mach one, none of them creates a supersonic flow across the entire vent area and thus, all experience only partially choked flow. Figures 11 and 12 visualize the flow fields of all four loading densities at 200 percent and 400 percent nominal reaction surface areas, respectively, with the same characteristics as the flow fields in Figure 10. The two exceptions are the 500,000 and 1.0 million pound cases with 400 percent nominal reaction surface area, which exhibit fully choked flow.

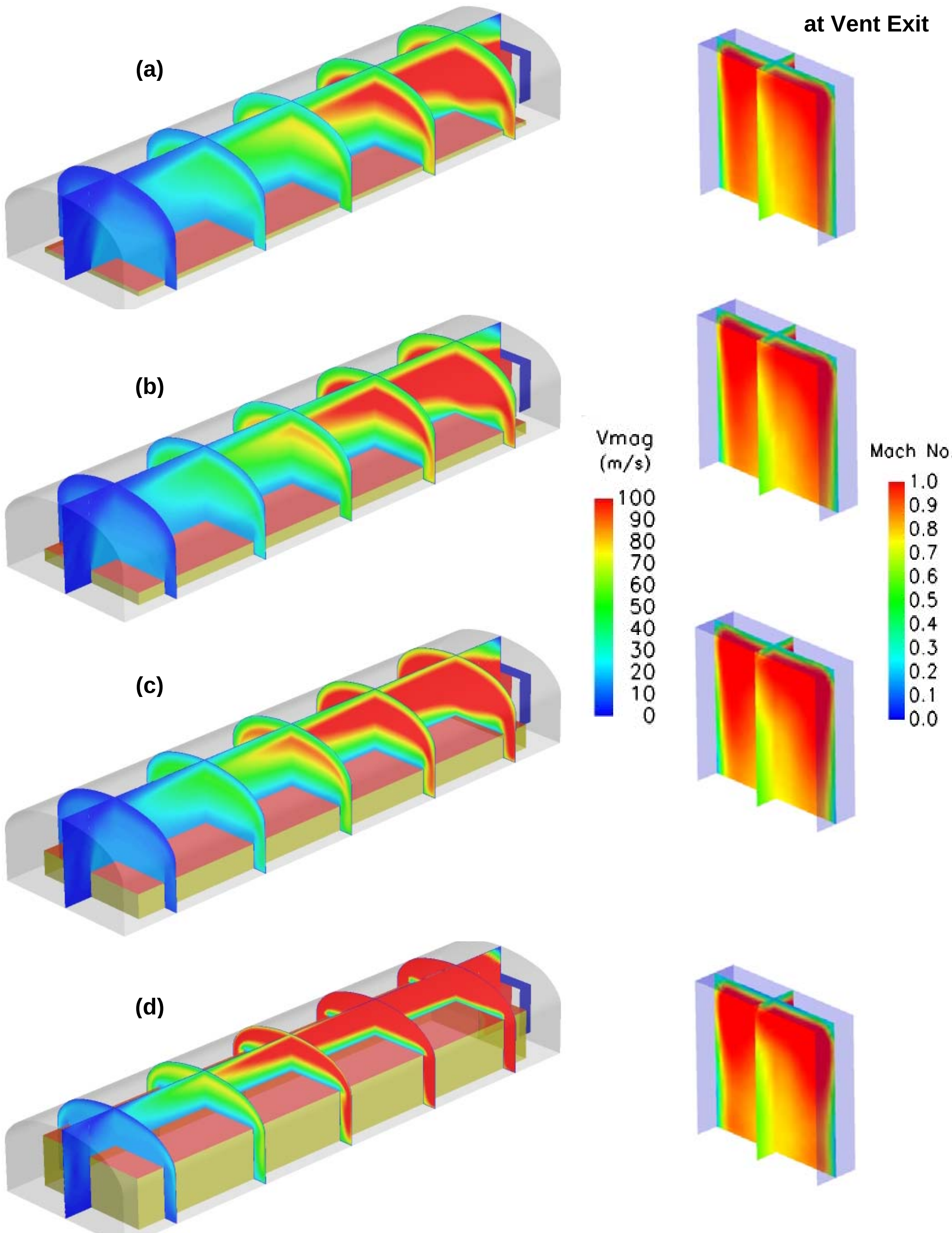

FIGURE 10. Velocity Magnitude and Mach Number Contours at Propellant Burn-out With Nominal Burning Surface Area for Four Weights: (a) 1.0E5 lb (4.53E4 kg), (b) 2.5E5 lb (1.13E5 kg), (c) 5.0E5 lb (2.27E5 kg), (d) 1.024E6 lb (4.65E5 kg).

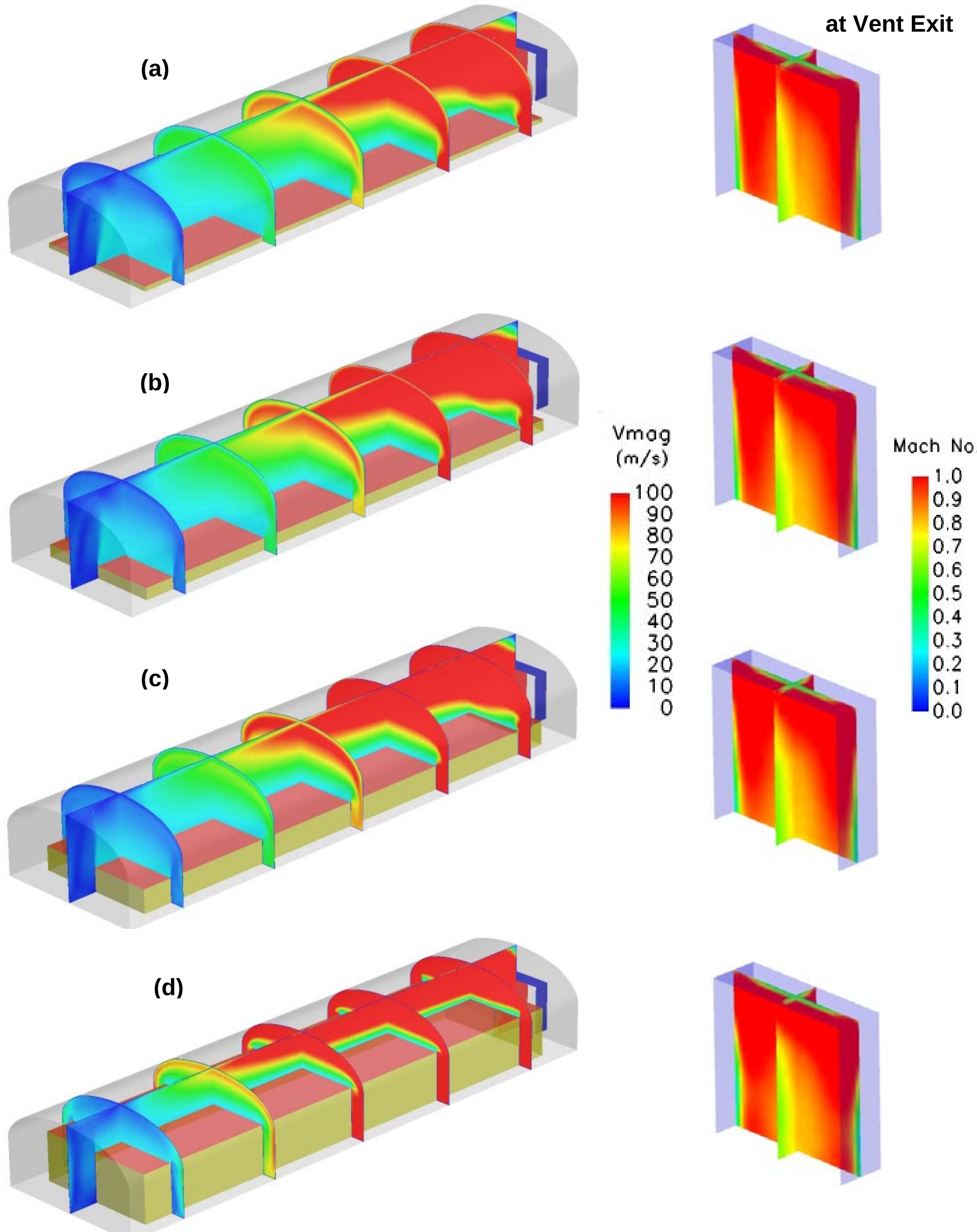

FIGURE 11. Velocity Magnitude and Mach Number Contours With 200 Percent Nominal Burning Surface Area for Four Weights: (a) 1.0E5 lb (4.53E4 kg), (b) 2.5E5 lb (1.13E5 kg), (c) 5.0E5 lb (2.27E5 kg), (d) 1.024E6 lb (4.65E5 kg).

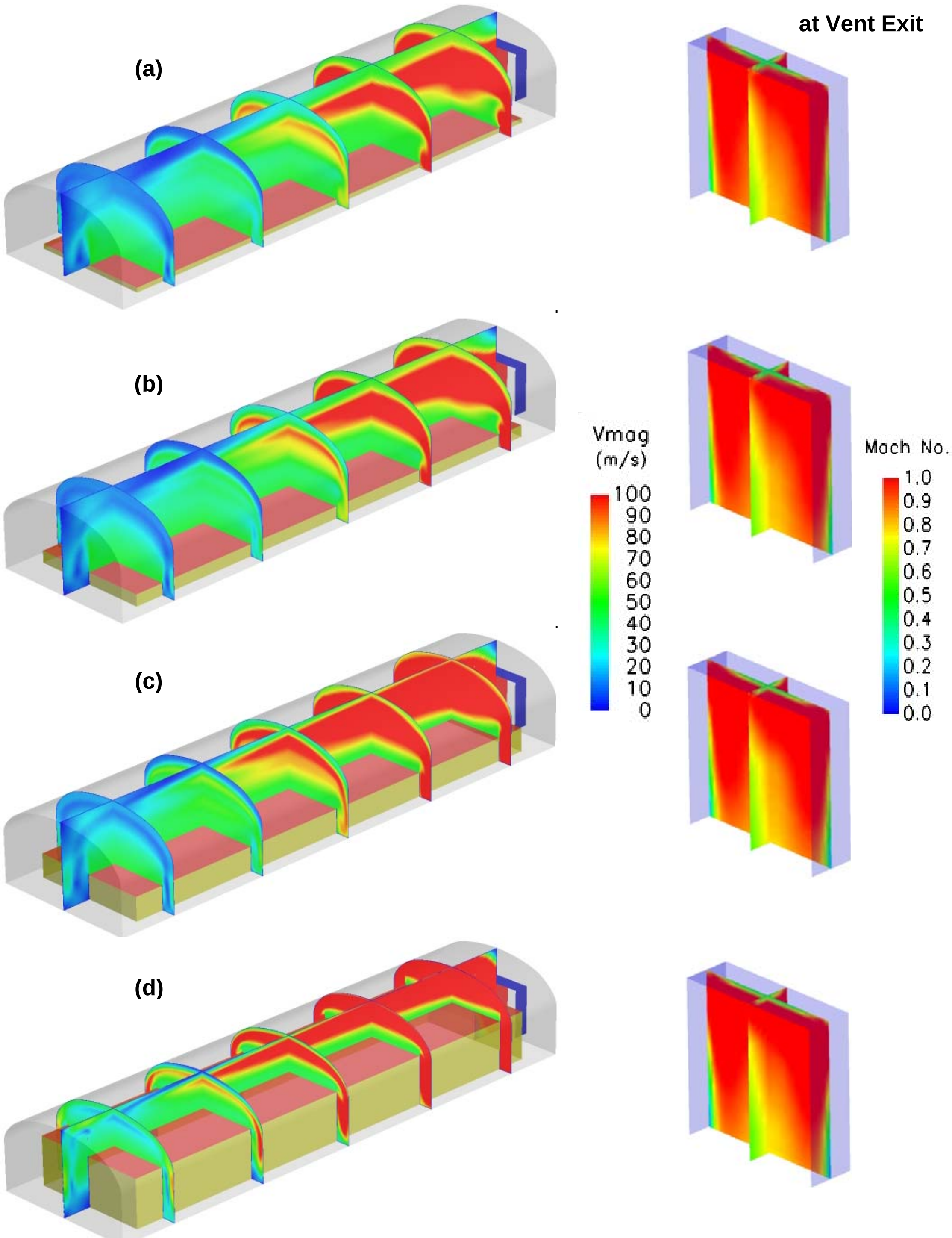

FIGURE 12. Velocity Magnitude and Mach No. Contours With 400 Percent Nominal Burning Surface Area for Four Weights: (a) 1.0E5 lb (4.53E4 kg), (b) 2.5E5 lb (1.13E5 kg), (c) 5.0E5 lb (2.27E5 kg), (d) 1.024E6 lb (4.65E5 kg).

It is desirable to compare the structural damage potential of a confined HD1.3 burn to an HD1.1 detonation. According to explosive safety standard 6055.09 (Reference 11), the IBD for 1.0 million pounds of HD1.3 material is 800 feet (244 meters). The IBD for HD1.1 material between 500 pounds and 45,000 pounds is 1,250 feet (381 meters). The constant-volume detonation properties of M10 were calculated using the computer code Propellant Evaluation Program (PEP). The ECM and M10 were modeled in the hydro-code SHAMRC. Three weights of M10 were simulated: 500, 2.25E4, and 4.5E4 pounds (227, 1.02E4, and 2.04E4 kg) to cover the range of weights that apply to an IBD of 1,250 feet. Each simulation was run to a simulation time of 0.1 seconds. Overpressure at points along the ECM wall surfaces were recorded during each simulation. Overpressure values were then averaged for each surface to obtain impulse plots comparable to the CRM data. Comparing the pressure histories of burning M10 and detonating M10 allows for analysis of damage potential between the two scenarios.

The ECM and M10 were modeled in SHAMRC, and due to its restrictions the geometries were not exactly the same as the FLUENT models, but were close and should not produce any significant error in results. A visualization of the SHAMRC model is shown in Figure 13.

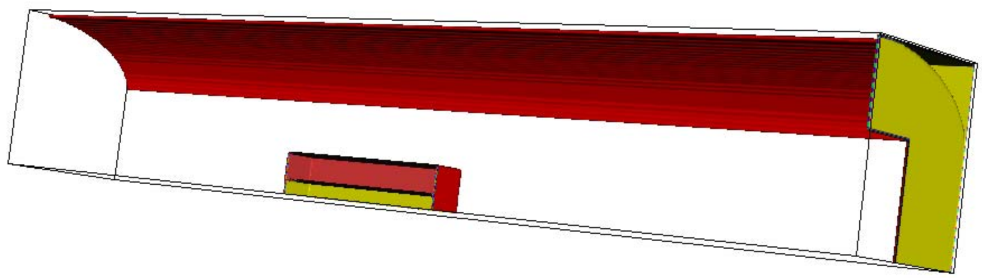

FIGURE 13. Visualization of SHAMRC Grid for 500 pounds M10 Before Detonation.

The rectangular colored regions are the propellant (red) and inert material (yellow). There is no significance to the color of the walls; they are an artifact of the simulation output. The open door vent can be seen in the front wall, and the curved top of the magazine can be seen. Mentally projecting the image into three dimensions, the plane closest to the reader is the symmetry plane, and all other magazine walls (rear, right side, and floor) are solid but hidden for easier viewing of the significant model features. The three-dimensional computational grid was composed of 7.12 million rectangular cells, roughly 4 cm long in each direction. The simulation was only run to 0.1 seconds of simulation time, due to constraints on computer resources. The pressure curves in Figure 14 compare the pressure history of 500 pounds of detonating M10 to 100,000 pounds of burning M10.

As expected, the detonation produces much higher pressures than pressure-dependent burn. These pressures are short-lived however, due to their manifestation as shock waves. Reflections of the shock waves are seen around 0.05 and 0.09 seconds, but with greatly diminished effect. The last simulated pressure of approximately 3 bar was extrapolated in order to perform a comparison of impulse (area under the pressure history curves). The detonation simulation at 0.7 seconds has an impulse of 1.6 bar*seconds. The impulse of the CRM simulation at 0.7 seconds is 2.7 bar*seconds, higher than the detonation. The total impulse of the CRM simulation will continue to rise, resulting in a much higher total impulse than for the detonation case. While the pressure history and associated impulse values are not alone able to predict damage, the impulse values indicate that the IBD value for HD1.1 may be more applicable to gun propellant than HD1.3 when a mass fire with large weights of propellant are present. High-fidelity structural simulations need to be performed to determine which IBD value is truly more appropriate.

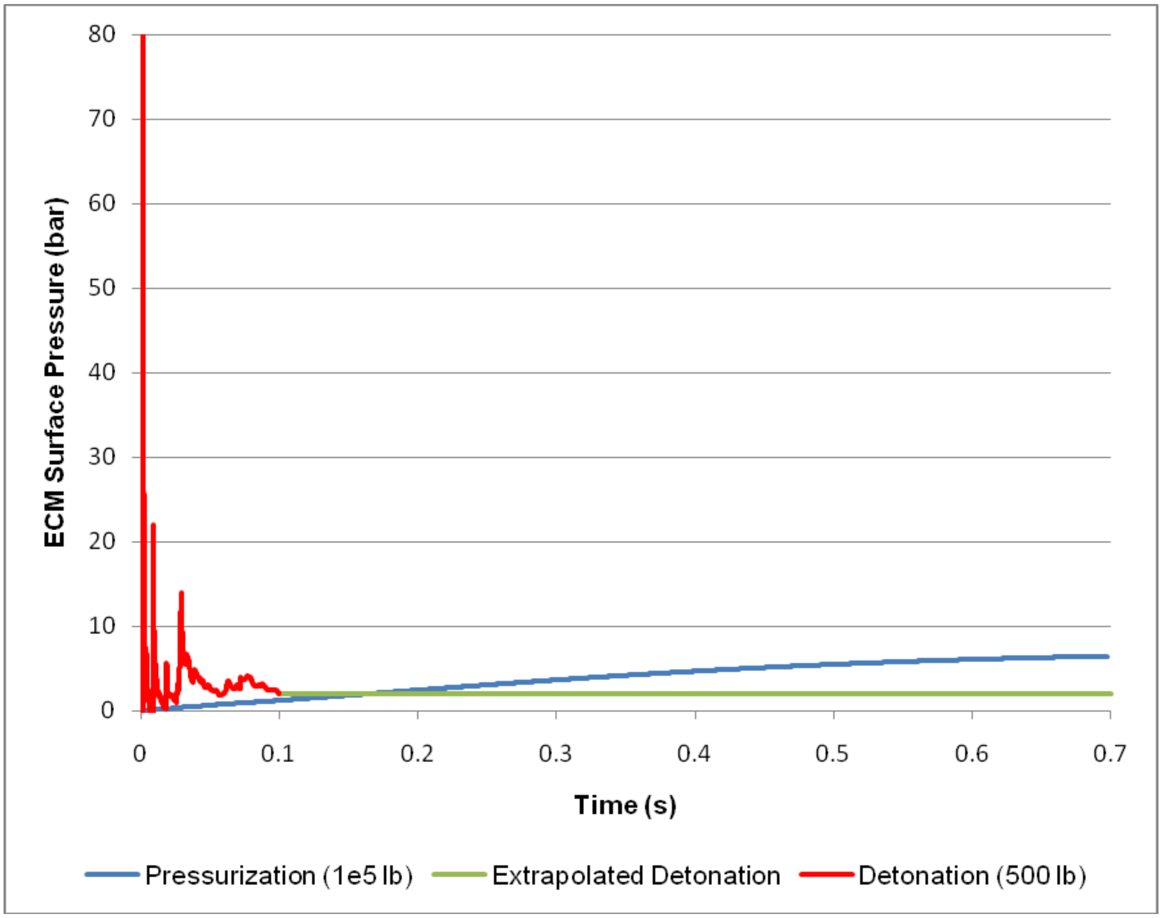

FIGURE 14. Compared Pressure Histories of 500 Pounds of Detonated M10 and 100,000 Pounds of Burned M10 (200 Percent Nominal Area).

CONCLUSIONS

The CRM was used to study damage effects of a mass fire of HD1.3 material inside a storage structure. It simulated the pressure rise inside a magazine due to the confined reaction of HD1.3 material. The CRM was applied to twelve storage configurations inside a model of the RC Freloc Stradley 33-15-74 ECM: four weights of M10 gun propellant and three burn surface areas. Results predict that for weights above 100,000 pounds internal magazine pressurization depends on the reaction surface area. Predicted pressurization is high enough to indicate a likely rupture of the magazine, depending on the reaction surface area. These results derive the need for further study as well as a recommendation in actual storage conditions to not store large weights of HD1.3 material next to each other inside a magazine. Having material stored in multiple locations will require a fire to propagate further before more material is ignited, thus lowering the surface area of HD1.3 material burning at any given point in time. The shock waves created by mass detonation of gun propellant caused much higher pressures than a mass fire, but the pressure was applied to the magazine surfaces for much less time, leading the mass fire to impinge a larger impulse on the magazine. These findings warrant further study to compare the specific damage effects and IBD associated with each HD event.

FUTURE WORK

In the future the capabilities of the CRM will be expanded to allow for more accurate calculations with a smaller set of limitations. Currently every energetic volume immediately begins reacting at the beginning of a simulation. A feature will be added to allow each energetic volume to either start reacting immediately or to begin reacting after a certain condition is met, such as a minimum temperature or pressure at the surface of the volume. This capability will improve the flexibility of the CRM, allowing it to simulate situations where a reaction propagates through items in a magazine. Increasing the number of reacting surfaces on an energetic volume to all exposed surfaces will allow the local pressure around the volume to be more accurately calculated. The currently averaged pressure at a reacting surface leading to a single mass release rate will be changed to an individual cell-level pressure reading and mass release rate calculation, which should increase the detail in the flow field adjacent to reacting surfaces. Other changes that will be considered are the use of more complicated energetic material volumes than boxes and porting the CRM to other CFD codes.

The CRM will be further used in support of the HD1.3 siting review effort to simulate a larger set of potential hazard situations. The pressurization rates of additional storage scenarios will be simulated to include smaller weights of HD1.3 material. Structural calculations will be run on the scenarios deemed most critical to determine the pressurization effects on the respective magazines. Literature shows that in pressurization incidents energetic material is often thrown from the magazine to burn outside. Adding an external burning feature to the CRM will be investigated.

ACKNOWLEDGMENT

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Model Predictions of Pressurization of Ordnance Magazines by Inadvertent Ignition of Energetic Material

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Background

- High-strength ordnance magazines designed against HD 1.1 incidents may allow pressurization during HD 1.3 incidents
- Pressurization may lead to magazine structural failure
- Example: Milan Army Ammunition Plant 2004

Problem Analysis

- Literature search conducted on confined HD 1.3 system reactions
  - Mass fire effects reported in several cases
  - May amplify damage from later HD 1.1 detonation
  - Severity of fire effects during incidents is being studied but is still not well understood
- Use high-fidelity modeling and simulation to better characterize mass fire behavior and structural effects on magazine

Modeling and Simulation Goal

- Provide a predictive capability of the pressure rise involved in an ordnance magazine mishap
  - Pressure-dependent reaction rate ($r=b*P^n$)
  - Reduction of energetic volume
  - Pressure loss from vent areas
- Output pressure history on magazine surfaces, flow field inside vent area
  - Input to structural calculations
  - Determine whether flow is choked

Validation Case

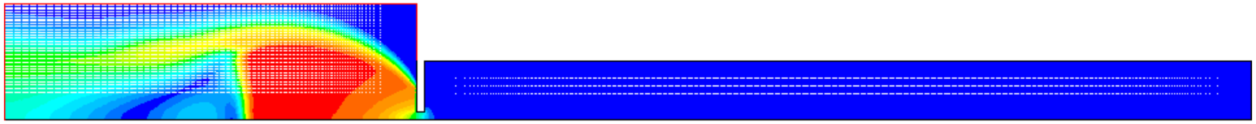
- DDESB funded pressurization test documented in TNO Defence authored paper PFP(AC/326-SG5,6)(NLD/DLD)IWP/01-2008
- 100 g of M4C4 gun propellant ignited inside a 500mm long, 35mm diameter hollow metal cylinder; "pipe bomb"
  - M4C4 data unavailable, M10 used as a substitute
- Pressure history of cylinder gases was measured

Simulated Validation Case

- Two-dimensional, axi-symmetric grid created
- Propellant contained in a bag with 100g of M4C4 (361 7-perf, 0.28g grains); assumed a solid cylinder of M10 in simulation
- Reaction surface area assumed constant
  - Total surface area of the grains

Fluid flow properties at propellant burn-out

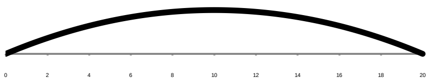
Pressure



Velocity

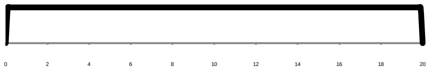
Burn Area

Realistic



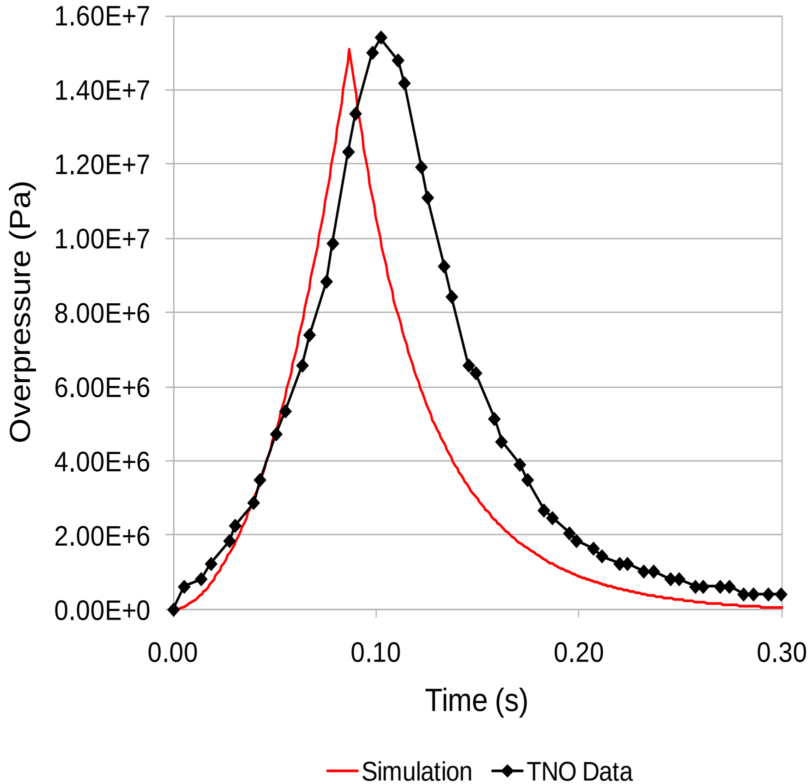
Time

Assumed



Time

Validation Results



* TNO Data line was digitized

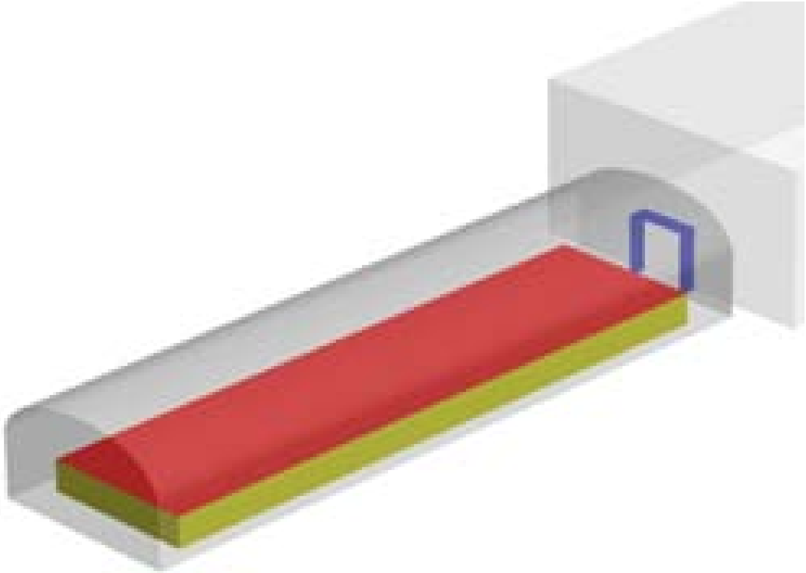
- Shape of simulated pressure history is comparable to test data
- Maximum simulated pressure has 2% error
- Faster simulated reaction consistent with surface area assumption

Simulated Magazine Conditions

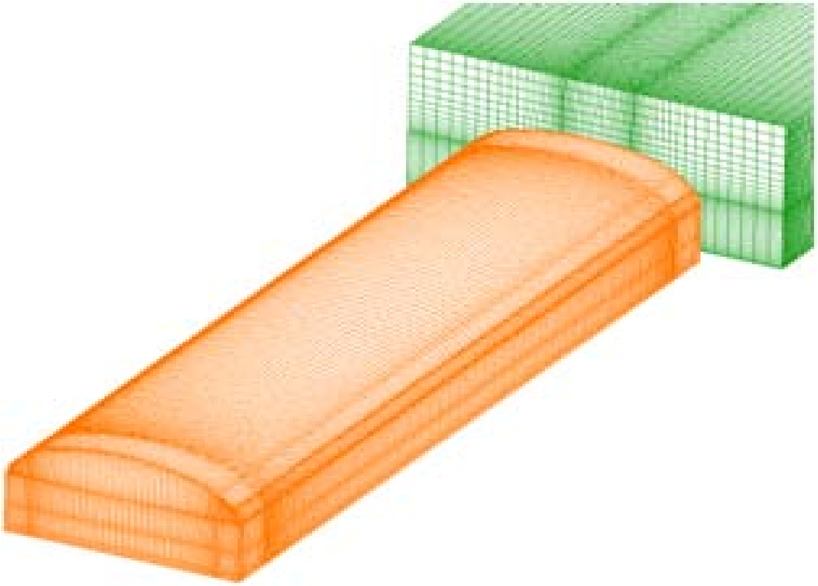
- RC Freloc-Stradley 33-15-74 ECM used as representative magazine model
  - Designed to withstand 7 bar external pressures
- M10 gun propellant used as representative HD 1.3 material
- Range of NEW HD 1.3 studied (*1000 lb)
  - 100, 250, 500, 1024
- Range of burn surface areas studied:
  - Nominal, 200% nominal, 400% nominal
- Ullage (e.g. packaging) must be considered; assumed to have 1/3 the volume of the M10

Representative Model

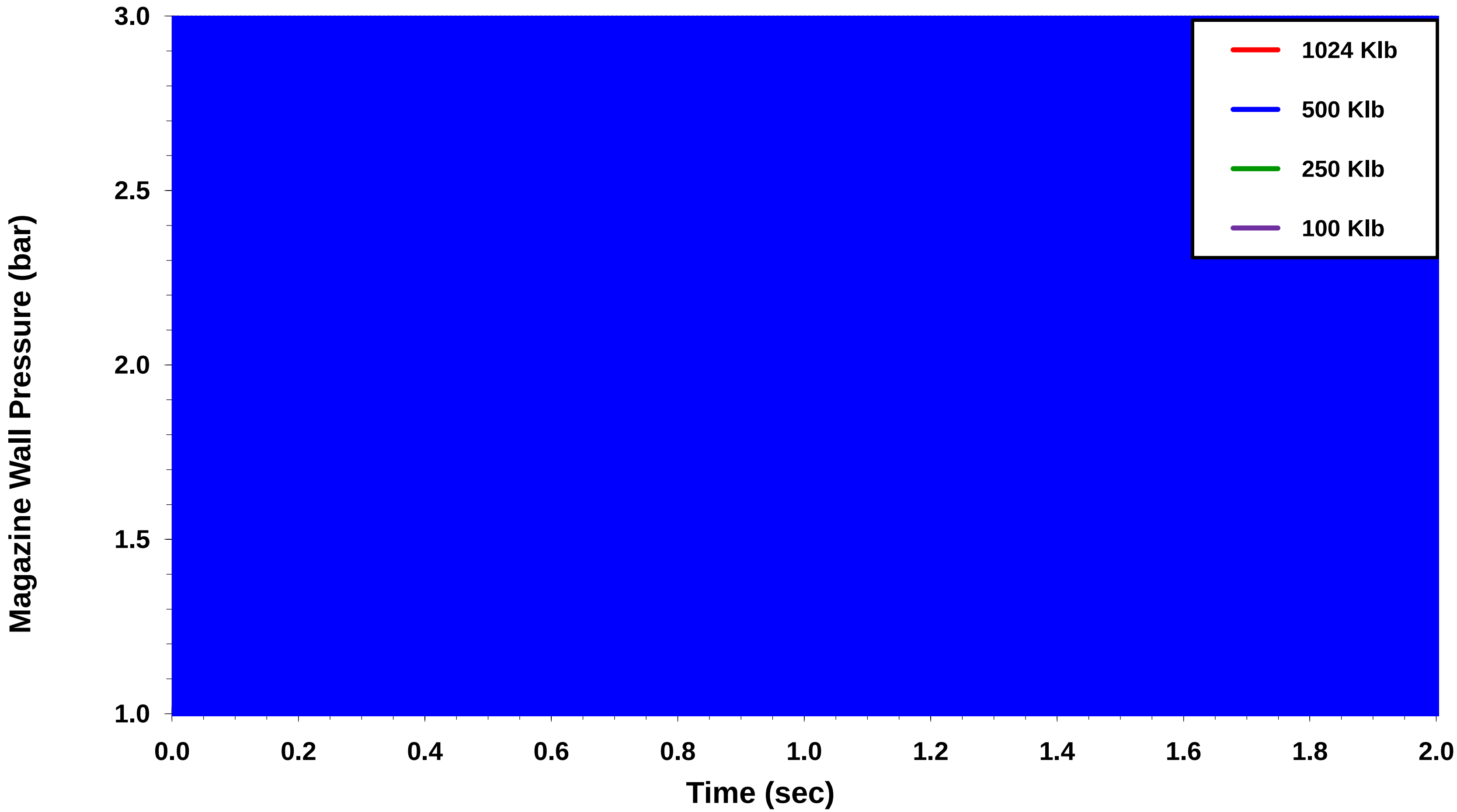
Geometry



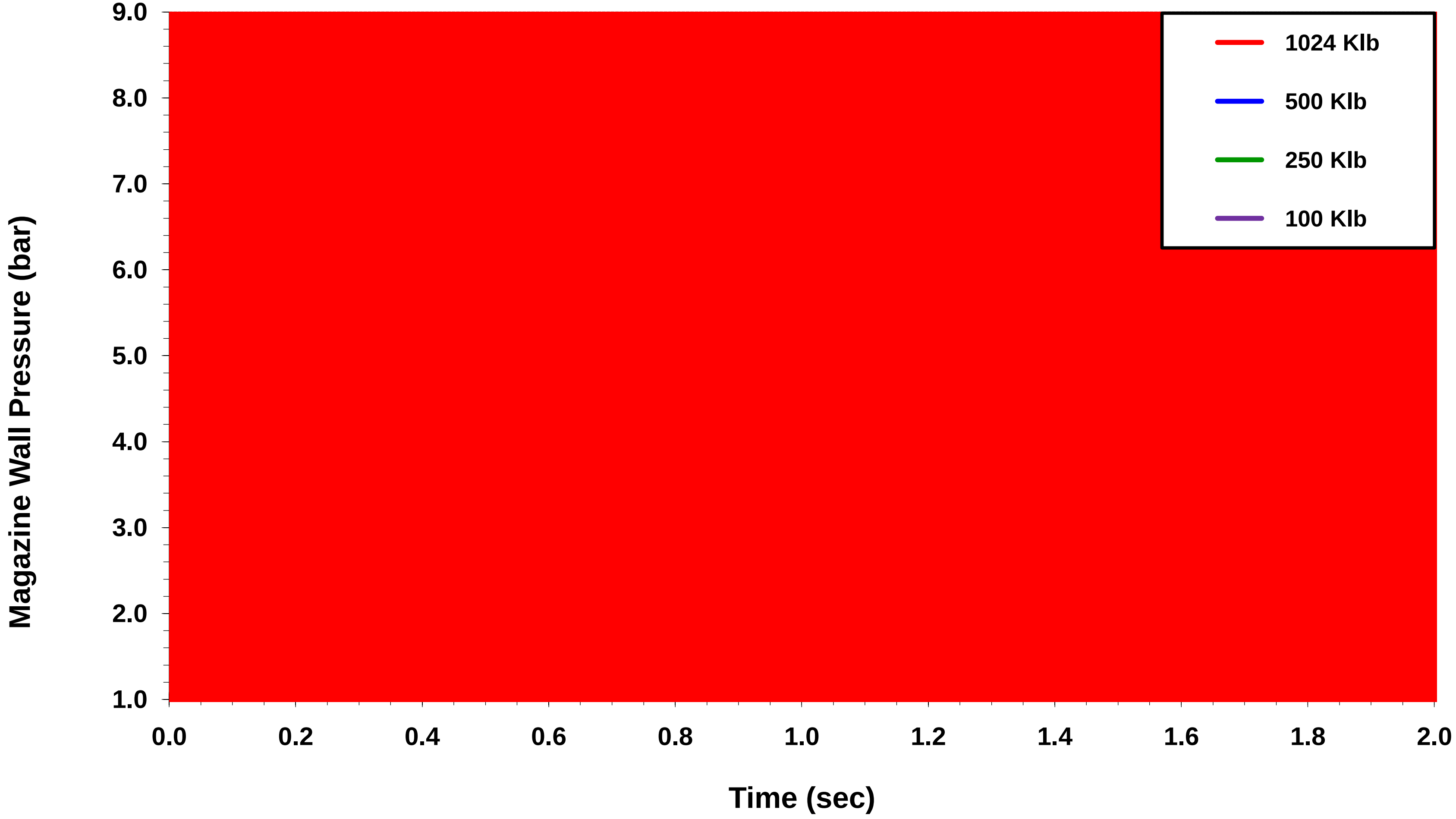
Mesh



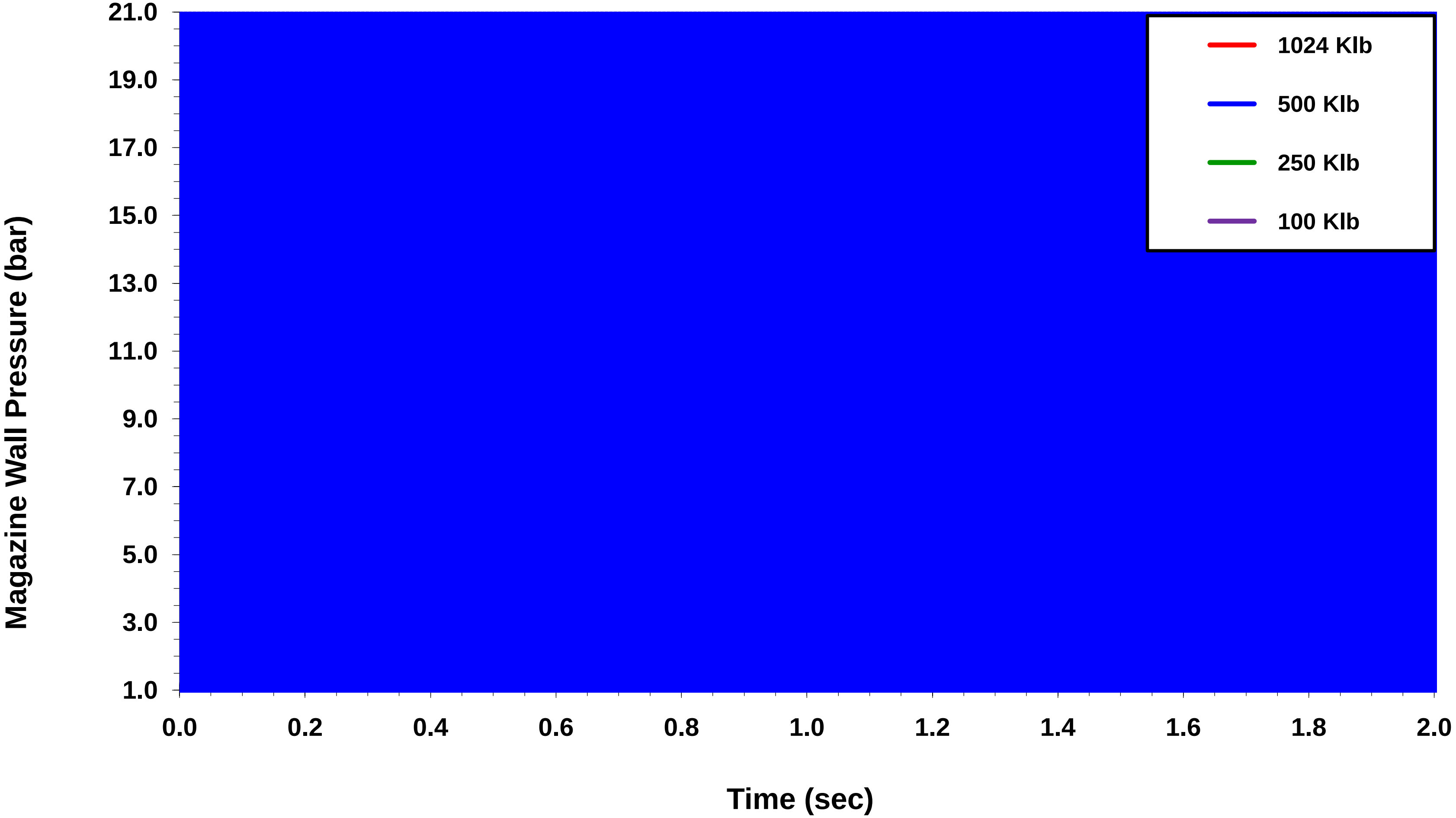
Results: Nominal SA



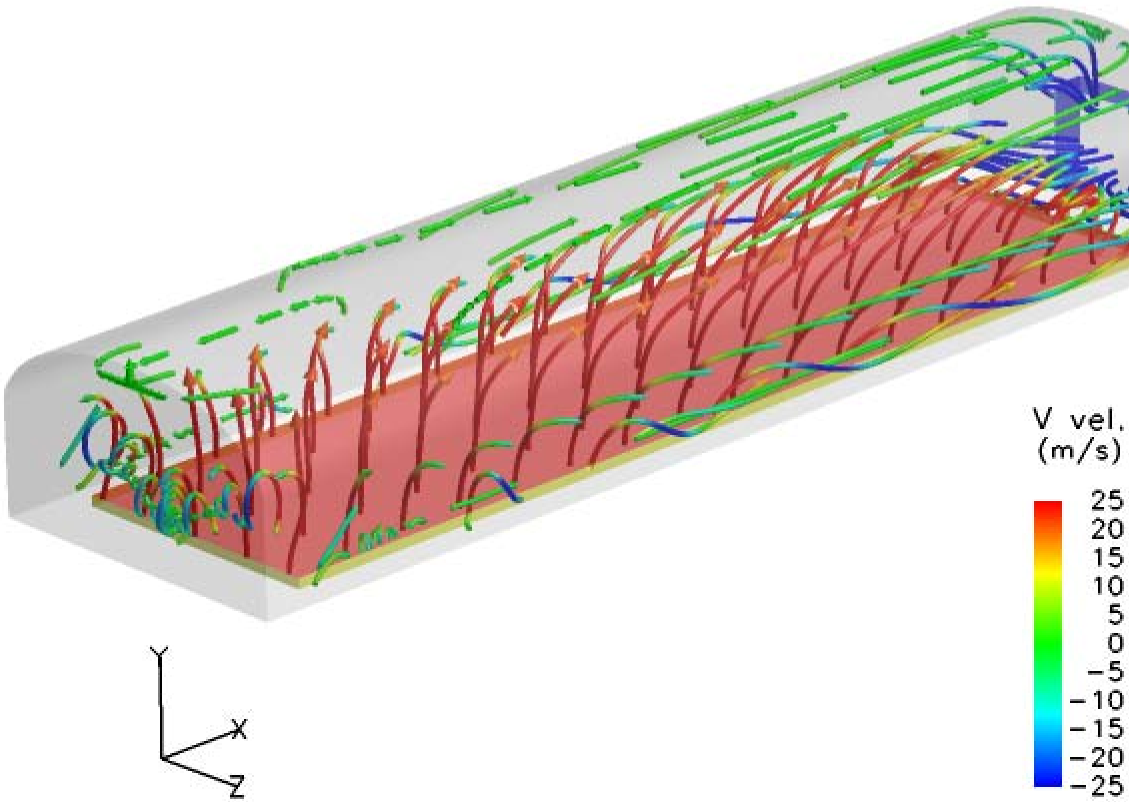
Results: 200% Nominal SA

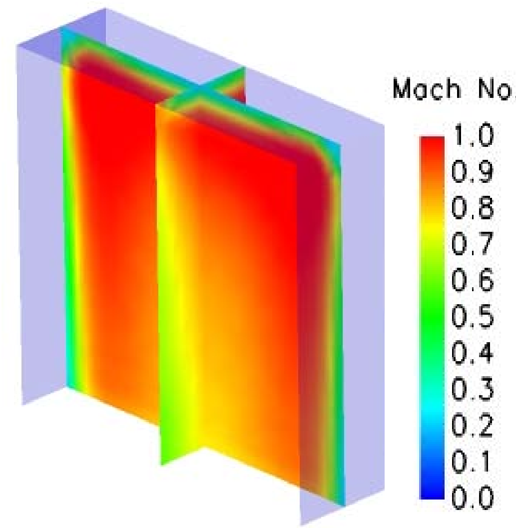


Results: 400% Nominal SA

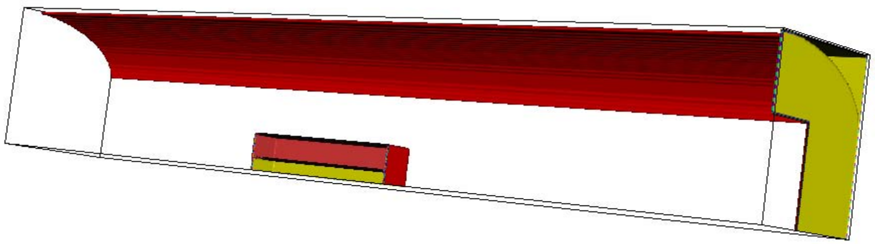


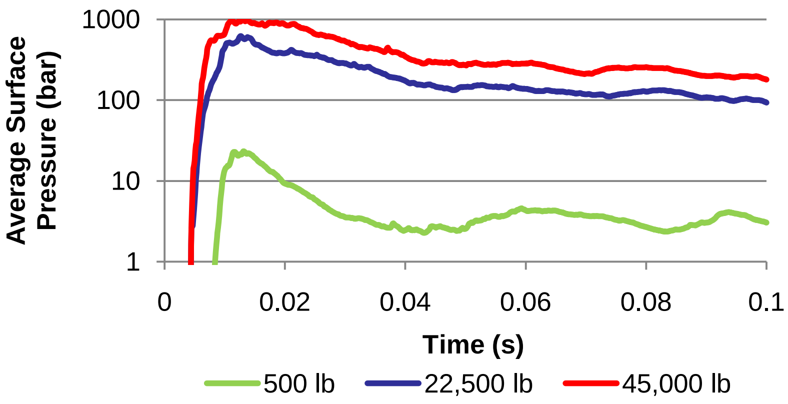
Results: 100,000 lb Velocity





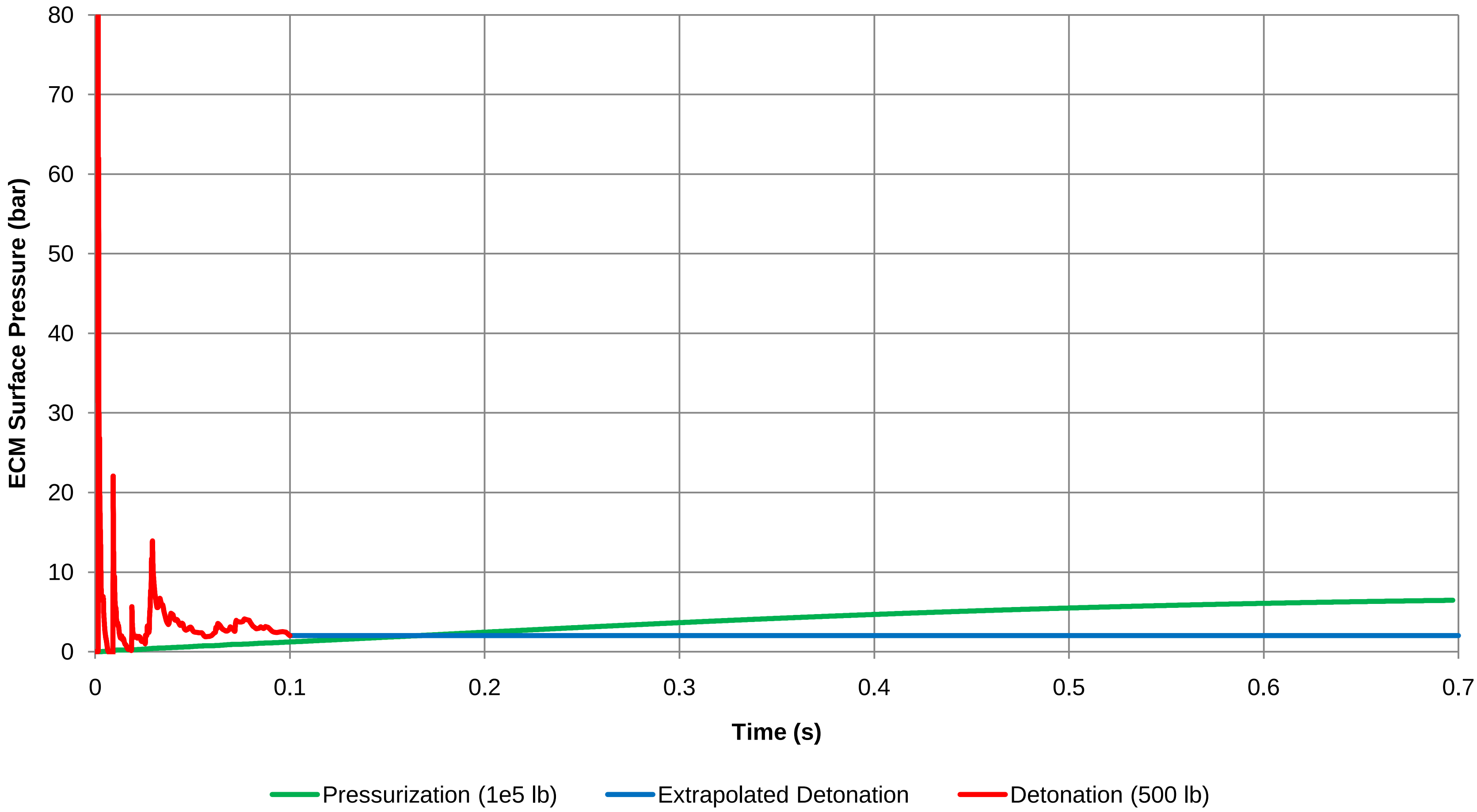
Simulated Detonation





- Representative model simulated in SHAMRC, assuming the M10 detonates
- Compares the pressurization impulse to the impulse of HD 1.1 with similar sited IBD

Pressurization vs. Detonation



Conclusions

- Pressurization and choked flow occur for all weights; depends mainly on burn surface area
- Current HD 1.3 system IBD siting may not be adequate in all situations; further study is required
- The impulse of pressurization is greater than that of detonation

Future Work

- Add Features to Pressurization Model
- Continue Pressurization Simulations
  - Lower weights of HD 1.3 material
  - Energetic Material Thrown Outside Magazine in Unchoked Flow
  - DDT of HD 1.3 material
- Begin Structural Simulations
- Verify against a small-scale magazine mishap test

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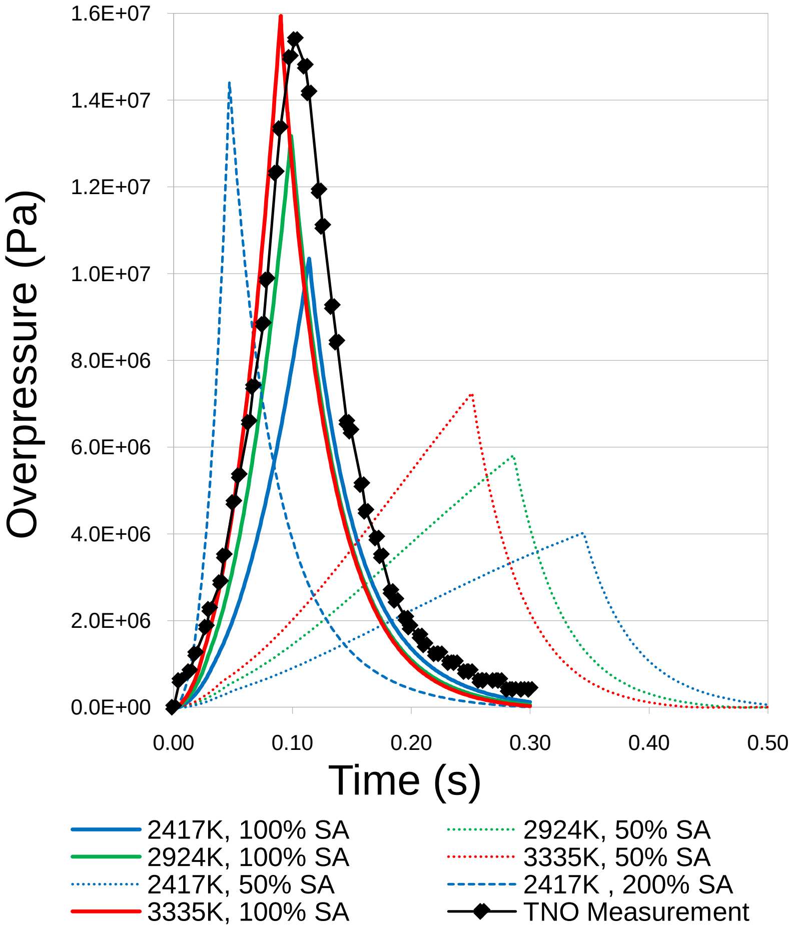
- NAVFAC (Port Hueneme)
- ANSYS Inc.
- Applied Research Associates, Inc.
- DOD High Performance Computing Modernization Office (HPCMO)

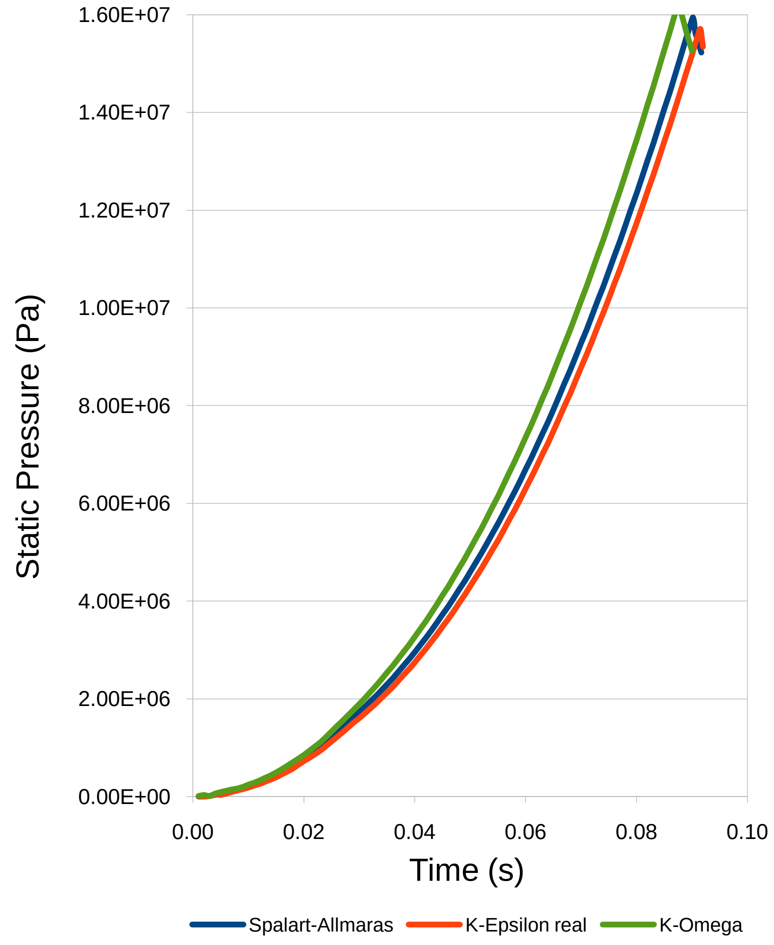
BACKUP SLIDES

Surface Area and Temperature Sensitivities



- Larger surface area increases reaction rate
- Higher reaction products temperature also increases reaction rate
- Model is fairly sensitive to both parameters
  – Proper choice is key to simulation accuracy

Turbulence Model Sensitivity



- Pressure difference between K-Omega and K-Epsilon real 10% - 20%
  - Burnout point difference less drastic
- Spalart-Allmaras gives the fastest calculation
- Turbulence model choice should not change qualitative result

Pressurization Model Development

- Developed on top of CFD code ANSYS FLUENT
- Solid volumes are defined to represent energetic materials/ordnance items
- Problem-specific properties such as reaction products are assigned to each solid volume
- Top surface of each volume reacts at a rate according to the material's pressure-dependent burn equation ($r=b*p^a$) and mass reaction rate ($\delta m/\delta t = r*\rho*SA$)
- FLUENT dynamic mesh feature is used to reduce the volume of each ordnance item as it reacts
- When the total volume has reacted the energetic material stops reacting, and takes up no volume inside the magazine
- Pressure along magazine structural surfaces is tracked