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TRANSIENT THERMAL RESPONSE OF A PROJECTILE MISFIRED IN A MORTAR TUBE

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14. ABSTRACT

Valuable insight into the response of various projectile features under misfire conditions can be drawn from an accurate finite element analysis. This is important since it can model the response and performance of safety critical features including vent plugs and propellant cook-off times. This paper describes the approach used to model the transient thermal analysis of a misfired Precision Guided Mortar Munition (PGMM) in a mortar tube. The analysis of the PGMM described here can be applied to a wide range of projectiles, from large caliber artillery to small caliber bullets with similar environmental conditions. In developing the model, projectile and gun tube components are assigned temperature states representative of misfire. Hand calculations are then performed to determine the dominant heat transfer mode. Lastly, critical parameters are used to setup a finite element model in ABAQUS/CAE for an uncoupled heat transfer analysis.

15. SUBJECT TERMS

Precision guided mortar munition (PGMM), Projectile, Insensitive munition, Mortar, Misfired projectile, Thermal vent plugs, Transient thermal analysis, Uncoupled thermal analysis, Transient temperature response, Thermal response, Heat transfer mode, and Heat transfer analysis

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INTRODUCTION

The Precision Guided Mortar Munition (PGMM) is a laser guided mortar. It has the ability to selectively strike point targets. The precision is from a semi-active laser guidance system. The PGMM round consists of three major subsystems: guidance, navigation, and control (nose - 1); Mid-body (warhead and control thrust mechanism - 2); and tail (boom and tailfins - 3). See figure 1 for locations.

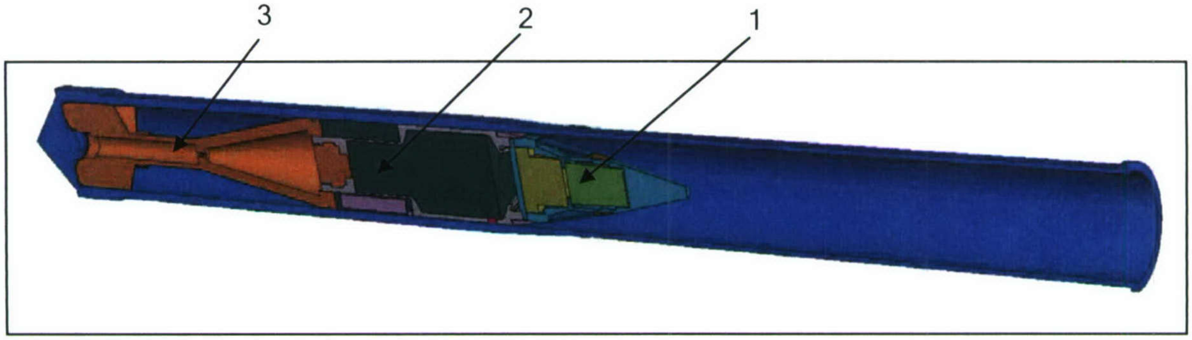


Figure 1
Geometry of PGMM projectile and mortar tube

Modeling a misfired projectile's transient thermal response in the gun tube provides a transient temperature profile of the entire projectile, as well as insight into the performance of vent plugs and other specific features. This type of analysis could also be used as a first step to evaluate propellant or explosive cook-off for a misfired projectile.

This report will concentrate on the thermal effects of the mid-body section, which include the insensitive munition vent plugs on the warhead and the nozzle plugs on the control thrust mechanism. Live fire testing at Yuma Proving Ground, Maryland for the M931 Full Range Practice Round has shown cook-off times for propellant increments are less than 2 sec at the maximum operating temperature.

In the analysis conducted for the PGMM projectile, the round was dropped into the mortar tube at an initially uniform ambient temperature of 70°F. The mortar tube was assumed to be at a uniform temperature of 800°F, the worst case operating temperature. The round misfired (propellant does not ignite) and remained in the tube, at which point it was important to know the time before the warhead vent plugs and the CTM nozzle plugs began to melt. Figure 2 shows the locations of the warhead vent plug and CTM nozzle plug.

This paper describes the approach used to conduct the transient thermal analysis for the PBMM projectile and discusses how to evaluate the different modes of heat transfer.

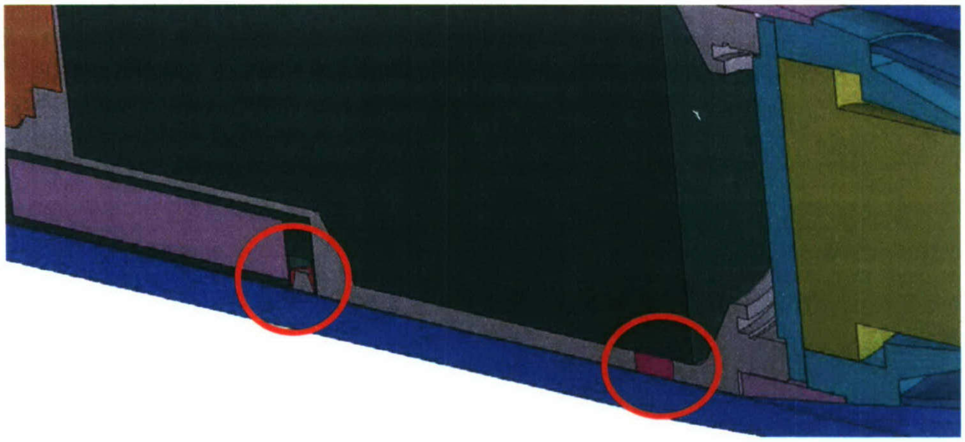


Figure 2
Locations of CTM nozzle plug (left) and warhead vent plug (right)

DEFINITION OF HEAT TRANSFER MODES

There are three types of heat transfer modes applicable to the transient thermal response of a misfired projectile. These heat transfer modes are listed and briefly described next.

- Thermal conduction between the tube wall and projectile body at contact points: At the contact points, perfect contact can not be assumed, as there is a significant amount of interface contact resistance. This contact resistance can be the controlling factor in conduction heat transfer when high conductivity metals are present; e.g., aluminum.

- Natural convection between the tube wall and projectile body: A projectile sitting in a tube will form cavities of air between the tube and projectile body. In these cavities, the air will form natural convection cells due to the large temperature gradient between the projectile and tube walls.

- Thermal radiation between the tube wall and projectile body: Radiation is always present between two bodies of different temperatures as there is no required heat transfer medium between them, but is significant only when the absolute temperature is higher than 1000°F. Since the mortar tube is close to this temperature, radiation effects will be evaluated to determine if they are significant in this analysis.

COMPARISON OF HEAT FLUXES

To determine which modes of heat transfer are significant in this analysis, approximate calculations of each of the heat fluxes are performed and compared. These calculated magnitudes of the heat fluxes show the heat transfer rate per unit area. The active area for conduction is only slightly larger than the convection area. Thermal radiation is active over the entire area; approximately double that of either the conduction or convection.

In order to compute the respective heat fluxes for the heat transfer modes, characteristic quantity values must be determined. These are the interfacial conductance h_i between the metal surfaces, the coefficient of natural convection h_c for air, and the emissivity ε of the steel mortar tube wall. These values are readily available in the typical heat transfer text or reference book. In general there will be uncertainty in the values, so ranges are used for the following comparison.

- Conduction heat flux, through contact resistance: $q = h_i \cdot \Delta T$

  h_i (interfacial conductance, steel to steel) = 300 to 650 Btu/hr·ft^2·°F; ΔT = 730°F

  $$q - 219{,}000 \textit{ to } 475{,}500 \; Btu/hr \cdot ft^2$$

- Natural convection heat flux: $q = h_c \cdot \Delta T$

  h_c (coefficient of natural convection) = 0.50 to 4.40 Btu/hr·ft^2·°F; ΔT = 730°F

  $$q = 365 \textit{ to } 3{,}212 \; Btu/hr \cdot ft^2$$

- Thermal radiation, radiant heat flux: $J = \varepsilon \cdot \sigma \cdot T^4$

  ε (emissivity of steel) = 0.050 to 0.95; T = 800°F (1260°R); where σ is the Stefan-Boltzmann constant, $\sigma = 1.712 \times 10^{-9}$ Btu/hr·ft^2·°R^4

  $$J = 2{,}158 \textit{ to } 4{,}099 \; Btu/hr \cdot ft^2$$

As seen, it is possible to determine the relevant modes of heat transfer with a simple hand calculation. In this case, conduction is the dominant mode of heat transfer. For the purposes of this analysis, the convection and radiation effects can be ignored, as the heat fluxes are two orders of magnitude smaller than that of conduction.

Generally, values for the interface contact resistance should be considered representative. Available data for interface contact resistances are strongly dependent on pressure and are usually sparse and unreliable. Consequently, any analysis results should also be considered representative, giving an indication of the approximate time range for the thermal responses.

TRANSIENT HEAT TRANSFER ANALYSIS - SETUP FOR FINITE ELEMENT ANALYSIS (FEA)

Once it was determined that only conduction was to be considered, a model was developed for ABAQUS/CAE using half symmetry (specific part geometry prevented the use of quarter symmetry). Figures 3 and 4 show the mesh generated for this geometry.

Figure 3
Overall model mesh

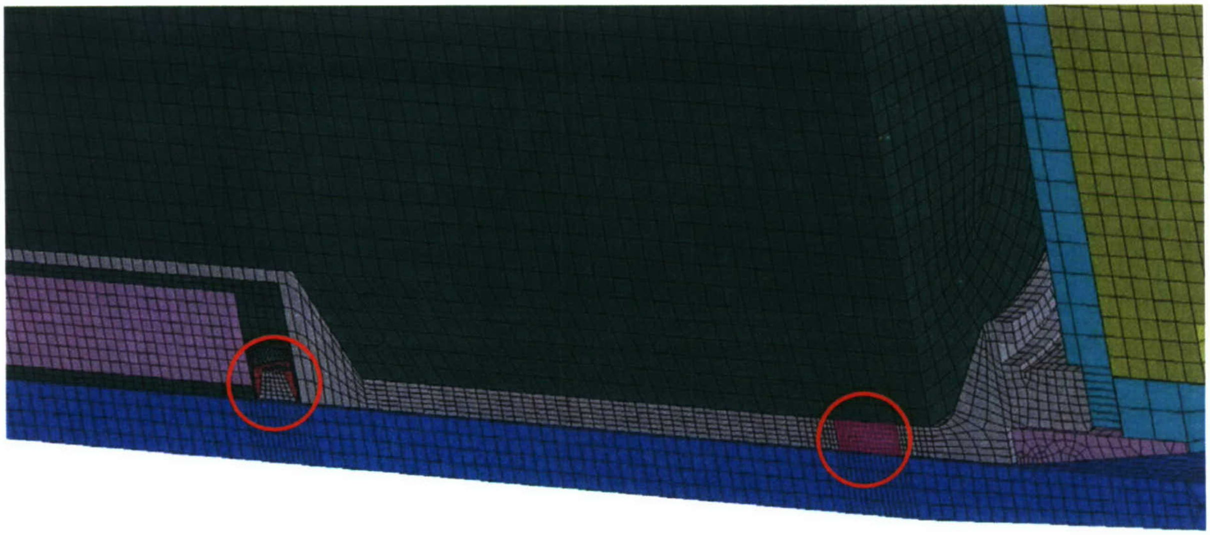


Figure 4
Model mesh in regions of interest

As seen in figure 3 and 4, the mesh is refined only in area where contact occurs. A course mesh is used everywhere else, where heat transfer is insignificant. The regions of interest are the warhead vent plug and CTM nozzle plug, which contain the most refined mesh. Perfect contact (no contact resistance) is assumed to occur between the individual parts. Contact resistance is prescribed only between the projectile and tube, as this assumption reduces the computation time. This assumption is appropriate since the large temperature gradients occur only between the projectile and tube surfaces and the time scale at which the plugs melt is both relatively short and happens before any significant temperature change occurs throughout the projectile.

This analysis was conducted as an uncoupled heat transfer analysis, ignoring both thermal expansion and stresses. While the interface contact resistance is dependent on pressure, detailed pressure information was not available. As a result, the analysis was run with the upper and lower values of the contact resistance providing upper and lower bounds for the thermal response time. If pressure dependent data is available, ABAQUS would allow for these inputs although the analysis would then have to be coupled.

Since the analysis needed to determine when the vent plug and CTM plug would melt, the melting temperatures and heats of fusion were required for each of these materials. It is important to note that phase change (solid to liquid) introduces strong nonlinearity to the analysis. Consequently, first-order elements are recommended for use in the analysis instead of the second-order elements, which are recommended for smooth conduction/diffusion problems.

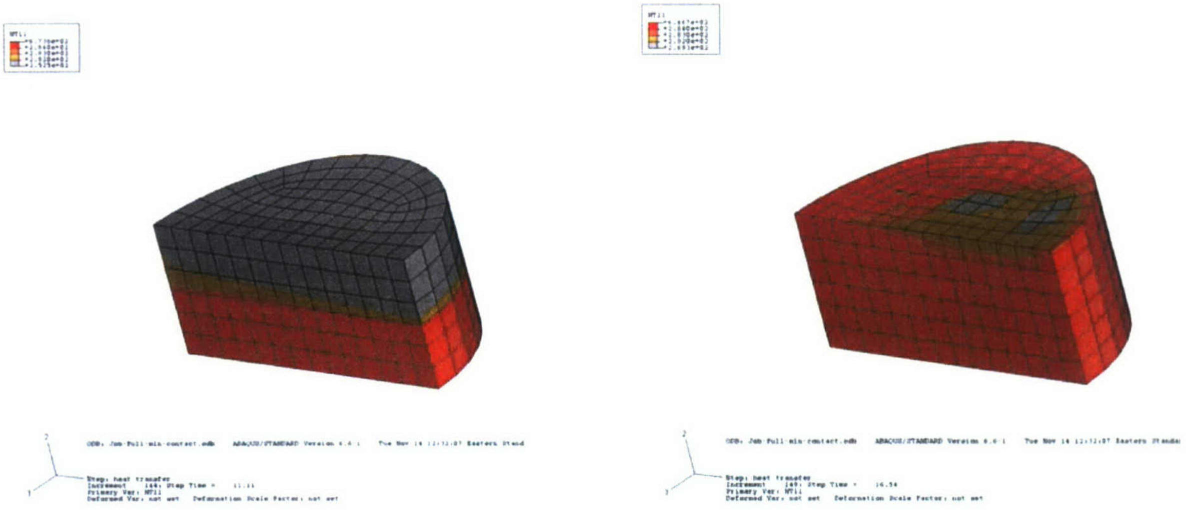
Additionally, when conducting a transient therma! analysis using ABAQUS Standard (an implicit code) there is a *minimum* useable time step:

$$\Delta t \geq \left(\Delta l^2 / 6\alpha\right)$$

Where α is the thermal diffusivity of the material and Δl is the distance between nodes for the surface element with the largest temperature gradient. The selected time step must be larger when using second-order elements, but a larger value is also strongly recommended when using first-order elements. If the time increment is smaller than this limit the results may have temperature oscillations or temperatures may change inversely to what is expected. The issue can be resolved by either refining the mesh in the region with large temperature gradients, or using larger time steps. By using larger time steps, the early transient solution is not resolved, but the analysis still yields good results (only true for an implicit code).

TRANSIENT HEAT TRANSFER ANALYSIS - RESULTS

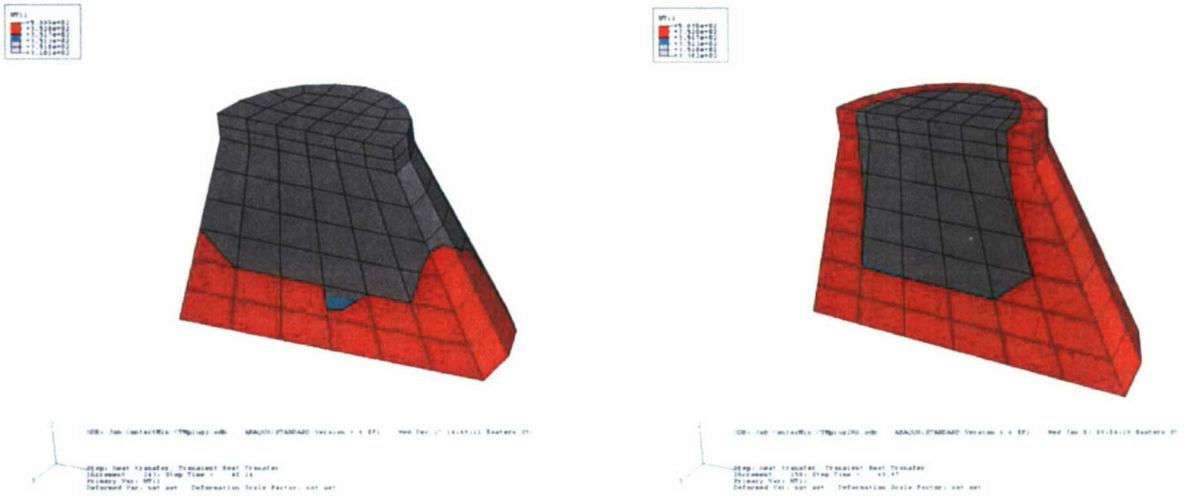
Figures 5 through 8 show the results of the transient thermal analysis using the minimum values for the interfacial conductance:



11.11 sec

16.54 sec

Figure 5
Solid liquid (red) transitions of warhead vent plug



40.24 sec

49.97 sec

Figure 6
Solid to liquid (red) transition of CTM nozzle plug

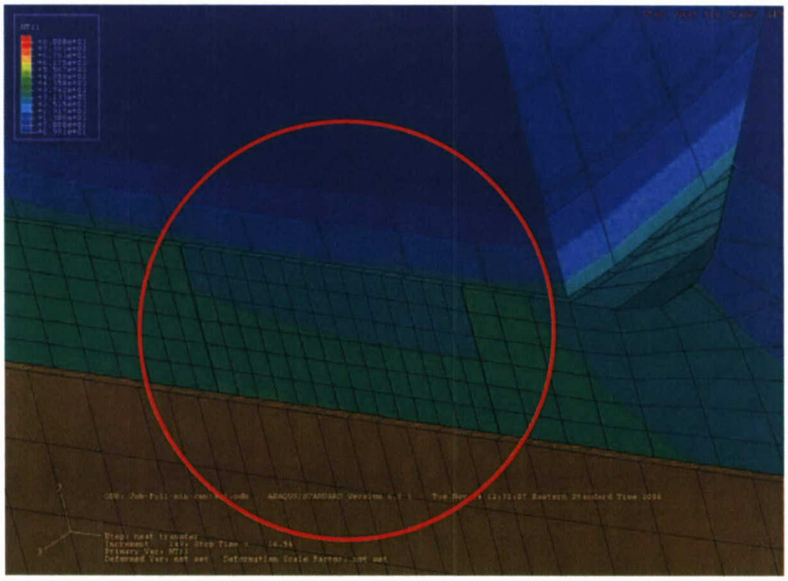


Figure 7
Warhead vent plug region temperature distribution at 16.54 sec

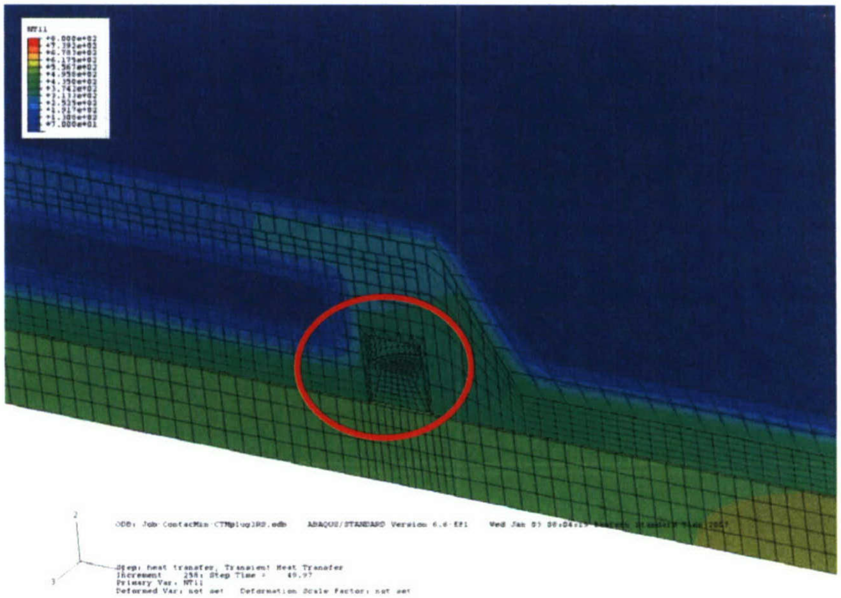


Figure 8
CTM nozzle plug region temperature distribution at 49.97 sec

CONCLUSIONS

A misfired projectile sitting in its gun-tube represents a fairly complex transient heat transfer problem, though simple hand calculations reduce the complexity of the problem significantly. The modes of heat transfer that are significant to the analysis will depend mainly on the initial temperature difference between the projectile and gun-tube, although conduction at the contact points is generally dominant. Modeling of phase-change (e.g., melting vent plugs) introduces significant non-linearity to the problem and requires careful setup of the model.

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