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# 5.56 MM CERAMIC GUN BARREL THERMAL ANALYSES WITH CYCLED AMMUNITION

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The ceramic gun barrel has a potential for lighter weight and longer tube life. However, the combination of thermal and structural loading can result in a severe thermal stress state at the inner barrel surface. The U.S. Army Research Laboratory (ARL) ceramic gun barrel project is an investigation into the feasibility of ceramics for application in various weapons. The current finite element analysis is focused on the thermal effects during the firing for 5.56mm ceramic gun barrels. The single shot thermal response was investigated in detail, such as inner wall elevated temperature, the temperature distribution as well as the barrel surface temperature gradient. Multiple shot thermal modeling was performed for a burst firing of 200 rounds over a period of 2 minutes. The results obtained were used to describe the transient heating of the gun tube over a long period of continuous firing. The experimental results were compared with the simulation.

## 1. Introduction

Ceramics offer inherently higher erosion-resistance, higher operating temperature capabilities, and lower densities than refractory metal-coated steels. These attributes can extend gun barrel life, sustain accuracy, and enable the use of more energetic propellants that generate higher adiabatic flame temperatures and yield higher in-bore pressures with less weight [1]. However, to take advantage of these attractive ceramic properties, the ceramic gun barrel must be investigated for its ballistic thermal behavior and response in order to minimize the likelihood of thermally induced tensile stress failure.

Material evaluations were conducted by the U.S. Army Research Laboratory (ARL) [2], the results of which were incorporated into modeling the heat transfer for the 5.56 mm ceramic gun barrel. Knowledge of the temperature profile is essential for assuring that the thermal stress state at the inner wall surface remain in compression at all times. Given the extremely high gas temperatures generated by interior ballistic event, it is imperative that an approach be developed that predicts the gun barrel temperature profiles.

In the analysis, the M249 steel_4340 gun barrel was modeled as a baseline and compared with Aberdeen Test Center (ATC), George Niewenhous)[3] experimental thermocouple data. Then the model was modified to represent an M16 5.56mm ceramic lined gun barrel to predict the thermal behavior for single and multiple shots. Figure 1 (a) schematically demonstrates the M249 gun barrel. The M249 uses a brass cartridge case (red color part in figure 1(a)) that absorbs heat during firing and subsequently is then extracted. Without this brass case the temperatures experienced by the chamber would be much greater.

Figure 1 (b) shows the STK4 ceramic barrel press fit [4] into an M16 gun barrel The ceramic STK4 is a SiAlON material produced by Kennametal using sintering and a post sintering hot iso-static pressing step to produce a fully dense material. The microstructure contains elongated grains and consists of 60% alpha phase and 40% of the beta phase. The ceramic tube is 7.62cm long as shown in the figure 1 (b).

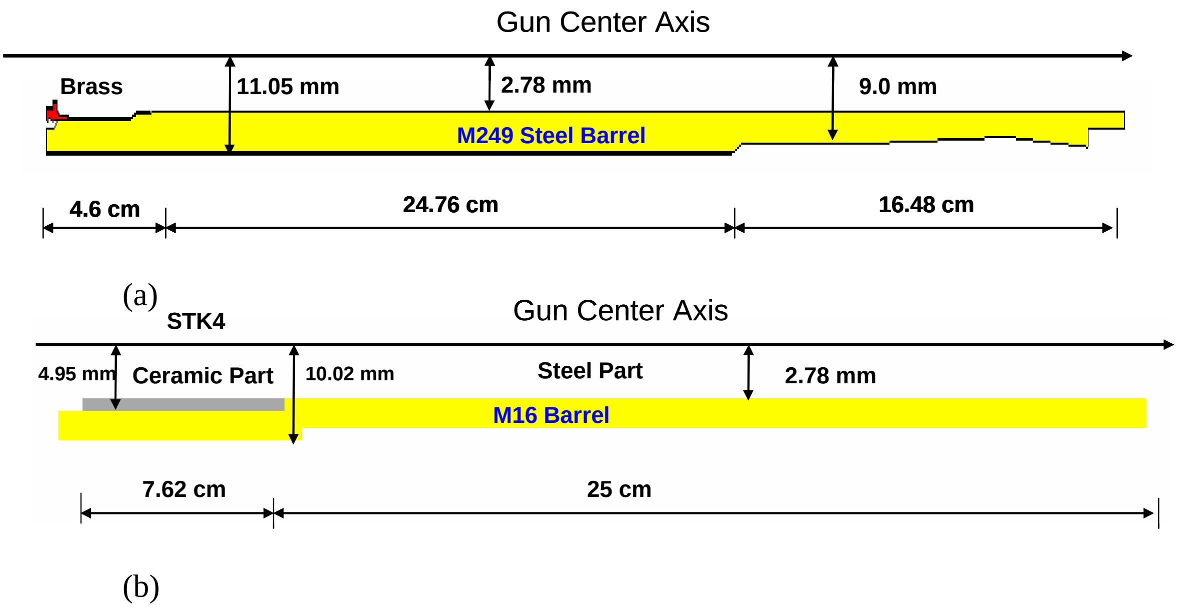

Figure 1. (a) M249 Steel Gun Barrel (b) The STK4 Ceramic Lined Gun Barrel

In the following sections, the modeled heat conductive time and space dependent boundary condition is briefly introduced. Then the detail of the finite element model (FEM) is presented for the heat transfer analysis. The steel gun result is discussed and compared with the experimental 5.56mm data. The model finally is used to predict the ceramic gun barrel in multiple shots.

## 2. The Interior Ballistic Input and Finite Element Code

In the past, extensive interior ballistic (IB) tests were conducted to determine the barrel temperature and internal pressure for the several propellants. Inside the barrel, the gas temperature was found to be space dependent. Gas temperature and pressure profiles are generated, using IB modeling, along the barrel centerline. Figure 2 shows an example of gas product temperature for a typical 5.56mm cartridge. It is seen that the profiles are not only time dependent but also spatially dependant as well. The peak gas temperature produced for this cartridge is around 2150 $^oK$.

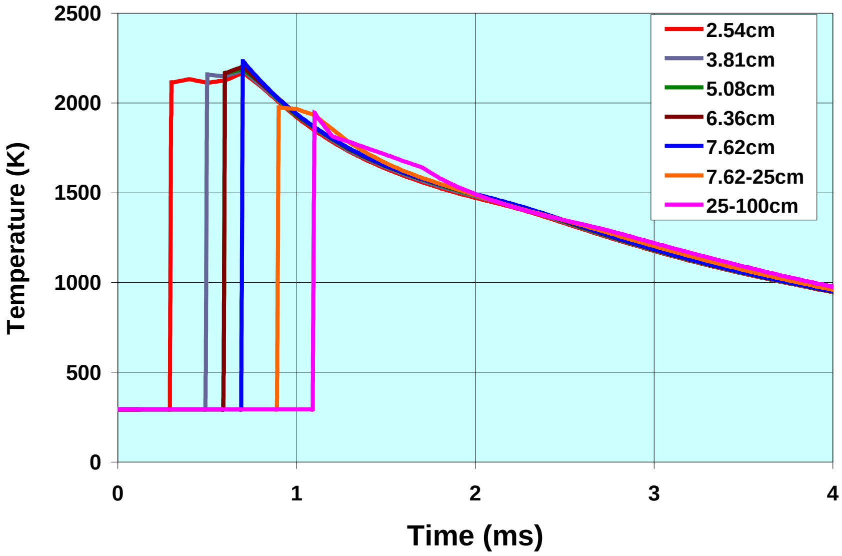

Figure 2. The Time and Space Dependent Barrel Gas Temperature for a Typical 5.56mm Cartridge

Inside the barrel, the heat convective coefficient is both spatially and temporally variant as well during the IB cycle. The ceramic barrel convective coefficient profiles are in figure 3. The peak values in various locations are quite different. The maximum 45% value difference is found between the barrel entrance and end.

Both the film temperature and heat transfer coefficients were obtained by using the XKTC [5] interior ballistic code to produce the spatially and temporally varying state variables as well as gas velocity along the centerline of the gun bore. This data was then used through the applications of the ARL Gun Tube Heat Transfer Code (2003 version) [6] to generate the data necessary for export to a secondary code, such as an FEM code, for more rigorous analysis of complex geometries.

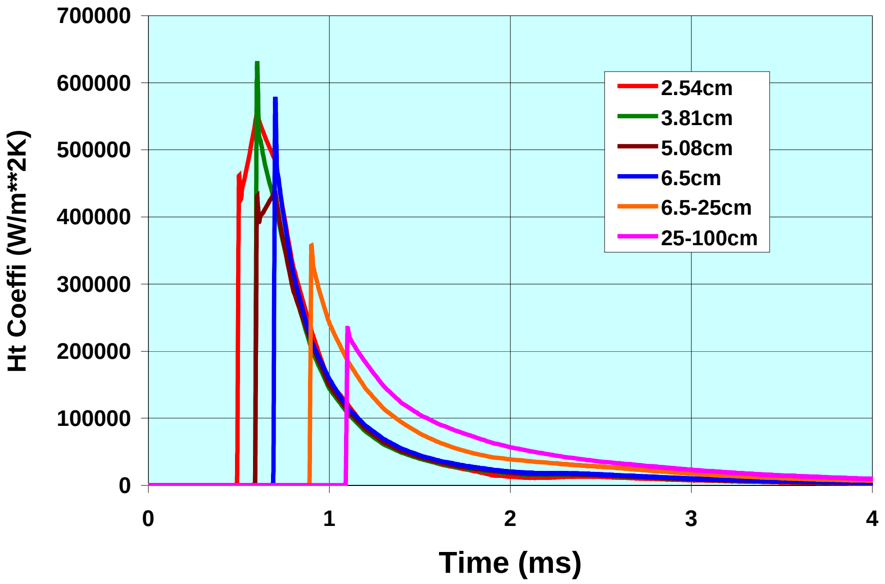

Figure 3. The Time and Space Dependent Heat Convective Coefficient for a Typical 5.56mm Cartridge.

The material properties used in the model are listed in table 1. It is noted that the thermal conductivities and heat capacities are valid within certain temperature ranges. In reference [7], the relationships between the property and temperature can be found. These temperature dependent material properties were programmed into the model.

| **Properties** | **Density $\rho$ (kg/m$^3$)** | **E (Gpa)** | **$\mu$** | **K (W/M$^o$C)** | **$C_p$ (J/kg$^o$C)** | **CTE $\alpha$ (10$^{-6}$/$^o$C)** |
|---|---|---|---|---|---|---|
| **Steel_4340** | **7800** | **208** | **0.3** | **27~36** | **470~1100** | **8.4** |
| **STK4 Ceramic** | **3400** | **310** | **0.24** | **8.5~10.8** | **735~1240** | **3.2** |
| **Brass** | **8526** | **110** | **0.38** | **142** | **376** | **19.1** |

Table 1. Material Properties of Steel_4340, STK4 Ceramic and Brass

The finite element code ABAQUS developed by Hibbitt, Karlsson & Sorensen, Inc. is used to solve the heat conducting problem formulated above. The model was meshed directly using ABAQUS meshing keyword input cards according to the User's menu [8]. The temperature dependent material properties in the table 1 were coded by using user subroutines. The formulations for the gas temperature and convective coefficient shown in the figure 2 and 3 were externally programmed and linked into existing ABAQUS main code.

The model, shown in figure 1, has interfaces along some of the different components which are fixed with the joining elements sharing common nodes at the interfaces. Two dimensional 4-node axi-symmetric elements were used in the model. Extra care was taken for meshing each part of the model, especially along their common edges. More fine meshes were applied for the barrel inner surface area. The ABAQUS CAE software was used for post processing which includes contour plots and temperature profile curves [9].

## 3. Steel and Ceramic Gun Barrel Single Shot Heat Conductive Analysis

The simulations of the steel_4340 M249 gun barrel and STK4 ceramic lined gun barrel were conducted first for a single shot evaluation. The accuracy of the single shot analysis is quite important. Any small deviation will cause significant error in the multiple shot analyses due to its accumulation. Figure 4 shows the temperature contour

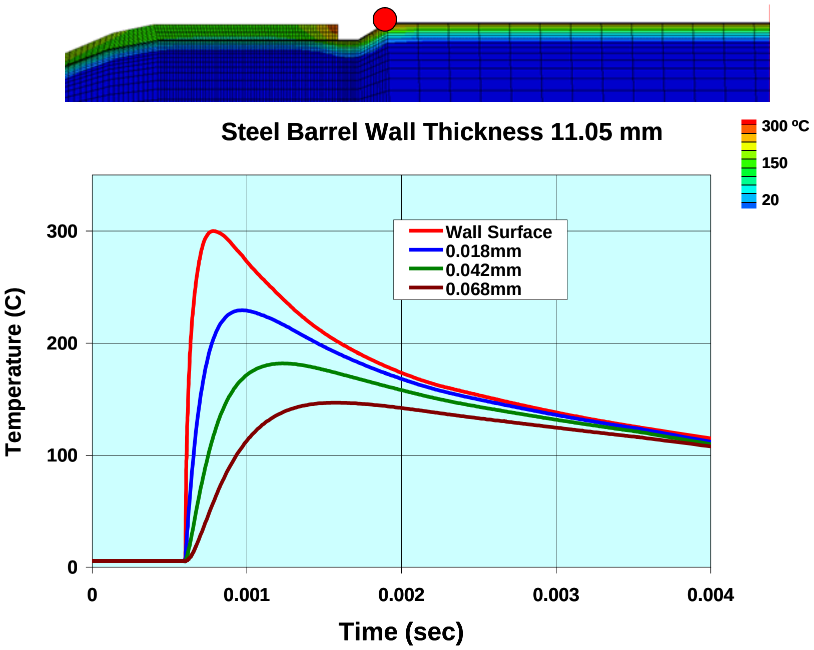

Figure 4. Temperature Contour and Profiles for the Steel Gun Barrel

and profiles in the steel_4340 gun barrel near the chamber area and its vicinity. It is seen that the barrel entrance (red dot) has the highest temperature of 300°C. The temperature profiles were plotted as function of the distance near the barrel inner surface. The temperature dropped 150°C as the distance from the wall surface to 0.068mm inside the substrate barrel.

For the ceramic gun barrel, the hottest temperature, of about 520°C, occurred at the inside wall of the ceramic insert. The thermal gradient was high (see Figure 5). The temperature dropped more than 300°C at 0.042mm into the substrate from the inner wall surface. This temperature gradient may cause a significant thermal stress over such a small distance.

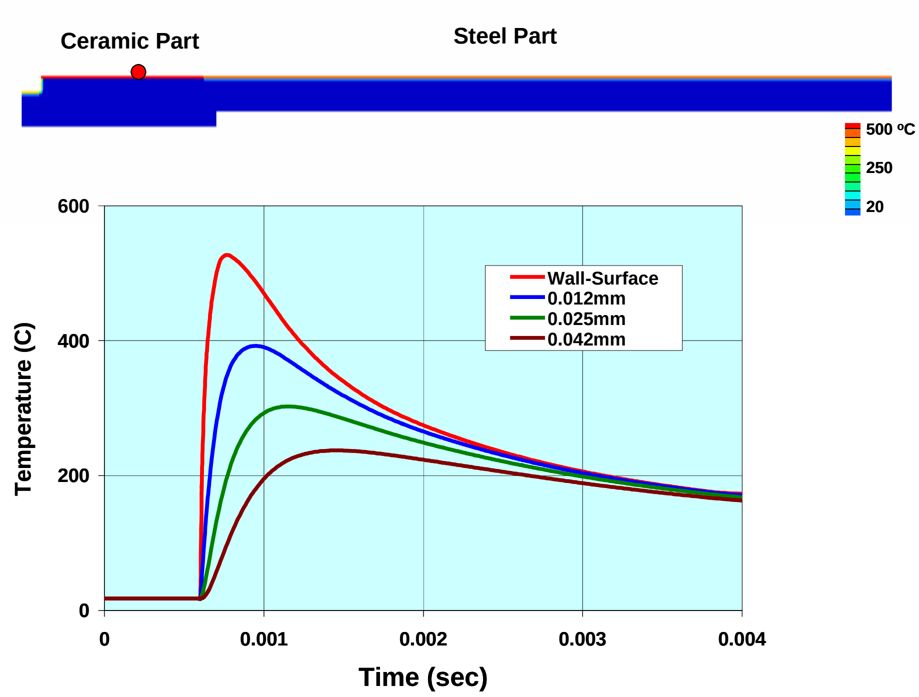

Figure 5. Temperature Contour and Profiles for the Ceramic Gun Barrel

## 4. Temperature Profiles for the Multiple Shot Scenarios

Based on the single shot analysis, the multiple shot analyses were performed. The film temperature and heat transfer coefficient convective boundary condition in each single shot period was repeated to create a sequential firing scenario. It was assumed that the thermal boundary condition was independent of the wall temperature. To a degree this is true as the heat transfer coefficient is modified weakly though the local viscosity which takes the wall temperature into account. During the multiple shot simulations, 200 rounds were fired over a period of 2 minutes, with each shot taking about 0.6 seconds. To perform the cycled ammunition analysis, 200 single 0.6 second shots were programmed time sequentially in an ABAQUS user subroutine.

Figure 6 (a) and (b) show the barrel temperature profiles for the first ten and last ten rounds in the same barrel axial location shown in Figure 4 for the single shot. The inner wall temperature (pink color) varied periodically up and down as the each shot occurred. The outer tube wall temperature (green color) rose steadily as the shot counts increased. The outer temperature was always lower than that of the inner wall no matter in the first ten or last ten rounds. The average difference was 5°C between the lowest inner wall and outer wall temperatures in each cycle. Figure 6(c) shows the temperature

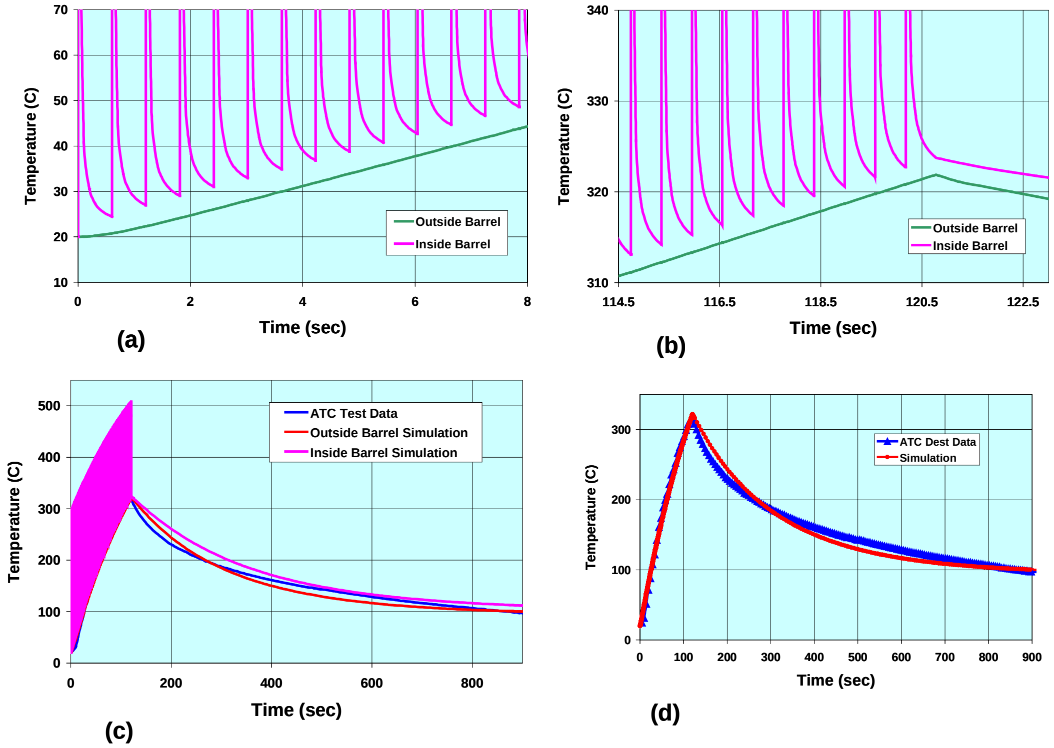

Figure 6. (a) Temperature profile for the first 10 shots

(b) Temperature profile for the last10 shots

(c) Temperature profile for the 200 shots

(d) Temperature Comparison between the simulation and ATC test data profiles for the entire 200 rounds fired. The inner wall temperature reached 600°C while outer wall reached 310°C. After 200 rounds, with a buoyant free convective heat transfer boundary condition applied to the external surface of the gun barrel, the outer wall temperature decreased rapidly. It reduces to 120°C after 6 minutes in shooting. The experiment data conducted in ATC was used to compare the 200 round simulation (see figure 6(d)). In the firing stage, i.e., the temperature elevated range the simulation fitted the test data very well. During the cooling period, the model fit the test data well enough though not good as previously since radiation may play some important role.

The ceramic barrel modeling results are shown in figure 7 (a), (b) and (c) for the first 10 shots, last 10 shots and 200 shots respectively, at the red-dot location of the ceramic section shown in figure 5. The firing rate was the same as previously at 200 rounds over 2 minutes. The average temperature difference between the inner wall and outer wall was 18°C which was much larger than that of the steel tube. That indicated that the ceramic tube diffusivity didn't transfer the heat into the barrel substrate rapidly as the steel tube could. The outer barrel wall temperature reached 350°C then decreased rapidly. This high temperature gradient near the inner wall surface also existed in the multiple shots which would most likely cause severe thermally induced stress.

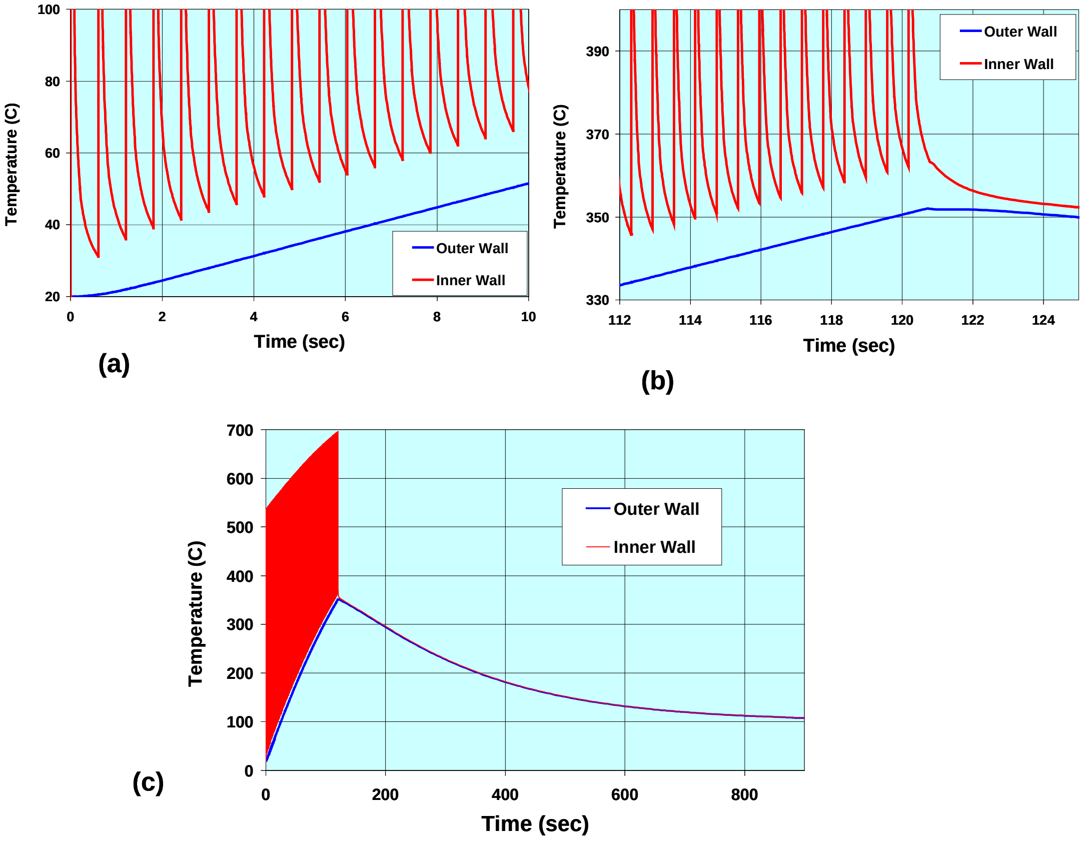

Figure 7. (a) STK4 Ceramic Barrel Temperature profile for the first 10 shots
(b) STK4 Ceramic Barrel Temperature profile for the last10 shots
(c) STK4 Ceramic Barrel Temperature profile for the 200 shots

## 5. Summary

A two dimensional FEA thermal analyses was conducted for the 5.56mm steel_4340 gun and STK4 ceramic gun barrels. Spatially and temporally varying film temperatures and heat convective coefficients were applied throughout the analysis. Temperature dependent heat conductivities and heat capacities were used in modeling the gun barrels. Single shot analyses for both steel and ceramic gun barrels showed significant temperature gradients occurring in the inner wall areas. A 200 round burst firing (over 2 minutes) simulation was performed. The outer wall temperature of this scenario compared extremely well with ATC test data. The verified model was used to predict multiple shot thermal behavior of a ceramic lined gun. The obtained thermal profiles were essential for future thermal stress analyses.

## Acknowledgments

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## 6. References

[1] Underwood, J.H., Todaro, M.E. and Vigilante, G.N. “Modeling of Transient Thermal Damage in Ceramics for Cannon Bore Applications”, Army Armament RD&E Center, Benet Laboratories, Building 115, Watervliet, NY 12189, 2004.

[2] Swab, Jeffrey J., Wereszczak, Andrew A., “Mechanical and Thermal Properties of Advanced Ceramics for Gun Barrel Applications”, Army Research Laboratory, ARL-TR-3417, 2005.

[3] George Niewenhous, Aberdeen Test Center, Aberdeen Proving Ground, MD– Personal Communication April 2006.

[4] Emerson, Ryan, Carter, Robert H., “Press-Fit Sheathing for Ceramic Gun Liners”, 2005 Advanced Gun Barrel Materials and Manufacturing Symposium, St. Michaels, MD, July, 2005.

[5] Gough, P.S., “The XNOVAKTC Code,” BRL-CR-627, Ballistic Research Laboratory, Aberdeen, Proving Ground, MD, 1990.

[6] Conroy, P.J., “Gun Tube Heating,” BRL-CR-3300, Ballistic Research Laboratory, Aberdeen, Proving Ground, MD, 1991.

[7] Huang, Xiaogang, Garner, James, Conroy, Paul, “Thermal Analysis for 37 mm Gun Chamber with Ceramic Nozzles” ARL-MR-624, Sep. 2005

[8] ABAQUS/Standard User’s Manual, Hibbitt, Kkarlsson & Sorensen, Inc. Version 6.6, 2006.

[9] ABAQUS/CAE, User’s Manual, Hibbitt, Kkarlsson & Sorensen, Inc., Version 6.6, 2006.