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Technical Report ARAEW-TR-06022

A THERMAL PERFORMANCE STUDY OF THE 155MM XM297 ACTIVELY COOLED BARREL

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NOVEMBER 2006

ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
Armaments Engineering & Technology Center
Weapon Systems & Technology
Benét Laboratories

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
November 2006	Final	

4. TITLE AND SUBTITLE

A THERMAL PERFORMANCE STUDY OF THE 155MM XM297 ACTIVELY COOLED BARREL

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army ARDEC, AETC, WS&T
Benet Laboratories, AMSRD-AAR-AEW, B. 40
1 Buffington Street
Watervliet Arsenal, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER

ARAEW-TR-06022

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army ARDEC, AETC, WS&T
Benet Laboratories, AMSRD-AAR-AEW, B. 40
1 Buffington Street
Watervliet Arsenal, NY 12189-4050

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Crusader Self Propelled Howitzer will employ an actively cooled 155mm cannon to meet its high rate of fire performance requirements. The actively cooled cannon includes both integral mid-wall cooling of the barrel's chamber region, and outer surface cooling for the remaining length of the barrel. A thermal study was conducted to better understand the thermal performance characteristics of the actively cooled 155mm XM297 barrel under severe firing conditions. Thermal calculations were made using the FDHEAT gun tube heat transfer model which was modified to include an active cooling capability. The FDHEAT program models the effects of barrel heating due to round firing, radial and axial conduction within the barrel wall, convective and radiative cooling, and heat removal by the active cooling system. The study identified an optimum radiator size for the cannon and also showed that, compared to an un-cooled barrel, an actively cooled cannon has superior performance characteristics for firing engagements involving multiple, high rate of fire missions.

15. SUBJECT TERMS

Thermal studies, 155MM XM297 howitzer, FDHEAT heat transfer model

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	U	10	19b. TELEPHONE NUMBER *(Include area code)*

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INTRODUCTION

In order for the Crusader Weapons System to safely meet its multi-mission performance objectives, it will be necessary to employ an active cooling system on its main armament, the 155mm XM297 cannon. A mid-wall cooling system, involving a cooling fluid, was identified by an Army study in 1993 to be the most effective means of cooling artillery cannon that have high rate of fire performance requirements (ref 1). Without active cooling, the buildup of heat in the barrel at the end of one or two high rate of fire missions, would prevent, for safety reasons, the firing of subsequent high rate of fire missions.

Two of the most serious safety concerns during the operation of a hot weapon are propellant cook-off and projectile exudation. Propellant cook-off occurs when heat from the barrel causes a premature, unintended, ignition of the propellant. Projectile exudation occurs when heat from barrel causes the explosive to melt, expand, and exude out of the warhead, most commonly through the fuze threads. Both of these issues become a major concern when there is a misfire event and the charge and projectile remain in the chamber for relatively long periods of time while corrective measures are taken. In order for safe misfire procedures to be developed, it is necessary to identify the minimum time required to produce a propellant cook-off or projectile exudation event. Although propellant cook-off and projectile exudation are both time and temperature phenomena, propellant cook-off has the potential to occur more rapidly due to the fact that the charge, unlike the explosive which is shielded to some degree by the warhead shell, is in direct contact with the hot chamber surface. The active cooling system used on the cannon provides the means for maintaining cannon temperatures at acceptable levels such that the weapon can safely operate during a multi-mission scenario.

The benefits of the active cooling system employed on the XM297 barrel are not readily apparent if only a single high rate of fire mission is considered. This is because the cooling fluid flowing at the mid-wall location of the flutes does not have sufficient time available to affect a significant reduction in the chamber surface temperature during a single, high rate of fire, mission. For example, during a 30 round mission at 10 rounds per minute, the active cooling system has just under 3 minutes to affect the chamber surface temperature at the time round 30 is loaded. Of the 3 minutes available, some time is required for the heat from each round to travel from the chamber surface to the cooling flute position at the mid-wall. Additional time is required for the chamber surface material to “feel” the affects of the cooled material around the flutes. From a heat removal perspective, a more optimum location for the cooling flutes would be closer to the chamber surface, but the negative impact on fatigue life associated with moving the flutes inward would need to be weighed against overall system performance objectives.

The benefits of using an active cooling system are readily apparent when the weapon is employed during a multi-mission engagement where there is a sufficient time period between missions, such as that available during a survivability move, to remove the heat received by the cannon during each mission. For this situation, the XM297 actively cooled barrel has superior performance capability when compared to a similar cannon design that does not employ an active cooling system.

HEAT TRANSFER MODEL

The FDHEAT model was used to calculate barrel and coolant temperatures during a firing engagement involving two 43 round mission. Relevant model inputs are as follows:

Barrel Data: The 155mm XM297 actively cooled barrel is 8392mm (330 inches) long. The barrel model uses 47 axial stations (approximately 182mm (7.17inches) apart) with 39 nodes through the thickness at each of these stations. The model includes a 0.1016mm (0.004 inches) thick chrome bore coating. The thermal properties of both the chrome coating and steel base material are considered to be functions of temperature. The initial barrel temperature is assumed to be $120\ ^{o}\mathrm{F}$. The exterior boundary conditions of the barrel are assumed to be natural convection and radiation using a surface emissivity of 0.8.

Firing Scenario: Since one goal of this study is to evaluate the thermal performance characteristics of the barrel for a multi-mission environment, a 2 mission firing scenario will be considered. Although the vehicle can hold 60 projectiles, the charge capacity on board the vehicle will be at 72% of full charge, meaning that a maximum of $0.72 \times 60 = 43$ full zone 6 charges can be fired prior to vehicle re-supply (the cannon could also fire 51 zone 5 charges or 60 zone 4 charges). For this study, the firing scenario modeled involves 2 identical 43 round missions fired back to back where each mission is given by: 30 rounds (zone 6) at 10 rounds per minute + 13 rounds (zone 6) at 3 rounds per minute + 12 minute re-supply/survivability move.

Active Cooling Model Parameters: The active cooling system model was developed assuming that all the coolant resides in 3 regions: region 1 – the barrel, region 2- between the end of the barrel and the midpoint of the radiator, and region 3 – between the midpoint of the radiator and the entrance of the barrel. All heat loss from the cooling fluid is assumed to occur via the radiator. The cooling fluid in the barrel (region 1) is distributed into 46 segments, where each segment of fluid can take on a different temperature. The 46 fluid segments consist of 19 segments in the fluted region and 27 annular segments for the outer surface cooling region. All the fluid that exists between the end of the barrel and the midpoint of the radiator (region 2) is assumed to be lumped into Reservoir A. Similarly, all the coolant that exists between the midpoint of the radiator and the entrance to the barrel (region 3) is assumed to be lumped into Reservoir B. Consistent with a lumped model approach, the temperature within each reservoir is assumed to be uniform at any particular point in time.

Since FDHEAT is an axisymmetric model, it was not possible to precisely model the flute geometry and its associated 2-D temperature distribution in the r-theta plane. However, a reasonable approximation to the heat extraction from the barrel at a cooling flute was obtained by discretizing the geometry with 3 nodes across a flute and removing an appropriate amount of heat from the node located at the center of the flute. The rate of heat removal at this node was based on the actual flute geometry, the local coolant temperature, and a local film coefficient based on the fluid flow parameters. This approach was calibrated using results from a precise 2-D finite element model of a barrel section including the actual flute geometry, with the calibration factor for the FDHEAT axisymmetric model being an effective flute perimeter slightly lower than the actual flute perimeter.

The cooling fluid is assumed to be a 50/50 mixture of ethylene glycol and water. The following set of parameters defines the important cooling model input data:

- Cooling Flutes: The actual barrel geometry has 24 equally spaced (around the circumference) semi-circular cross section flutes, each of 0.5 inch diameter. The flutes are machined into the outer surface of a liner having an outer diameter of 9 inches. The model incorporates this geometry information into the calculation using the approach discussed above.

- Cooling Fluid Flow Rate = 50 GPM

- Initial Temperature of the Cooling Fluid: $120\ ^{o}\mathrm{F}$

- Ambient Air Temperature: $120\ ^{o}\mathrm{F}$

- Capacity Factor of Radiator: three cases are considered, 45, 65, & 85 Btu/min-$^{o}\mathrm{F}$

- Volume of Reservoir A: 5 gallons – In the model's idealization, this is the volume of fluid that exists between the end of the barrel and the mid point of the radiator.

- Volume of Reservoir B: 5 gallons - In the model's idealization this is the volume of fluid that exists between the midpoint of the radiator and the entrance to the barrel.

- Film Coefficient used in Flute Section – This value is calculated using the Dittus-Boelter correlation for turbulent heat transfer in smooth tubes, and is the minimum value expected during the scenario = 4278 $\mathrm{W/m^2 \cdot K}$.

- Film Coefficient used in O.D. Cooling Section - This value is also calculated using the Dittus-Boelter correlation for turbulent heat transfer in smooth tubes, and is the minimum value expected during the scenario = 2167 $\mathrm{W/m^2 \cdot K}$.

DISCUSSION OF RESULTS

Figure 1 shows a plot of the load time bore temperature (LTBT) as a function of round number for the 86 round scenario outlined above. The LTBT is the temperature at the bore when the charge is loaded and is an important temperature to consider when evaluating propellant cook-off and projectile exudation potential. The LTBT plotted is that at the origin of rifling (O.R.) which is at a position of 1157 mm (45.6 inches) from the rear face of the tube (RFT). Each round is assumed to be loaded 1.2 seconds before it will be fired. This 1.2 second load time was agreed upon by Prime Contractor (United Defense Limited Partnership) and Benet personnel to be the earliest, and therefore most severe, time a round could be loaded into the barrel. The plot shows 4 curves, including 1 curve for no active cooling, and 3 active cooling curves for radiator capacity factors of 45, 65, and 85 Btu/min-^{o}F. The plot clearly shows the effectiveness of the active cooling system at reducing barrel temperatures. During Mission 2 (rounds 44 – 86) the LTBT's of the actively cooled barrel are approximately 150 ^{o}F below the LTBT's of the un-cooled barrel. Although there is a small benefit in employing the active cooling system during the first 43 round mission, there is a very significant reduction in LTBT, upwards of 150 ^{o}F, during the second 43 round mission.

If we assume that $400\ ^{o}F$ is a critical bore temperature (CBT), indicative of propellant cookoff potential, the three curves for active cooling show that no propellant cook-off problem is expected during the first 43 round mission. Without active cooling, the LTBT exceeds the CBT for round 27. For the second 43 round mission (rounds 44 through 86), the plot shows that the CBT is exceeded at round 48 (no active cooling), round 63 (CF=45 Btu/min-^{o}F), round 68 (CF=65 Btu/min-^{o}F), round 72 (CF=85 Btu/min-^{o}F). It should be mentioned that for a CF=85 Btu/min-^{o}F, the LTBT is only $1.6\ ^{o}F$ above the CBT for round 72, indicating that a capacity factor slightly larger than this would be the minimum size radiator to keep the LTBT below the CBT throughout the entire 86 round scenario. In addition, for a capacity factor of CF=85 Btu/min-^{o}F, the soak out temperature at the end of the second 12 min re-supply time is nearly the same as that at the end of the first 12 min re-supply time down, indicating a steady state cool down temperature, and an optimal radiator size.

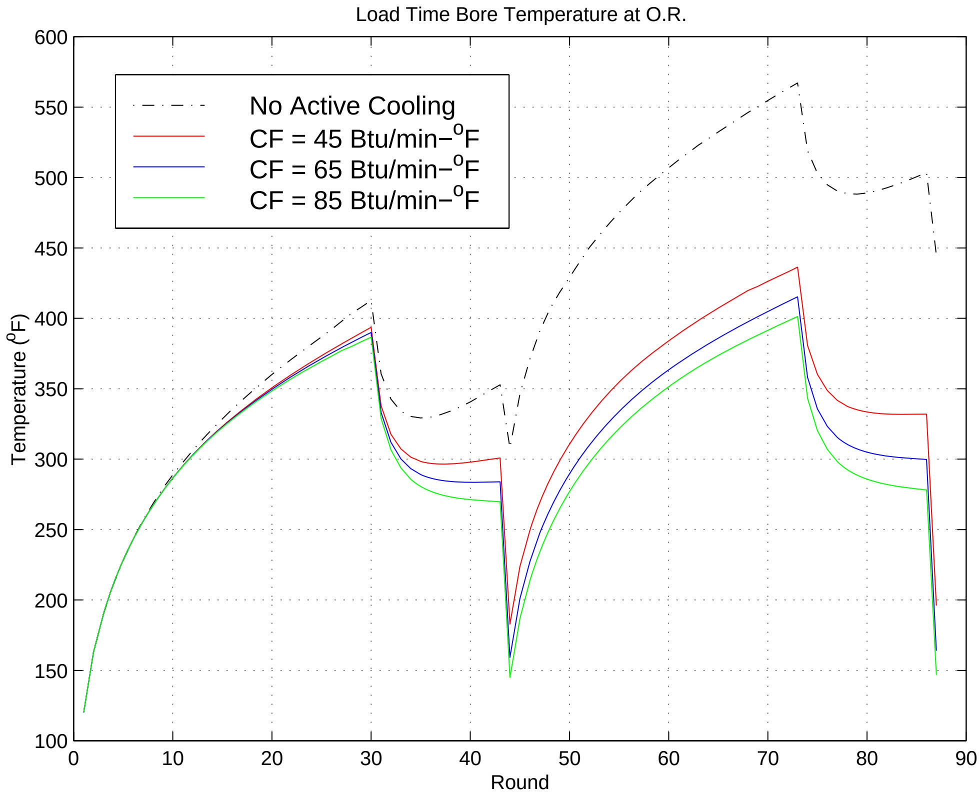

Figure 1. Impact of active cooling and radiator size on load time bore temperature.

Figure 2 shows 4 separate plots each giving the variation of heat added to the thermal sinks of the active cooling system. Plot 1 shows the variation of $Q_{fluidgun}$ throughout the scenario, where $Q_{fluidgun}$ is the heat that has been added to the fluid contained within the cooling flutes and the cooling jacket. Plot 2 shows the variation of Q_{resA} throughout the scenario, where Q_{resA} is the heat that has been added to reservoir A in the model. Plot 3 shows the variation of Q_{rad} throughout the scenario, where Q_{rad} is the total heat that has been removed by the radiator. Plot 4 shows the variation of Q_{resB} throughout the scenario, where Q_{resB} is the heat that has been added to reservoir B in the model.

Figure 3 also gives 4 separate plots showing total heat removed from the barrel and cooling fluid temperatures. Plot 1 shows the variation of Q_{remgun} throughout the scenario, where Q_{remgun} is the total heat that has been removed from the barrel by the active cooling system. Plot 2 shows the variation of T_{Inlet} throughout the scenario, where T_{Inlet} is the temperature of the cooling fluid entering the barrel. Plot 3 shows the variation of T_{Exit} throughout the scenario, where T_{Exit} is the temperature of the cooling fluid exiting the barrel. Plot 4 shows the variation of the difference between T_{Exit} and T_{Inlet} throughout the scenario. The curves in plots 2 and 3 show that the coolant temperatures can get above $250\ ^{o}F$ and pose a coolant boiling problem. The problem of coolant boiling would most certainly exist when CF=45 Btu/min-^{o}F where the peak T_{Exit} is approximately 300 ^{o}F. The coolant boiling problem could be mitigated by adding cooling fluid to the system, thereby creating a greater thermal mass to dump heat into.

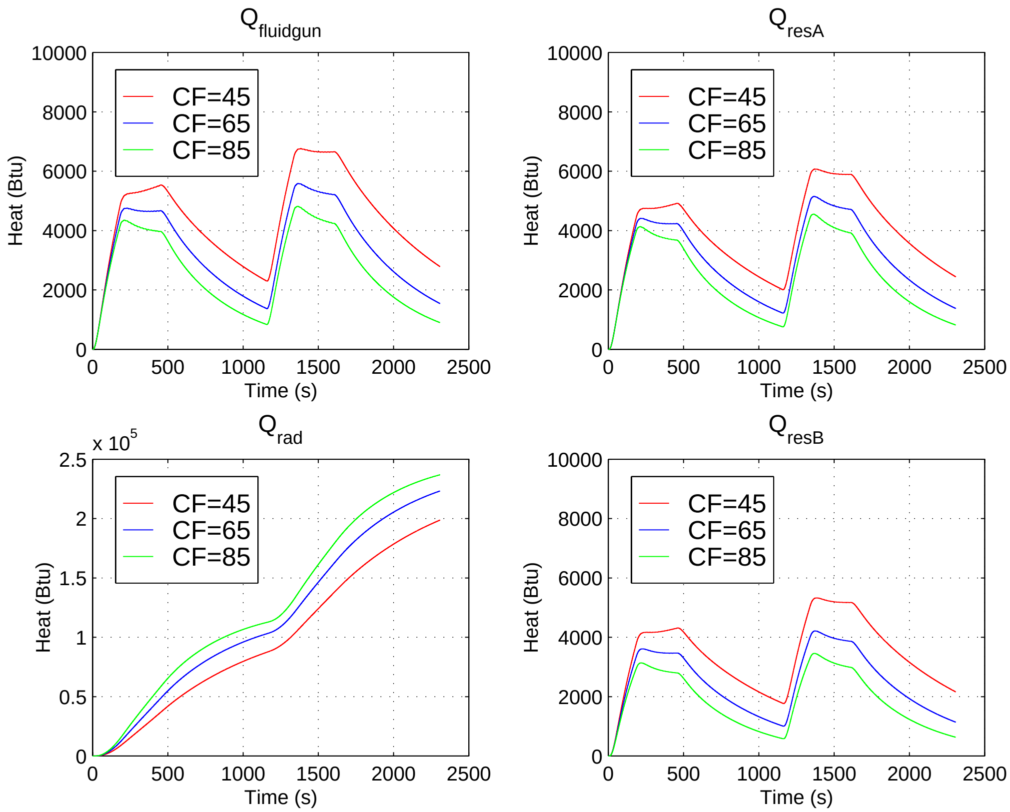

Figure 2. Cooling fluid heat levels for reservoir A & B, and gun fluid, along with heat removed by radiator.

In the event of a misfire, it is important to know how much time the crew has available to take corrective action before the likelihood of propellant cook-off and/or projectile exudation becomes unacceptably high. Previous work by the Army (refs 2, 3, 4) has produced practical information, including useful experimental data, for characterizing propellant cook-off and projectile exudation times in 155mm cannon. This experimental data, coupled with analytical predictions of barrel temperatures, provide a viable approach for defining safe misfire procedures for the weapon.

Figure 4 gives important barrel temperature predictions associated with the 5 minute time period following a misfire of round 30 for an actively cooled barrel using a radiator size of CF=45 Btu/min-^{o}F. The time average temperature is given in the plot and, for our purposes, is defined as the integral average of bore temperature at the O.R. once the charge is loaded (time =0 is when round 30 is loaded). Two time average temperature curves are shown in the plot and correspond to the cases where 1) active cooling remains on during the misfire event and 2) where the active cooling system has failed just as round 30 has been loaded. Although the charge will never come into contact with the barrel at the O.R. axial position, the temperature at this location is a convenient conservative estimate for the maximum temperature the charge could see, since chamber temperatures are lower than O.R. temperatures. As is seen in the plot, failure of the active cooling system at the start of the misfire event does not have a significant impact during the 5 minute time frame. The graph does show that the two time average temperature curves are well below the propellant cook-off curve, indicating a safe condition in regards to propellant cook-off during the 5 minute time frame.

The two time average temperature curves of figure 4 are also both below the exudation curve for the M107 projectile conditioned at 125 $^{\circ}F$. However, for the M549A1 projectile conditioned at 145 $^{\circ}F$, the exudation curve falls below both time average temperature curves somewhere between the 4.5 and 5 minute time period. This would indicate that the crew would have less than 5 minutes to take corrective action, and potentially evacuate the vehicle and move away from the weapon, prior to the onset of the exudation process.

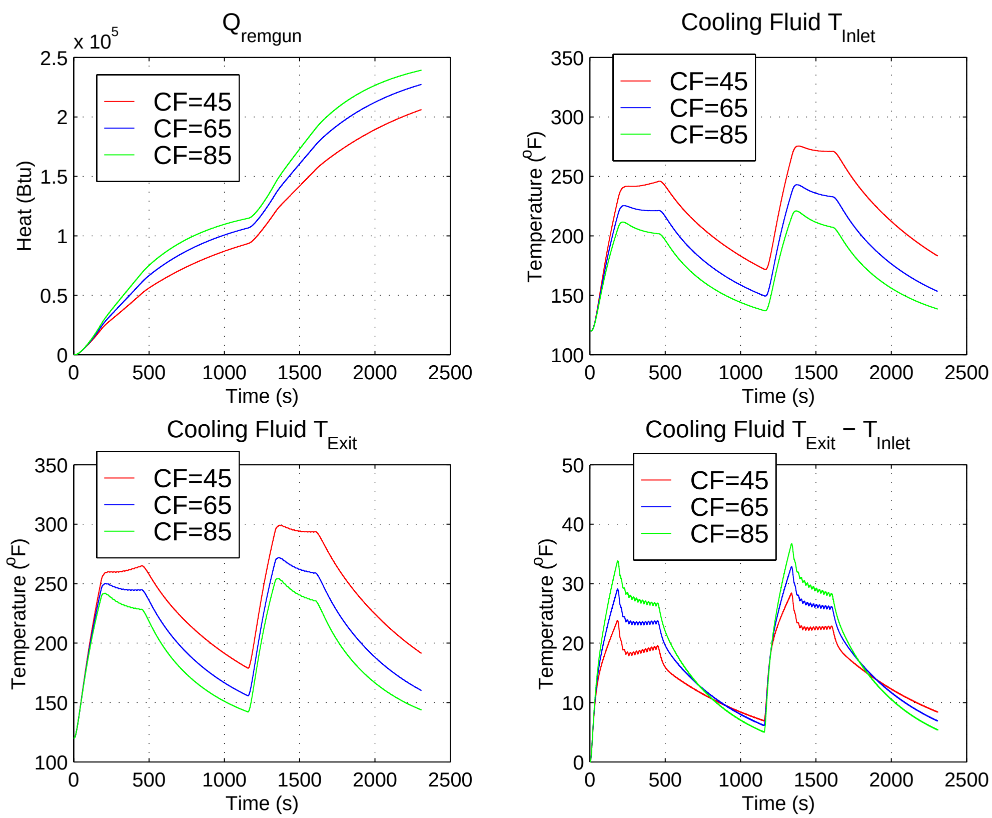

Figure 3. Total heat removed from gun, and cooling fluid inlet temperature, outlet temperature, and outlet-inlet differential temperature.

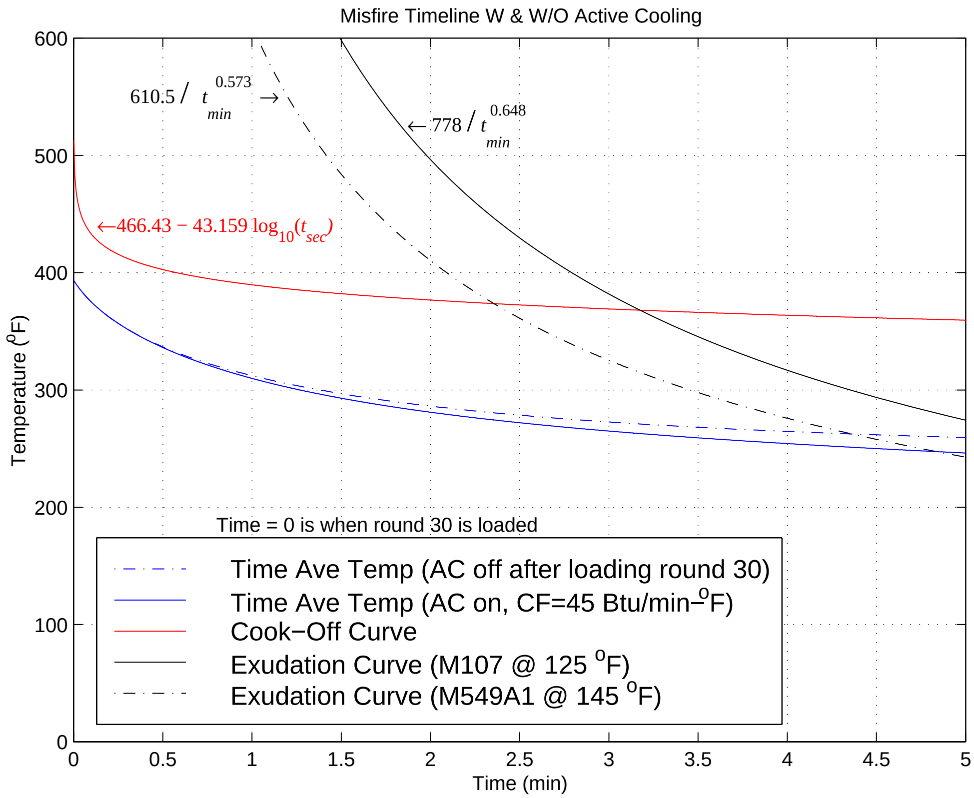

Figure 4. Important barrel, propellant, and projectile temperatures associated with a round 30 misfire event for an actively cooled barrel using a radiator size of CF=45 Btu/min-^{o}F radiator.

CONCLUSIONS

A thermal study was performed to predict barrel and cooling fluid temperatures for the 155mm XM297 actively cooled barrel during a two mission engagement. The two missions were fired back to back and each was given by: 30 rounds (zone 6) at 10 rounds per minute + 13 rounds (zone 6) at 3 rounds per minute + 12 minute re-supply/survivability move. The investigation studied the impact of radiator size (capacity factors of 45, 65, & 85 Btu/min-^{o}F were modeled) on the thermal performance of the cannon. The important results of the analysis include:

- The peak load time bore temperature during each 43 round mission occurs when the last round at the maximum firing rate (round 30) is loaded.

- All three radiator sizes (CF=45, 65, and 85 Btu/min-^{o}F) provide enough cooling to keep the load time bore temperature below 400 ^{o}F during the first 43 rounds of mission 1. Without active cooling, the load time bore temperature during mission 1 would exceed 400 ^{o}F for round 27.

- For a radiator capacity factor of 45 Btu/min-^{o}F, cooling fluid exit temperatures are predicted to exceed 250 ^{o}F during mission 1, and reach 300 ^{o}F during mission 2, indicating a potential problem with fluid boiling. Cooling fluid exit temperatures are predicted to exceed 250 ^{o}F during mission 2 for all three radiator sizes investigated.

- For a cooling system having a radiator capacity factor of 45 Btu/min-^{o}F, and a M549A1 projectile conditioned at 145 ^{o}F, a misfire of round 30 during mission 1 would leave approximately 4.9 minutes (Active Cooling ON) and 4.4 minutes (Active Cooling OFF) of time for corrective measures to be taken prior to the onset of exudation.

- Assuming a critical bore temperature of 400^{o}F, a radiator size of CF= 85 Btu/min-^{o}F appears to be near optimum in that, 1) it keeps peak mission temperatures near (with in 2^{o}F), or below the 400 ^{o}F critical level, and 2) it is capable of extracting sufficient heat from the barrel during a 12 minute survivability such that subsequent 43 round missions can be safely fired.

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