(2)

TECHNICAL REPORT BRL-TR-3300

BRL

GUN TUBE HEATING

PAUL J. CONROY

DECEMBER 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

UNCLASSIFIED

REPORT DOCUMENT PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
December 1991

3. REPORT TYPE AND DATES COVERED
Final, Feb 90 - Dec 90

4. TITLE AND SUBTITLE
Gun Tube Heating

5. FUNDING NUMBERS
PR: 1L161102AH43

6. AUTHOR(S)
Paul J. Conroy

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

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
USA Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
BRL-TR-3300

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release - Distribution is Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A one-dimensional gun tube heating model has been coupled to an interior ballistic code. The ballistic code models the two-phase interior ballistic cycle and provides intensive and extensive properties throughout the cycle. At the inner wall of the gun tube, a turbulent boundary layer correlation is used to compute the heat flux to the wall. This correlation incorporates the compressibility of the flow in calculating the Reynolds number and skin friction coefficient. Within the tube wall, the one-dimensional radial heat conduction equation is solved.

The model is used to investigate gun tube thermal profiles over multiple firings with variable firing rates for two different weapons. Results are used to describe the transient heating of the gun tube over a long period of continuous firing. Potential firing scenarios are presented and discussed. Numerical results are compared to experimental work performed in the past. An extensive reference list is also included.

14. SUBJECT TERMS
interior ballistics, barrel heating, heat transfer, heat conduction, thermal management

15. NUMBER OF PAGES
32

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

UNCLASSIFIED

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

INTENTIONALLY LEFT BLANK.

ACKNOWLEDGMENTS

I wish to thank Dr. George Keller and Mr. Albert Horst for providing me the atmosphere, tools, and time to do this work. Also, I would like to express my appreciation to Satish Chandra of Veritay Corporation for many discussions on the heat conduction code and Hugh McEiroy and his group at Olin Corporation for the deterred ball propellant chemical data.

INTENTIONALLY LEFT BLANK.

1. INTRODUCTION

The development of the Advanced Field Artillery System (AFAS), with its high rate-of-fire requirement, has refocussed interest in the thermal management of gun tubes, which includes consideration of cook-off of propellants and/or projectiles, tank gun accuracy, barrel wear and erosion, and thermal signature. In the past, investigators have measured gun tube thermal profiles for various weapons and they have employed heat conduction codes to model the gun tube heating (see references). The lack of appropriate boundary conditions at the inner wall surface compelled researchers to use ingenious approximation techniques (Rapp 1990) and curve fitting to produce a history of tube heating during the interior ballistic cycle. One method to produce the inner wall boundary condition was to use thermocouple measurements to compute the heat input to the gun tube along its length. These measurements provided an experimental axial heat input profile which then was used to model other similar systems. This was accomplished by modifying the input profile using a ratio based on the total energy of the charge. This type of model neglects the mechanisms which lead to the development of the thermal profile and, thus, does not allow the model to make predictions for a weapons system significantly different from that used for the model calibration.

Barrel heating is due to forced convection of hot combustion gases, the projectile's sliding friction, and obturator galling. In addition, there may be a significant radiative contribution to the heating in the region of the breech (Leech 1972). Plastic obturators have reduced the galling and sliding friction component considerably. A one-dimensional interior ballistic (IB) code can supply the information which is necessary for computing the interior boundary condition at the wall, given a proper convective coefficient, which must include the effects of pressure, gas velocity, and compressibility of the combustion products both spatially and temporally.

Recently, Chandra (1990) and Chandra and Fisher (1989) have applied an IB code (Gough 1980) to barrel heating. This work utilized the results from IB codes to provide an appropriate inner wall boundary condition to the heat transfer/conduction routine.

2. ANALYTICAL DESCRIPTION

The analysis used by Chandra and Fisher (1990) is presented below. It incorporates a compressible turbulent boundary layer with an arbitrary pressure gradient model (Stratford and Beavers 1961). An equivalent flat-plate length is calculated

$$\chi = \frac{\sum_{1}^{z}(P_z \Delta Z)}{P_z} \tag{1}$$

using a Mach number weighted pressure

$$P_z = M^4\left[1 - \frac{1}{2}(\gamma - 1)M^2\right]^{\frac{(3\gamma-1)}{2(\gamma-1)}} \tag{2}$$

where

$$M = \frac{u}{\sqrt{\gamma R_g T_g}} . \tag{3}$$

The compressible Reynolds number is then computed as

$$Re^* = \frac{\chi \rho u}{\mu^*} , \tag{4}$$

with the viscosity, $\mu^* = \nu^* \cdot \rho$, computed using a modified form of Sutherland's law (Schlichting 1979)

$$\nu^* = \frac{1.492 \cdot 10^{-6} T^{*1.5}}{145.8 + T^*} , \tag{5}$$

having determined the static temperature, T^*, from the reference enthalpy (Chandra and Fisher 1989). The compressible skin friction given by (Carpenter and Klavins 1965)

$$\frac{c_f}{c_{fi}} = [1 + (\gamma - 1)^2 M^2]^{-0.6} \tag{6}$$

is incorporated with Re^*, C_p, μ^*, and χ to create the heat transfer correlation (Chandra and Fisher 1989)

$$Q_w = \left[0.037\frac{\mu^*}{\chi}Re^{*0.8}\frac{C_f}{C_{fi}}C_p(T_g - T_w)\right] . \tag{7}$$

Thus, the heat transfer coefficient is

$$h = 0.037\frac{\mu^*}{\chi}Re^{*0.8}\frac{C_f}{C_{fi}}C_p . \tag{8}$$

This system of equations has been shown to work fairly well for short periods of firing (Talley 1989). Due to the boundary at the breech of the gun tube, this velocity-dependent correlation fails to physically represent the rear portion of the gun tube. To correct for this, a turbulent velocity has been introduced into the system. It effectively raises the magnitude of the local gas velocity by using a turbulent Mach number of 0.1 (Chandra 1990).

Leech (1972) has investigated the effects of thermal radiation inside the chamber using a participating medium model. His results indicate that within a few inches from the breech the significant mode of heat transfer is radiation, while farther down the chamber the particles in the developing boundary layer absorb most of the radiation. The incorporation of a particle-laden, absorbing boundary layer is a possible addition to the future version of the model which may reduce the reliance on the turbulent convection and increase the physical accuracy of the model.

The method used for solving for the tube temperature utilizes the one-dimensional radial heat conduction equation

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{9}$$

with the internal boundary condition given as a specified heat flux

$$-k\frac{\partial T}{\partial r} = h(T_g - T_w) \tag{10}$$

and an insulated external boundary. The physical properties of the gun steel are treated as constants throughout the calculation; however, the properties presented by the Mechanical Properties Data Center (Belfour Stulen Inc. 1973) show a reduction in the conductivity and a sharp spike at 1,400 K in the specific heat with an increase in temperature.

The equations are explicitly computed using central differences and the grid has been generated using a geometric factor to account for the radial geometry and the fine grid necessary at the inner wall. An allowance has been made for various materials, such as chrome, to be included in the tube.

The model used in this paper incorporates the one-dimensional NOVA (Gough 1980) IB code to provide the necessary state variables for the calculation of the convective heat transfer coefficient described previously. Typically, the duration of an IB cycle is on the order of 50 ms or less; however, for heat transfer studies, the IB cycle is assumed to be from the time of the first round until the barrel reaches ambient temperature or until the next round is fired. The requirement on the IB code to produce the necessary state variables after shot exit for up to six orders of magnitude in time greater than a typical IB calculation necessitates the use of a open muzzle boundary condition after shot exit. Gough (1980) uses an isentropic (Eq. 11)

$$\dot{M} = A_{ext}\frac{\left[\frac{2g_o}{\gamma-1} - (\gamma R_g T_o)\left[1 - \left(\frac{P}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right] + 2g_o b P_o\left[1 - \frac{P}{P_o}\right]\right]^{\frac{1}{2}}}{\frac{R_g T_o}{P_o}\left(\frac{P_o}{P}\right)^{\frac{1}{\gamma}} + b} \tag{11}$$

or choked (Eq. 12)

$$\dot{M} = A_* \frac{P_o}{\sqrt{T_o}} \sqrt{\frac{\gamma g_o}{R_g}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}} \; [1. - 0.224y + 0.104y^2] \qquad (12)$$

mass flux calculation for either subsonic or supersonic exit flow, respectively, thus allowing the gas flow out the gun muzzle to continue to empty the gun tube. This allows the IB code to compute the thermodynamic expansion cooling, rather than using a linear interpolation to ambient conditions. This calculation can be maintained for about 80 ms, by which time the breech pressure has reached ambient and the NOVA code stops. The other state variables are then brought to ambient through either a conservative linear interpolation or a special exponential function which reduces the state variables to ambient after a short amount of time (about 1–2 s) with respect to the cycle time. The exponential decay function resulted in the prediction of approximately 3% lower inner wall temperatures after 30 rounds at 12 rounds per minute are fired in the 155-mm M199 cannon, using an M203 charge. This implies that a conservative approach will trade a small increase in wall temperature for confidence that the experimental temperature will not exceed the computed values.

Figure 1 presents the flow chart of a conduction calculation using the Chandra and Fisher model. The state variables are stored temporally and spatially in the HTEMP.OUT file, thus creating an IB "signature" for a specific charge. This signature can then be utilized to study various firing scenarios assuming that the feedback to the IB calculation is small. The heat transfer and conduction code XB is used to make various scenario studies with the signature file as an input along with the desired scenario defined in the input deck XB.IN.

The output of this IB code for one round is then used in a separate uncoupled interpolation and heat transfer/conduction routine. Given the history of one round, this stand-alone routine allows the user to define various firing scenarios assuming no feedback to the next charge by the rising tube temperature.

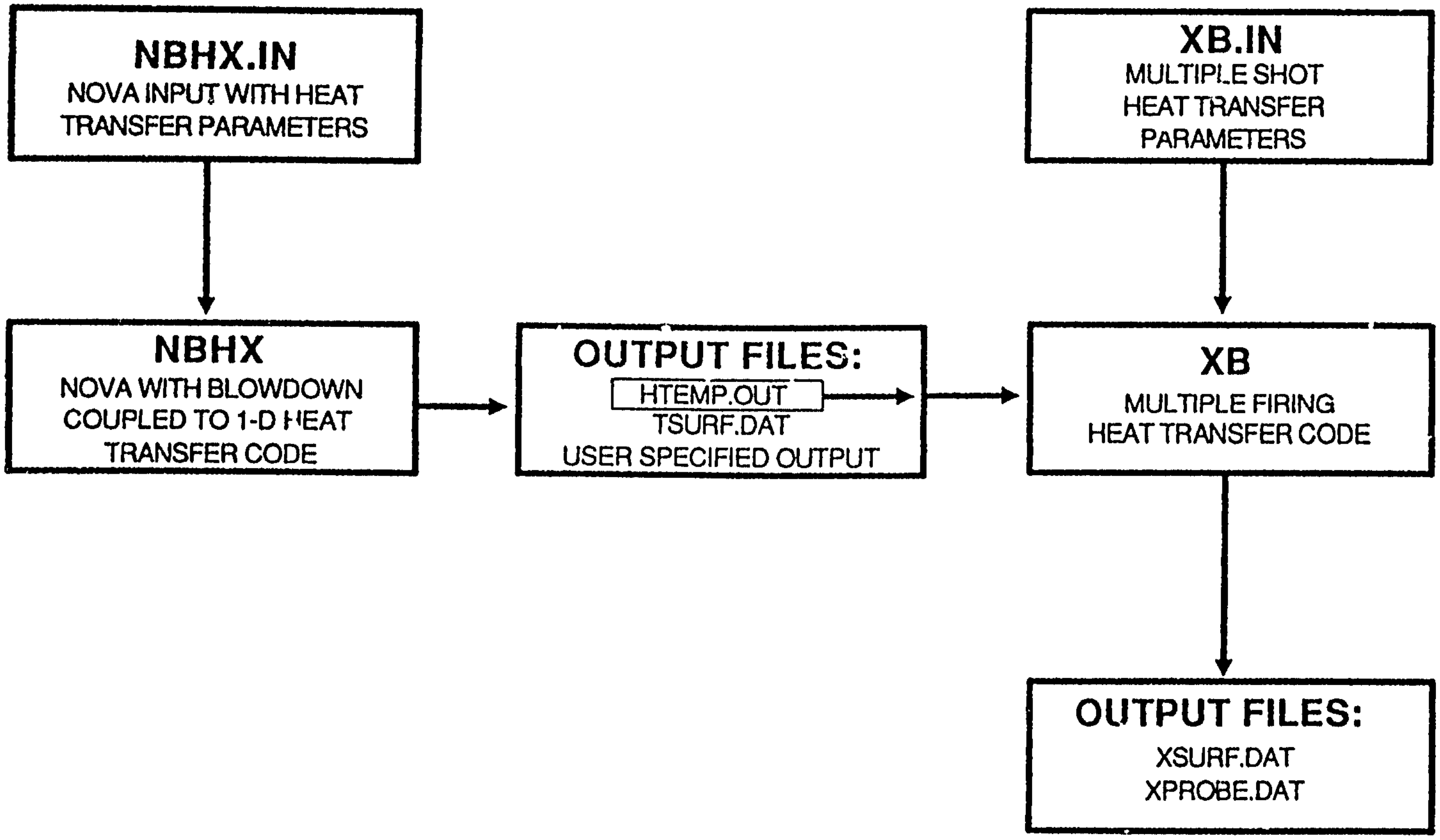


Figure 1. <u>Heat Transfer Code Flow Chart</u>.

3. NUMERICAL CALCULATIONS

There are two weapons systems for which experimental heating data exist; we chose to perform this study by modeling these two systems. One system involves the use of the M203 charge in a 155-mm howitzer; the other is a 27-mm caseless Olin round. The 1979 Thermal Warning Device (TWD) study by Vottis and Hasenbein (1979) provides the 155-mm data. The 27-mm charge (Williams 1972) presents a rapid, uniform rate of fire.

4. DISCUSSION

The M203 experimental data are presented in the TWD study in many forms with various rates of fire over periods of time. The scenario of 6 rounds per minute for 3 min followed by 3 rounds per minute continuous has been modeled and presented in Figure 2. A comparison of the experimental and numerical outer tube wall temperature history shown in Figure 3 has been made at the origin of rifling. This comparison reveals the importance of an external heat transfer coefficient if the calculation is to cover long periods of firing, for the temperatures keep rising while the experimental data level off. The temperature rise rate for the numerical calculation is about 1.8 times that of the experimental data. This causes the data presented here to be incorrect quantitatively, but qualitatively useful. There is a significant lag in the response of the outer tube wall from the first round for the numerical computations which reflects the amount of time for the heat to diffuse to the outer wall.

Two other scenarios performed on the M203 charge were 6 vs. 12 rounds per minute for 5 minutes and then 3 rounds minute thereafter for 100 rounds. The temperature was recorded at the origin of rifling. The results are presented for the inner and outer wall surface temperatures in Figures 4 and 5. The differences between 6 and 12 rounds per minute reveal themselves in the radial thermal profile of the gun tube over a period of time. Figure 6 shows the radial profile of the gun tube for three situations: 12 rounds per minute for 30 rounds and 6 rounds per minute for 15 and 30 rounds. What is seen between the two scenarios is that the tube's constant diffusivity does not transport the heat into the barrel as rapidly when the heat-flux rate at the inner wall is higher. This is true because a thermal barrier develops at the inner wall which prevents as much heat transfer to occur per round as that of the lower firing rate scenario. This shows that given a fixed number of rounds fired, the heat capacity of

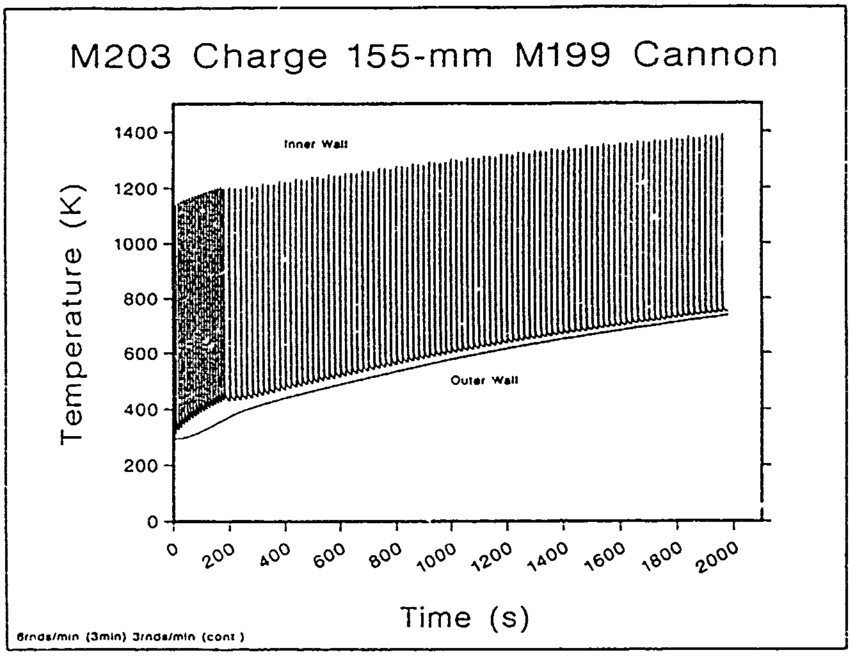


Figure 2. Numerical Gun Tube Temperature Calculation Results at Both the Inner and Outer Walls for the M203 Charge in a 155-mm Howitzer at the Origin of Rifling for 6 Rounds Per Minute for 3 Minutes Followed by 3 Rounds Per Minute Continuous.

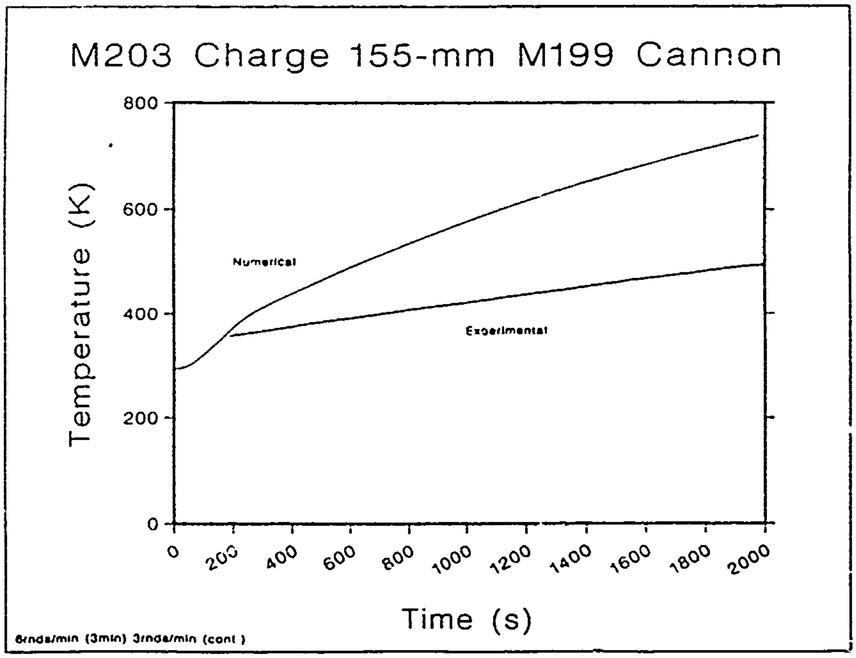


Figure 3. Experimental vs. Numerical Results for the Outer Gun Tube Temperature at the Origin of Rifling for the M203 Charge in a 155-mm Howitzer, Given the Firing Rate in Figure 2.

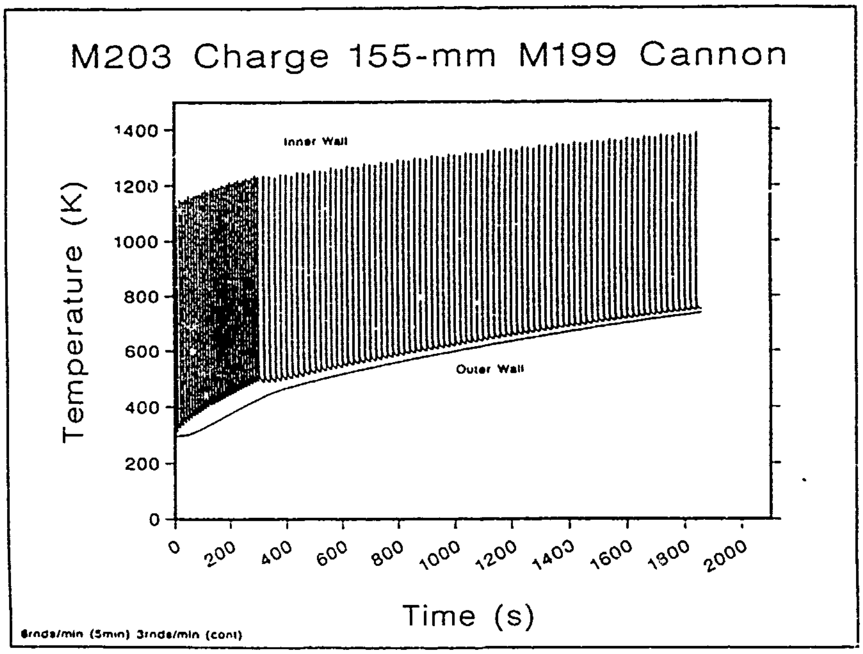


Figure 4. Numerical Gun Tube Temperature Calculation Results at Both the Inner and Outer Walls for the M203 Charge in a 155-mm Howitzer at the Origin of Rifling for 6 Rounds Per Minute for 5 Minutes Followed by 3 Rounds Per Minute Continuous.

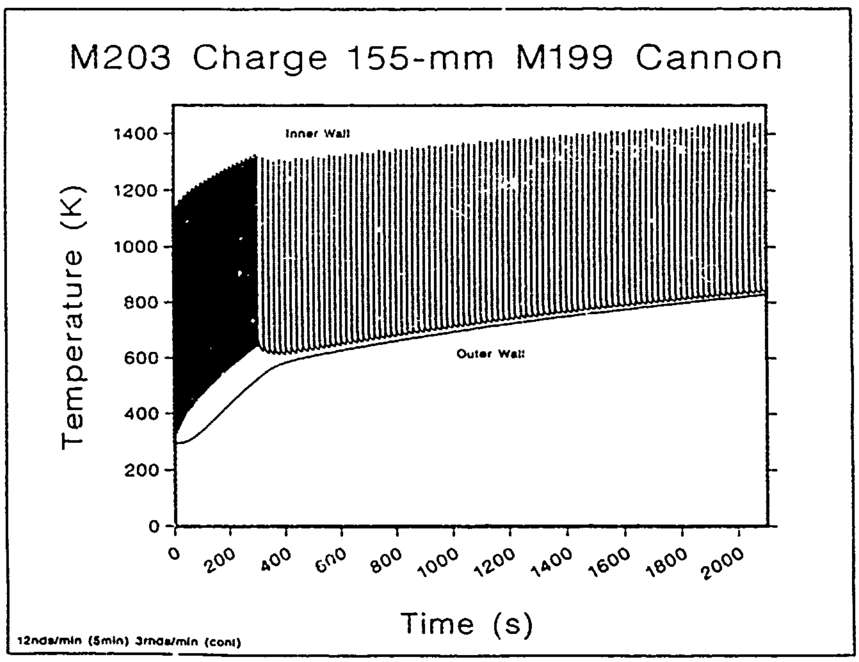


Figure 5. Numerical Gun Tube Temperature Calculation Results at Both the Inner and Outer Walls for the M203 Charge in a 155-mm Howitzer at the Origin of Rifling for 12 Rounds Per Minute for 5 Minutes Followed by 3 Rounds Per Minute Continuous.

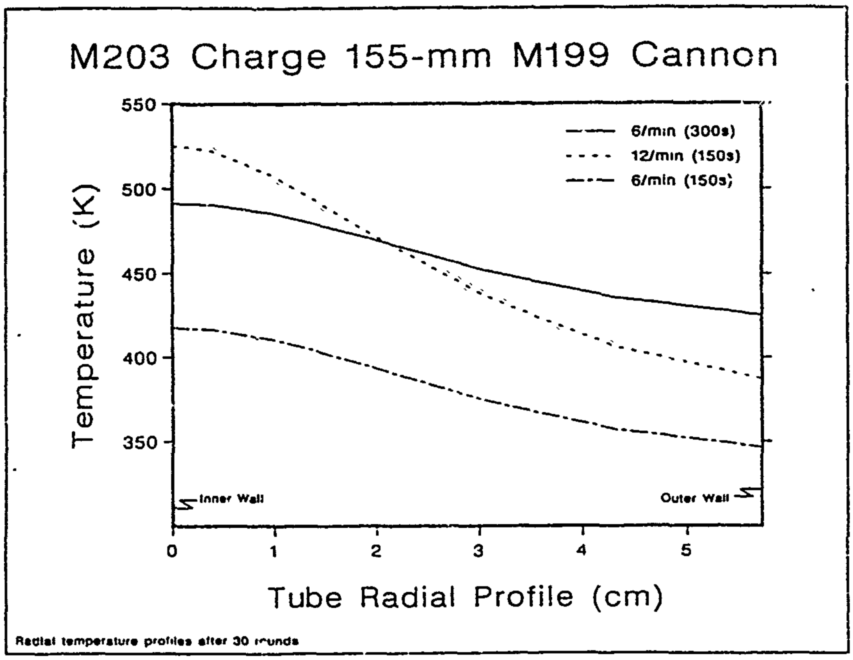


Figure 6. A Comparison of Wall Temperature Profiles for the 12 Rounds Per Minute vs. 6 Rounds Per Minute Scenarios After 30 Rounds and 6 Rounds Per Minute After 18 Rounds.

the tube near the inner wall is used under a relatively higher firing rate to store rather than transfer the energy, thus building a larger difference between the inner and outer wall temperatures (as seen in Figures 4 and 5) from 0 to 350 seconds. This difference decreases rapidly as the firing scenario is changed to the three rounds per minute sustained case, bringing the convection rate down closer to the conduction rate. Thus, after 110 rounds, both the 12 rounds per minute and 6 rounds per minute scenarios have the same thermal profile.

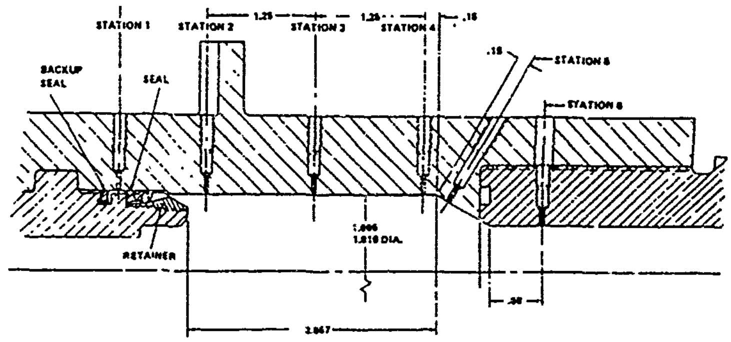
There is a 22.5-s lag in the response of the outer tube wall for the 6 rounds per minute and a 20.75-s lag for the 12 rounds per minute scenario. This reflects the amount of time for a thermal disturbance to propagate to the outer wall. The faster the firing rate, the higher the inner wall surface temperature and the larger the total thermal disturbance, but the rate of propagation does not present itself as a strong function of the firing rate. For linear conduction, the propagation rate is given by (Carslaw and Yaeger 1959)

$$a = \sqrt{\frac{2\omega k}{\rho C_p}} , \qquad (13)$$

with C_p being the specific heat of the barrel. The propagation rate is not so easily traceable analytically for radial systems with time-dependant boundary conditions. However, from the numerical experiment, it appears that a ratio difference of $10^{1/2}$, or about π, exists between the linear propagation function and that of the higher numerical result.

Figure 7 shows the experimental chamber and thermocouple placements for the 27-mm Caseless Automatic Weapon (CAW). The thermocouples were designed and built by Cornell Aeronautical Laboratory and placed between 0.0254 cm and 0.0508 cm away from the inner wall. Typical thermocouple traces are shown in Figure 8. What can be seen in Figure 8 is the convective nature of the heat transfer in that the recorded temperature decreases from the front of the chamber to the breech where the cross flow is small. The stop shoulder location was used for demonstrative modeling, the results of which are presented in Figure 9. The experimental and numerical peak temperatures match well after four rounds. The simulation models the experiment well because the outer barrel wall does not respond during the 3-s burst. There is a lag not numerically represented in the experimental data at the initiation of the burst. This could possibly be due to a small amount of ambient air surrounding the back side of the thermocouple acting as a heat sink, thus lowering the thermocouple's reading until the air became heated.

The rate dependency of the outer wall temperature shows the futility of using a TWD on the outer wall without the gun's recent firing history. A TWD could be very effective without any historical knowledge or tabularized data if it gave the inner tube wall temperature prior to loading.



Station 5 - Stop-Shoulder

Station 4 - Front Chamber

Station 3 - Mid-Chamber

Station 2 - Rear Chamber

Figure 7. Experimental Location of the Thermocouples for the 27-mm CAW Study.

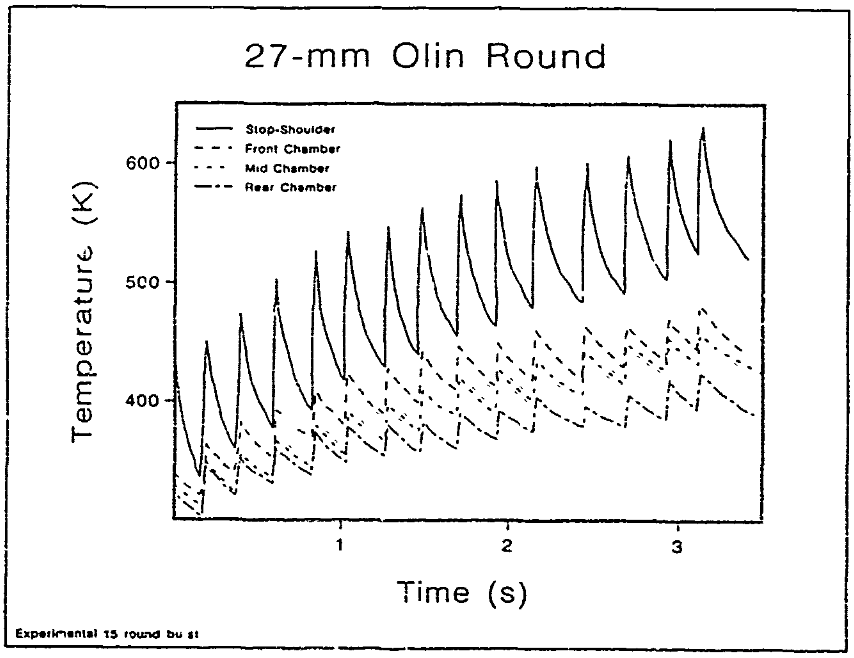


Figure 8. Typical Experimental Thermocouple Traces for the 27-mm CAW Study 0.000254 m (0.01 in) from the Inner Wall.

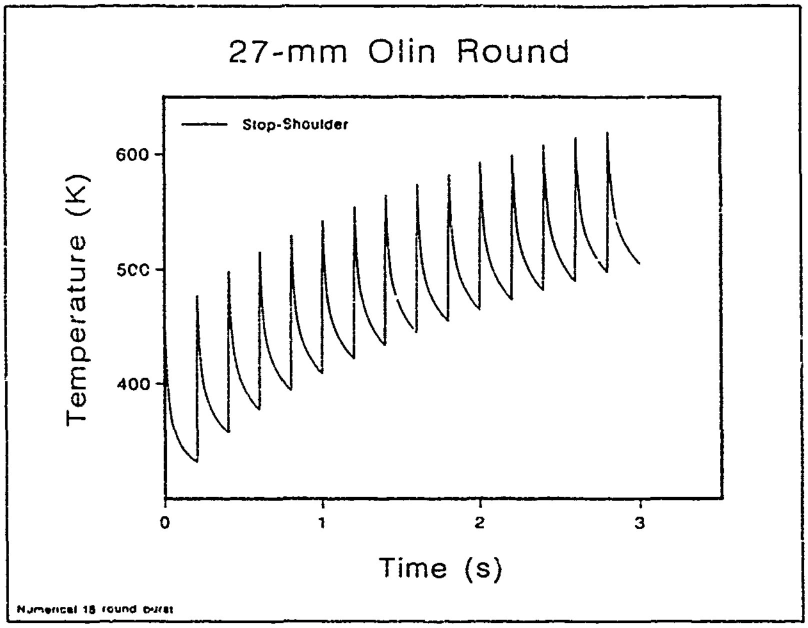


Figure 9. Numerical Results for the 27-mm CAW Study at the Stop Shoulder 0.0900254 m (0.01 in) From the Inner Wall.

5. CONCLUSIONS

A one-dimensional radial heat conduction code has been successfully coupled to a one-dimensional, two-phase flow IB code. The heat conduction code works fairly well during the initial temperature rise in a gun barrel as seen in the 27-mm data. Various scenarios for the 155-mm system qualitatively show the form of the gun tube's thermal profile. The results of the 155-mm study show that external heat transfer is needed if the long-term effects are to be quantitatively modeled.

6. CODE IMPROVEMENTS UNDER IMPLEMENTATION OR CONSIDERATION

The heat conduction analysis is currently being upgraded to a two-dimensional representation with internal radiation and external heat convection and radiation heat transfer models. The conduction and the internal wall heat transfer are being uncoupled to allow temporal and spatial heat convection coefficients and gas temperatures to be computed for use in other conduction codes in the community. Possible revisions include variable physical properties of the material, a more complex participating medium radiation model inside the gun tube, and coupling between the IB code and the heat conduction code for a more physically authentic calculation.

INTENTIONALLY LEFT BLANK.

7. REFERENCES

Anderson, L. W., ---------------. "Numerical Solution of the Nonsteady Boundary Layer Equations With the Application to Convective Heat Transfer in Guns." Aerotherm Final Report, Naval Ordinance Station, Indian Head, MD, 1972 (AD-894601).

Artus, B., and R. Hasenbein. "Thermal Study of the 120-mm M256 Cannon Tube." ARBCCB-TR-89029, Benet Weapons Laboratory, U.S. Army Armament Research, Development and Engineering Center, Watervliet, NY, October 1989.

Bannister, E. L., R. N. Jones, and D. W. Bagwell. "Heat Transfer, Barrel Temperatures, and Thermal Strains in Guns." BRL Report No. 1192, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, February 1963 (AD-404467).

Belfour Stulen Inc. Structural Alloys Handbook, Mechanical Properties Data Center, 1973.

Brosseau, T. L. "An Experimental Method for Accurately Determining the Temperature Distribution and the Heat Transferred in Gun Barrels." BRL-TR-1740, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1974 (AD-B0001712).

Brosseau, T. L., I. C. Stobie, J. R. Ward, and R. W. Greene. "120-mm Gun Heat Input Measurements." ARBRL-TR-02413, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1982 (AD-A118378).

Bundy, M. L. "Thermal Distortion of the M1A1 Muzzle Reference System Collimator (MRSC)." BRL-TR-3107, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1990.

Bundy, M. L., A. W. Horst, and F. W. Robbins. "Effect of In-Bore Heating of Projectile Fins." BRL-TR-3106, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1990.

Carpenter, J. E., and A. Klavins. "Heat Flux Calculations." Memorandum. Cornell Aeronautical Laboratory Hypersonic Tunnel Department, 16 June 1965.

Carslaw, H. S., and J. C. Yaeger. Conduction of Heat in Solids. Oxford University Press, Second Edition, 1959.

Chandra, S. "Reference Manual for Stand-Alone Version of NBHX's Barrel Radial Heat Conduction Routines With Burst Fire and Restart Options." XBR-3.0-001, Veritay Corp., East Amherst, NY, May 1990.

Chandra, S., and E. B. Fisher. "Simulation Of Barrel Heat Transfer." Final Report, Contract No. DAAA15-88-D-0014, Delivery Order 0002, U.S. Army Laboratory Command, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1989.

Edwards, A. L. "Trump: A Computer Program for Transient and Steady State Distributions in Multidimensional Systems." UCRL-14754, Rev. 3, Lawrence Livermore National Laboratory, Livermore, CA, 1972.

Gibeling, H. J., and H. McDonald. "Development of a Two-Dimensional Implicit Interior Ballistics Code." Scientific Research Associates Inc., Glastonbury, CT, 20 November 1979 (AD-A100276).

Gough, P. S. "The NOVA Code A Users Manual," Volume I, "Description and Use." IHCR-80-8, Naval Ordinance Center, Indian Head, MD, December 1980.

Hass, J. R. "Resistance Model and Suggested Improvements for Thermal Shrouds of Tank Guns." ARCCB-TR-88035, U.S. Army Research and Development Command, August 1988 (AD-B126969).

Heiser, R., and J. A. Schmitt. "Simulations of Special Interior Ballistic Phenomena With and Without Heat Transfer to the Gun Tube Wall." BRL-TR-2732, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, May 1986 (AD-A169318).

Kingsbury, H. B., and A. V. Kalbag. "A Study of Thermal Shield Temperature Changes on Gun Tube Curvature." BRL-CR-611, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1989 (AD-A209551).

Koszoru, A. A., and I. C. Stobie. "Comparison of 155-mm Gun Tube Heat Input With Solventless and Solvent Propellant." BRL-MR-3833, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1990.

Kuo, K. K., K. C. Hsieh, and M. M. Athavale. "Modeling of Combustion Processes of Stick Propellants via Combined Eulerian-Lagrangian Approach." Proceedings of the Eighth International Symposium on Ballistics, October 1984.

Lawton, B. "Heat Transfer in Gun Barrels." Mechanical Engineering Department RMCS, Swindon Wilts SN68LA, UK, 1988.

Lawton, B. "Measurement of Instantaneous Nusselt Number-Reynolds Number Relationships in Gun Barrels." Mechanical Engineering Department RMCS, Swindon Wilts SN68LA, UK, October 1990.

Leech, W. J. "An Analytical Study of Thermal Radiation Heat Transfer in Gun Tubes." SWERR TR-72-32, June 1972 (AD-746231).

Liedtke, L. L. "Heat Transfer Characteristics of a Rapid-Fire Liquid Propellant Gun." Naval Weapons Center, China Lake, CA, January 1976 (AD-A022083).

Minor, T. C., R. W. Deas, and F. R. Lynn. "Rational Design of Thermal Jackets for Tank Guns." ARBRL-TR-02247, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1980 (AD-B051586L).

Morphy, C. C., and E. B. Fisher. "Gas Chemistry Effects on Gun Barrel Erosion: A Shock Tube Gun Investigation." ARBRL-CR-00481, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1980 (AD-A116-192).

O'Hara, G. P. "Principles of Thermal Analysis of Failures in Machine Gun Barrels." Benet Weapons Laboratory draft report, Applied Mechanics, Watervliet, NY.

Olin Corp. "Feasibility Study Semitelescoped Caseless 27-mm Ammunition." Final Report, New Products Development Energy Systems Division, St. Marks, FL, April 1972 (AD-903908).

Polk, J. F. "An Algorithm for Heat Transfer in Gun Barrels." ARO Report 80-1, Transactions of the 25th Conference of Army Mathematicians, pp.125—145, U.S. Army Research Office, Triangle Park, NC, 1980.

Rapp, J. A. "Gun Tube Temperature Prediction Model." BRL-MR-3844, U.S. Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1990.

Schlichting, H. Boundary Layer Theory. New York, NY: McGraw-Hill Book Company, Seventh Edition, 1979.

Sill, M. H., Jr. "Theoretical and Experimental Analyses of a Cannon Launched Guided Projectile (CLGP)." Report R-TR-74-049, U.S. Army Armament, Munitions and Chemical Command, Rock Island, IL, October 1974 (AD-B001002).

Sterbutzel, G. A., D. E. Adams, and F. A. Vassallo. "Evaluation of Heating and Erosion for Experimental 105-mm Ammunition." ARLCD-CR-80068, U.S. Army Research and Development Command, August 1980 (AD-B056222).

Stiefel, L., and E. C. Grossmann. "The Cook-Off Problem in Caseless Liquid Propellant Guns." Report R-1686, Frankfort Arsenal, August 1963 (AD-345630)

Stobie, I. C., T. L. Brosseau, and R. P. Kaste. "Heat Transfer Measurements in 105-mm Tank Gun With M735 Rounds." ARBRL-TR-02265, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1980.

Stratford, B. S., and G. S. Beavers. "The Calculation of the Compressible Turbulent Boundary Layer in an Arbitrary Pressure Gradient - A Correlation of Certain Previous Methods." Aeronautical Research Council R&M No. 3207, 1961.

Sturek, W. B., H. A. Dwyer, and E. N. Ferry, Jr. "Prediction of In-Bore Heating of KE Projectile Fins." BRL-MR-3852, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1990.

Talley, Q. J. "Barrel Heating and Chrome Adhesion in the 120-mm M256 Gun Tube." Contractors Report DAAA21-85-C0389, U.S. Army Research and Development Command, 1989.

U.S. Army Materiel Command. Interior Ballistics of Guns, AMCP 706-150, Alexandria, VA, February 1965.

Vassallo, F.A. "An Evaluation of Heat Transfer and Erosion in the 155-mm M185 Cannon." Calspan Technical Report No. VL-5337-D, 1 July 1976a.

Vassallo, F. A. "Development of Tube Instrumentation and Shock Tube Gun Techniques for Investigation of Heat Transfer and Erosion in Large-Caliber Guns: 8-in Howitzer Studies." Calspan Report No. VL-5337-D-2, December 1976b (AD-B031206).

Vassallo, F. A. "Mathematical Models and Computer Routines Used in Evaluation of Caseless Ammunition Heat Transfer." Calspan Reports No. GM-2948-Z-1 through 3, June 1971. (AD-A034159).

Versteegen, P. L. --------------------. "A Heat Transfer Study in Folded Ammunition Gun Tube Chambers." ARBRL-CR-00342, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1977 (AD-A043280)

Versteegen, P. L., and F. D. Varcolik. "Heat Transfer in Gun Tubes." ARBRL-CR-00393, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, March 1979 (AD-A069649).

Vottis and Hasenbein. "Thermal Warning Device (TWD) for the M198 155-mm Howitzer." DRDAR-LCB-DA, Benet Weapons Laboratory, Watervliet, NY, August 1979.

Williams, D. S. "27-mm Experimental Caseless Firing Fixture Test Program CAW-T2." Technical Report R-RR-N-x-18-73, U.S. Army Armament, Munitions and Chemical Command, Rock Island, IL, August 1972 (AD-909092).

Yalamanchili, V. S. "Unsteady Heat Transfer Analysis for Chosen Ammunition and Gun." U.S. Army Armament, Munitions and Chemical Command, Rock Island, IL, November 1972 (AD-755111)

LIST OF SYMBOLS

A_{ext}	-	Cross-sectional area at the muzzle
A_*	-	Critical cross-sectional area at the muzzle
b	-	Covolume equation constant
C_f	-	Skin friction coefficient
C_{fi}	-	Reference skin friction coefficient
C_p	-	Specific heat at constant pressure
g_o	-	Gravitational constant
h	-	Enthalpy
K	-	Conductivity coefficient
M	-	Mach number
$\dot{M}$	-	Mass flux
P_o	-	Reference pressure
P_z	-	Pressure at the z'th location
Q_w	-	Heat flux to the wall
R	-	Reynolds number
Re^*	-	Reference Reynolds number
R_g	-	Gas constant
T	-	Temperature
T^*	-	Static temperature
T_g	-	Gas temperature
T_o	-	Reference gas temperature
T_w	-	Wall temperature
u	-	Axial gas velocity

y	-	Covolume correction
z	-	Axial position
α	-	Thermal diffusivity
γ	-	Ratio of specific heats
μ^*	-	Reference viscosity
ρ	-	Density
ν^*	-	Reference kinematic viscosity
χ	-	Equivalent flat plate length
ω	-	Frequency of heat input

LIST OF ABBREVIATIONS

AFAS	-	Advanced Field Artillery System
IB	-	Interior Ballistic
TWD	-	Thermal Warning Device
CAW	-	Caseless Automatic Weapon

INTENTIONALLY LEFT BLANK.

No. of Copies	Organization
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	Commander U.S. Army Materiel Command ATTN: AMCAM 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Commander U.S. Army Laboratory Command ATTN: AMSLC-DL 2800 Powder Mill Road Adelphi, MD 20783-1145
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-IMI-I Picatinny Arsenal, NJ 07806-5000
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000
1	Director Benet Weapons Laboratory U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050
(Unclass. only) 1	Commander U.S. Army Armament, Munitions and Chemical Command ATTN: AMSMC-IMF-L Rock Island, IL 61299-5000
1	Director U.S. Army Aviation Research and Technology Activity ATTN: SAVRT-R (Library) M/S 219-3 Ames Research Center Moffett Field, CA 94035-1000

No. of Copies	Organization
1	Commander U.S. Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010
1	Commander U.S. Army Tank-Automotive Command ATTN: ASQNC-TAC-DIT (Technical Information Center) Warren, MI 48397-5000
1	Director U.S. Army TRADOC Analysis Command ATTN: ATRC-WSR White Sands Missile Range, NM 88002-5502
1	Commandant U.S. Army Field Artillery School ATTN: ATSF-CSI Ft. Sill, OK 73503-5000
(Class. only) 1	Commandant U.S. Army Infantry School ATTN: ATSH-CD (Security Mgr.) Fort Benning, GA 31905-5660
(Unclass. only) 1	Commandant U.S. Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905-5660
1	Air Force Armament Laboratory ATTN: WL/MNOI Eglin AFB, FL 32542-5000
	<u>Aberdeen Proving Ground</u>
2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
1	Cdr, USATECOM ATTN: AMSTE-TC
3	Cdr, CRDEC, AMCCOM ATTN: SMCCR-RSP-A SMCCR-MU SMCCR-MSI
1	Dir, VLAMO ATTN: AMSLC-VL-D
10	Dir, BRL ATTN: SLCBR-DD-T

No. of Copies	Organization
1	Commander U.S. Army Concepts Analysis Agency ATTN: D. Hardison 8120 Woodmont Ave. Bethesda, MD 20014
1	C.I.A. 01R/DB/Standard Washington, DC 20505
1	Director U.S. Army Ballistic Missile Defense Systems Command Advanced Technology Center P. O. Box 1500 Huntsville, AL 35807-3801
1	Chairman DOD Explosives Safety Board Room 856-C Hoffman Bldg. 1 2461 Eisenhower Ave. Alexandria, VA 22331-0600
1	Commander U.S. Army Materiel Command ATTN: AMCDE-DW 5001 Eisenhower Ave. Alexandria, VA 22333-5001
1	Department of the Army Office of the Product Manager 155mm Howitzer, M109A6, Paladin ATTN: SFAE-AR-HIP-IP, Mr. R. De Kleine Picatinny Arsenal, NJ 07806-5000
2	Commander Production Base Modernization Agency U.S. Army Armament Research, Development, and Engineering Center ATTN: AMSMC-PBM, A. Siklosi AMSMC-PBM-E, L. Laibson Picatinny Arsenal, NJ 07806-5000

No. of Copies	Organization
3	PEO-Armaments Project Manager Tank Main Armament Systems ATTN: AMCPM-TMA, K. Russell AMCPM-TMA-105 AMCPM-TMA-120, C. Roller Picatinny Arsenal, NJ 07806-5000
15	Commander U.S. Army Armament Research. Development, and Engineering Center ATTN: SMCAR-AEE SMCAR-AEE-B, A. Beardell D. Downs S. Einstein S. Westley S. Bernstein J. Rutkowski B. Brodman P. Bostonian R. Cirincione A. Grabowsky P. Hui J. O'Reilly N. Ross SMCAR-AES, S. Kaplowitz, Bldg. 321 Picatinny Arsenal, NJ 07806-5000
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCD, D. Spring SMCAR-CCH-V, C. Mandala Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-HFM, E. Barrieres Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-FSA-T, M. Salsbury Picatinny Arsenal, NJ 07806-5000

No. of Copies	Organization
1	Commander, USACECOM R&D Technical Library ATTN: ASQNC-ELC-IS-L-R, Myer Center Fort Monmouth, NJ 07703-5301
1	Commander U.S. Army Harry Diamond Laboratories ATTN: SLCHD-TA-L 2800 Powder Mill Rd. Adelphi, MD 20783-1145
1	Commandant U.S. Army Aviation School ATTN: Aviation Agency Fort Rucker, AL 36360
2	Program Manager U.S. Army Tank-Automotive Command ATTN: AMCPM-ABMS, T. Dean (2 cps) Warren, MI 48092-2498
1	Program Manager U.S. Army Tank-Automotive Command Fighting Vehicles Systems ATTN: AMCPM-BFVS Warren, MI 48092-2498
1	President U.S. Army Armor & Engineer Board ATTN: ATZK-AD-S Fort Knox, KY 40121
1	Project Manager U.S. Army Tank-Automotive Command M-60 Tank Development ATTN: AMCPM-ABMS Warren, MI 48092-2498
1	Director HQ, TRAC RPD ATTN: ATCD-MA Fort Monroe, VA 23651-5143
2	Director U.S. Army Materials Technology Laboratory ATTN: SLCMT-ATL (2 cps) Watertown, MA 02172-0001

No. of Copies	Organization
1	Commander U.S. Army Research Office ATTN: Technical Library P.O. Box 12211 Research Triangle Park, NC 27709-2211
1	Commander U.S. Army Belvoir Research and Development Center ATTN: STRBE-WC Fort Belvoir, VA 22060-5006
1	Director U.S. Army TRAC-Ft. Lee ATTN: ATRC-L, Mr. Cameron Fort Lee, VA 23801-6140
1	Commandant U.S. Army Command and General Staff College Fort Leavenworth, KS 66027
1	Commandant U.S. Army Special Warfare School ATTN: Rev and Trng Lit Div Fort Bragg, NC 28307
3	Commander Radford Army Ammunition Plant ATTN: SMCAR-QA/HI LIB (3 cps) Radford, VA 24141-0298
1	Commander U.S. Army Foreign Science and Technology Center ATTN: AMXST-MC-3 220 Seventh Street, NE Charlottesville, VA 22901-5396
2	Commander Naval Sea Systems Command ATTN: SEA 62R SEA 64 Washington, DC 20362-5101
1	Commander Naval Air Systems Command ATTN: AIR-954-Technical Library Washington, DC 20360

No. of Copies	Organization
1	Assistant Secretary of the Navy (R, E, and S) ATTN: R. Reichenbach Room 5E787 Pentagon Bldg Washington, DC 20375
1	Naval Research Laboratory Technical Library Washington, DC 20375
2	Commandant U.S. Army Field Artillery Center and School ATTN: ATSF-CO-MW, E. Dublisky (2 cps) Fort Sill, OK 73503-5600
1	Office of Naval Research ATTN: Code 473, R. S. Miller 800 N. Quincy Street Arlington, VA 22217-9999
3	Commandant U.S. Army Armor School ATTN: ATZK-CD-MS, M. Falkovitch (3 cps) Armor Agency Fort Knox, KY 40121-5215
2	Commander U.S. Naval Surface Warfare Center ATTN: J. P. Consaga C. Gotzmer Indian Head, MD 20640-5000
4	Commander Naval Surface Warfare Center ATTN: Code 240, S. Jacobs Code 730 Code R-13, K. Kim R. Bernecker Silver Spring, MD 20903-5000

No. of Copies	Organization
2	Commanding Officer Naval Underwater Systems Center ATTN: Code 5B331, R. S. Lazar Technical Library Newport, RI 02840
5	Commander Naval Surface Warfare Center ATTN: Code G33, J. L. East W. Burrell J. Johndrow Code G23, D. McClure Code DX-21 Technical Library Dahlgren, VA 22448-5000
3	Commander Naval Weapons Center ATTN: Code 388, C. F. Price Code 3895, T. Parr Information Science Division China Lake, CA 93555-6001
1	OSD/SDIO/IST ATTN: Dr. Len Caveny Pentagon Washington, DC 20301-7100
3	Commander Naval Ordnance Station ATTN: T. C. Smith D. Brooks Technical Library Indian Head, MD 20640-5000
1	AL/TSTL (Technical Library) ATTN: J. Lamb Edwards AFB, CA 93523-5000
1	AFATL/DLYV Eglin AFB, FL 32542-5000
1	AFATL/DLXP Eglin AFB, FL 32542-5000
1	AFATL/DLJE Eglin AFB, FL 32542-5000

No. of Copies	Organization
1	NASA/Lyndon B. Johnson Space Center ATTN: NHS-22 Library Section Houston, TX 77054
1	AFELM, The Rand Corporation ATTN: Library D 1700 Main Street Santa Monica, CA 90401-3297
3	AAI Corporation ATTN: J. Hebert J. Frankle D. Cleveland P.O. Box 126 Hunt Valley, MD 21030-0126
2	Aerojet Solid Propulsion Company ATTN: P. Micheli L. Torreyson Sacramento, CA 96813
1	Atlantic Research Corporation ATTN: M. King 5390 Cherokee Ave. Alexandria, VA 22312-2302
3	AL/LSCF ATTN: J. Levine L. Quinn T. Edwards Edwards AFB, CA 93523-5000
1	AVCO Everett Research Laboratory ATTN: D. Stickler 2385 Revere Beach Parkway Everett, MA 02149-5936
2	Calspan Corporation ATTN: C. Murphy (2 cps) P.O. Box 400 Buffalo, NY 14225-0400
2	General Electric Company Tactical Systems Department ATTN: J. Mandzy J. Haberl 100 Plastics Ave. Pittsfield, MA 01201-3698

No. of Copies	Organization
1	IITRI ATTN: M. J. Klein 10 W. 35th Street Chicago, IL 60616-3799
1	Hercules, Inc. Allegheny Ballistics Laboratory ATTN: William B. Walkup P.O. Box 210 Rocket Center, WV 26726
1	Hercules, Inc. Radford Army Ammunition Plant ATTN: E. Hibshman Radford, VA 24141-0299
3	Director Lawrence Livermore National Laboratory ATTN: L-355, A. Buckingham M. Finger L-324, M. Constantino P.O. Box 808 Livermore, CA 94550-0622
1	Olin Corporation Badger Army Ammunition Plant ATTN: F. E. Wolf Baraboo, WI 53913
2	Olin Ordnance ATTN: E. J. Kirschke A. F. Gonzalez P.O. Box 222 St. Marks, FL 32355-0222
1	Paul Gough Associates, Inc. ATTN: Dr. Paul S. Gough 1048 South Street Portsmouth, NH 03801-5423
1	Physics International Company ATTN: Library, H. Wayne Wampler 2700 Merced Street San Leandro, CA 98457-5602

No. of Copies	Organization
1	Princeton Combustion Research Laboratory, Inc. ATTN: M. Summerfield 475 U.S. Highway One Monmouth Junction, NJ 08852-9650
2	Rockwell International Rocketdyne Division ATTN: BA08, J.E. Flanagan J. Gray 6633 Canoga Ave. Canoga Park, CA 91303-2703
1	Thiokol Corporation Huntsville Division ATTN: Technical Library Huntsville, AL 35807
1	Sverdrup Technology, Inc. ATTN: Dr. John Deur 2001 Aerospace Parkway Brook Park, OH 44142
2	Thiokol Corporation Elkton Division ATTN: R. Biddle Technical Library P.O. Box 241 Elkton, MD 21921-0241
1	Veritay Technology, Inc. ATTN: E. Fisher 4845 Millersport Highway East Amherst, NY 14501-0305
1	Universal Propulsion Company ATTN: H. J. McSpadden Black Canyon Stage 1 Box 1140 Phoenix, AZ 84029
1	Battelle ATTN: TACTEC Library, J.N. Huggins 505 King Ave. Columbus, OH 43201-2693

No. of Copies	Organization
1	Brigham Young University Department of Chemical Engineering ATTN: M. Beckstead Provo, UT 84601
1	California Institute of Technology 204 Karman Laboratory Main Stop 301-46 ATTN: F.E.C. Culick 1201 E. California Street Pasadena, CA 91109
1	California Institute of Technology Jet Propulsion Laboratory ATTN: L. D. Strand, MS 512/102 4800 Oak Grove Drive Pasadena, CA 91109-8099
1	University of Illinois Department of Mechanical/Industrial Engineering ATTN: H. Krier 144 MEB; 1206 N. Green Street Urbana, IL 61801-2978
1	University of Massachusetts Department of Mechanical Engineering ATTN: K. Jakus Amherst, MA 01002-0014
1	University of Minnesota Department of Mechanical Engineering ATTN: E. Fletcher Minneapolis, MN 55414-3368
3	Georgia Institute of Technology School of Aerospace Engineering ATTN: B.T. Zinn E. Price W.C. Strahle Atlanta, GA 30332
1	Institute of Gas Technology ATTN: D. Gidaspow 3424 S. State Street Chicago, IL 60616-3896

No. of Copies	Organization
1	Johns Hopkins University Applied Physics Laboratory Chemical Propulsion Information Agency ATTN: T. Christian Johns Hopkins Road Laurel, MD 20707-0690
1	Massachusetts Institute of Technology Department of Mechanical Engineering ATTN: T. Toong 77 Massachusetts Ave. Cambridge, MA 02139-4307
1	Pennsylvania State University Department of Mechanical Engineering ATTN: K. Kuo University Park, PA 16802-7501
1	Purdue University School of Mechanical Engineering ATTN: J. R. Osborn TSPC Chaffee Hall West Lafayette, IN 47907-1199
1	SRI International Propulsion Sciences Division ATTN: Technical Library 333 Ravenwood Ave. Menlo Park, CA 94025-3493
1	Rensselaer Ploytechnic Institute Department of Mathematics Troy, NY 12181
2	Director Los Alamos Scientific Laboratory ATTN: T3, D. Butler M. Division, B. Craig P.O. Box 1663 Los Alamos, NM 87544
1	General Applied Sciences Laboratory ATTN: J. Erdos 77 Raynor Ave. Ronkonkama, NY 11779-6649

No. of Copies	Organization
1	Battelle PNL ATTN: Mr. Mark Garnich P.O. Box 999 Richland, WA 99352
1	Stevens Institute of Technology Davidson Laboratory ATTN: R. McAlevy, III Castle Point Station Hoboken, NJ 07030-5907
1	Rutgers University Department of Mechanical and Aerospace Engineering ATTN: S. Temkin University Heights Campus New Brunswick, NJ 08903
1	University of Southern California Mechanical Engineering Department ATTN: 0HE200, M. Gerstein Los Angeles, CA 90089-5199
2	University of Utah Department of Chemical Engineering ATTN: A. Baer G. Flandro Salt Lake City, UT 84112-1194
1	Washington State University Department of Mechanical Engineering ATTN: C. T. Crowe Pullman, WA 99163-5201
1	Alliant Techsystems, Inc. ATTN: R. E. Tompkins MN38-3300 5700 Smetana Drive Minnetonka, MN 55343
1	Science Applications, Inc. ATTN: R. B. Edelman 23146 Cumorah Crest Drive Woodland Hills, CA 91364-3710

No. of
Copies Organization

1 Battelle Columbus Laboratories
ATTN: Mr. Victor Levin
505 King Ave.
Columbus, OH 43201-2693

1 Allegheny Ballistics Laboratory
Propulsion Technology Department
Hercules Aerospace Company
ATTN: Mr. Thomas F. Farabaugh
P.O. Box 210
Rocket Center, WV 26726

1 MBR Research Inc.
ATTN: Dr. Moshe Ben-Reuven
601 Ewing St., Suite C-22
Princeton, NJ 08540

Aberdeen Proving Ground

1 Cdr, CSTA
ATTN: STECS-PO, R. Hendricksen

USER EVALUATION SHEET/CHANGE OF ADDRESS

This laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers below will aid us in our efforts.

1. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______

2. How, specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______

3. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______

4. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______

BRL Report Number BRL-TR-3300 Division Symbol ______

Check here if desire to be removed from distribution list. ____

Check here for address change. ____

Current address: Organization ______
Address ______

DEPARTMENT OF THE ARMY
Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

OFFICIAL BUSINESS

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT No 0001, APG, MD

Postage will be paid by addressee

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066