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THE CANNON-PROJECTILE BLOW-BY FLOW FIELD

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13. ABSTRACT (*Maximum 200 words*)

The objective of this work was to document the numerical simulation of the cannon-projectile blow-by flow for a Zone six firing of an M549A1 with XM230 charge. The steady, axisymmetric flow was determined by use of the NPARC Computational Fluid Dynamics Code, given inflow boundary values at points on the ballistics path. We computed pressure distributions on the projectile, assuming a smooth cannon surface. Integration of the distribution over the projected lateral surface of the projectile gives an estimated side force of 500,000 pounds on the projectile as it enters the brake section of the tube. In a yawed attitude, such forces can effect inertial instabilities on the projectile which, in turn, contribute to balloting and mechanical wear of the tube. The same numerical solution computes local heat transfer rates on the obturator and rotating band surfaces. The effect of blow-by flow heat transfer on tube ersoion is a factor that is not well understood. An extension of the present work will provide a basis for further understanding the combined effects of abrasive and chemical erosion. The present computations assume that the wear gap between projectile and cannon wall is 0.020 inch and that the obturator protrudes 70% into the gap. Results are presented at two points on the ballistics trajectory, 2.212 and 5.256 meters from the rifle origin. Local heat transfer to the barrel wall was obtained for projectiles with and without obturator and band. At the 2.212 meter location, the latter yielded maximum local heat transfer rates on the barrel surface that exceeded 30 times the heat transfer computed at 1.7 inches upstream of the projectile's base (i.e., in the projectile's wake boundary layer). With the obturator and band, and at the same travel point, the heat transfer ratio peaked at 2040, with the wake heat transfer computed at 6.7 inches upstream of the projectile's base.

14. SUBJECT TERMS
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INTRODUCTION

The most striking evidence for cannon blow-by flow can be inferred by shadowgraphs of rifle muzzle flow fields (ref 1). A series of shadowgraphs of the M16 muzzle blast field shows that bore residue particles accelerate across the blast wave (ref 2), which, in turn, accelerates ahead of the exiting 7.62 mm projectile in the muzzle flow field. Figure 1 shows the residue particles that were expelled either by leakage flow over the boattail–during exit dynamics–or by becoming entrained during in-tube leakage past the projectile. It has not been determined which scenario prevails; but after many firings, it is likely that both processes have occurred. In-tube and exit flow expansions of the propellant gases entrain particles of unburned propellant and smoke (water vapor adhered to graphitic carbon), and extrapolating to the case of artillery, particles of eroded materials from the obturator, rotating band, and gun steel.

Evidence for the 155-mm cannon muzzle-end wear problem was presented by Hasenbein (ref 3), whose measurements indicated that disproportionate increases in cannon diameter, toward the muzzle-end of the barrel, correlate with increasing number of rounds fired. These data constitute the basis for a first hypothesis: that balloting, a mechanical instability of the projectile as it approaches the muzzle, is the cause of muzzle-end wear. Examining the same data at the breech-end indicates that the wear slope is significantly less there, than at the muzzle-end, for the number of rounds fired. Thus, a second hypothesis is supported: that turbulent boundary layer flow in the projectile's wake is the predominant flow mechanism initiating heat transfer to the barrel and high temperature gas-surface reactions, which cause erosion at the origin-of-rifling and downbore. The latter hypothesis has been the basis for several recent modeling efforts designed to predict gun tube wear and erosion (refs 4-7).

Blow-by flow, or shot leakage, has been variously mentioned or treated by Hasenbein (ref 8), Ahmad (ref 9), Buckingham (ref 10), and Lawton (refs 7,11). Most of these researchers have dealt with inferences from field observation. However, evidence of gas wash on projectile fragments and barrel section metallurgical examination have led to the construction of mathematical models and their laboratory validations for restricted blow-by flow systems (refs 10,11) aimed at the understanding and reduction of tube erosion. For example, Buckingham has studied particle-gas flow to examine the use of cannon wear reduction additives, while Lawton has adapted an interior ballistics code to correlate the observed gas leakage temperature rise on 30- and 40-mm guns. Body engraving may also be evidence of the imbalance of forces due to blow-by. In this case, sufficiently high temperatures occur–either by friction or blow-by gas or both–leaving large deposits of the band material on one side of the body. In summary, it is thought that blow-by gas dynamics may contribute to projectile instabilities, which can cause balloting, body engraving, and mechanical wear at the muzzle-end of the barrel.

The present work was motivated by a desire to better understand the mechanical problem. Moreover, Lawton's (ref 11) measurements of the in-bore temperature, pressure, and heat transfer on the barrel walls of 30-mm Rarden and 40-mm Bofors guns indicated that at least half of the heat transfer to the barrel near the origin-of-rifling is due to blow-by gas leakage (Figure 2). These data show large transient temperature fluctuations near the origin-of-rifling that exceed the melting point of gun steel, albeit samples that produced these results were 10% of the total population fired. Thus, a second motivation for the present work was to obtain an assessment of the local surface heat transfer rates during blow-by flow through a narrow gap. This is considered preliminary toward the calculation of the blow-by heat pulse for the ballistic cycle. Also, the computation of local surface heat transfer rates, temperature, and pressure distributions about the projectile can be useful in the design of obturators and rotating bands.

PROBLEM DESCRIPTION

Underlying effects of blow-by flow on the cannon wear and erosion can be studied, as with other modeling solutions, by examining the fundamental gas dynamic equations. For a viscous, compressible, and reacting propellant gas, the Navier-Stokes equations and constitutive laws provide the basis for solution. To ease the computational burden, and because the heat transfer gradients, $-\nabla \bullet (k \nabla T)$, are critical at the wall, subsets of these equations have traditionally been used to model only the viscous boundary layer at the barrel wall. These models (refs 4,6) are evolving. At first, these account for equilibrium reacting gases in the turbulent wake of the projectile, presently including finite rate chemistry, and eventually incorporating blow-by in a composite interior ballistics code. Contrasting this approach, the present work seeks to understand the baseline core flow, which can be validated by controlled laboratory measurements, and which can serve to guide experiments both in the laboratory and in the field, thus aiming to reduce the cost of field experimentation. The solution set is the full set of flow equations for the perfect gas to be used as control medium.

Our study provided results of numerical solutions to the conservation equations of gas dynamics applied to the problem of blow-by flow. The asymptotic steady-state, axisymmetric solution shows viscous and pressure stresses on the projectile. This allows calculation of drag and side forces that can destabilize the projectile. The temperature field and local transient heat transfer rates on the tube and projectile surfaces are obtained as by-products of that solution. We used the NPARC code (ref 12), Version 2.2, which simulates perfect gas flows by solving the Navier-Stokes equations. The code was tailored for the blow-by problem and was implemented on the SGI Power Challenge and Origin 2000 computers at Benet Laboratories. The code also operates on the IBM SP2 at Rensselaer Polytechnic Institute, Troy, NY, where it was used in the initial stages of this Computational Fluid Dynamics (CFD) project (ref 13). The present CFD project assumes a hot propellant gas, defined by the specific heat ratio, $\gamma = 1.25$, for the burned solid propellant in the gun chamber. That value is assumed constant, but may be varied as a function of the bore average gas temperature, T, and projectile base pressure, P_b, assumed as equilibrium values. The inflow boundary conditions were taken at travel points 2.212 and 5.256 meters on the ballistic base pressure curve obtained from the IBHVG2, interior ballistics code (ref 14). Further interior ballistics output information for this work is contained in Figure 3. Outflow conditions were calculated to account for the precursor shock wave.

NPARC (National Project for Applications-oriented Research in CFD)

We applied the time-dependent NPARC solver to compute the asymptotic steady-state simulation of flow in the narrow gap between a traveling 155-mm projectile and smooth cannon bore. Accordingly, we adjusted the flow solution to account for the relative velocity between cannon and projectile. It is important to select a set of assumptions that facilitates extension of these investigations from the present compressible, laminar, perfect gas flow to the real multi-component gas that can ablate the surface material, causing barrel erosion. The NPARC flow solver–Versions 2.2 and 3.1–was developed by the NPARC Alliance, a joint NASA and U.S. Air Force (Arnold Engineering Development Center) effort to produce a flow simulation code for problems in internal propulsion gas dynamics (refs 12,15). The time-dependent, compressible, Navier-Stokes flow equations were formulated in the divergence form, which includes the perfect gas equation. The numerical code was built upon the Beam-Warming algorithm (ref 16) that uses a Taylor series linearization of the governing equations and an approximate factorization to decouple the spatial directions. This code is a finite-volume scheme, second-order accurate in space and first-order in time. Second- and fourth-order artificial viscosity terms are employed to reduce dispersive oscillations that can appear downstream of shock waves and contact surfaces. We calculated the Reynolds number to be about 10^6 with respect to the gap height and choked-flow conditions, and we used Sutherland's law to obtain the viscosity of the hot propellant gas. Although both the laminar and several turbulent-flow options are given in NPARC, we selected the laminar-flow option. To decide which of these models is appropriate for the requisite validation of a certified real-gas blow-by code, we have proposed conducting pressure and thin-film heat transfer measurements on a shock tunnel model of the projectile-cannon annular flow region (ref 17).

Grid/Domain

The annular computational domain is described in Figure 4. Following NPARC procedure, the grid was constructed by using quadrilateral elements with their nodes regularly connected in a curvilinear coordinate system–within the solid border shown in the figure. The blow-by simulations for projectile without obturator and band employed 110,843 nodes. That increased to 129,492 for the obturated projectile in order to maintain accuracy in the high-gradient region and to extend the domain from 1.7 to 6.7 inches upstream of the projectile base.

Boundary Conditions

Six boundary conditions were imposed on the flow boundaries. Common to the projectile with and without obturator and band were the symmetry axis; and the inflow and outflow free surfaces, with input values from Figure 3 and the shock precursor, respectively. No-slip, isothermal, boundary surfaces for viscous flow were applied at the cannon wall, the projectile base, and body. These were adjusted to accommodate obturator and band geometry. Figure 4 shows the no-obturator case. The assumed blow-by gap of 0.02 inch (0.508 mm) is consistent with measured data for several 155-mm tubes (refs 3,17). That gap is narrowed at the obturator to 0.006 inch (0.1524 mm).

Procedure

Four flow problems were run, with and without obturator and band, for two points on the ballistic curve. After selection of the initial boundary conditions and the construction of code input in the form of a restart file, each problem, beginning with the no-obturator projectile travel at 2.212 meters, was executed over several thousand time steps with a large maximum time step size and artificial viscosity. This allowed the limit on percentage change in flow values to limit the time step size. The procedure also allowed the solution to develop from the initial restart through several restarts to a form that resembled the final steady-state result. Visualization of this result was obtained with the NASA postprocessor FAST. However, convergence is usually assured by running subsequent restarts with decreasing time step size limits to values small enough so the maximum percentage change in pressure or density is less than the maximum allowed value (about 10%) and so the total residual is decreasing. In our study, solution convergence was interrupted by large increases in the total residual when the relative velocity between projectile and tube wall was introduced, thus requiring several tens of thousands of time steps over as many as 30 restarts before acceptable (steady-state) convergence criteria were achieved.

Postprocesses

To postprocess and visualize results in a current restart file, the required grid and solution output files are suitably formatted for FAST by executing the restart operation file given in the NPARC source directory.

RESULTS

Figure 5 is a composite of numerical simulation results visualized by FAST for the blow-by flow field at the 5.256-m ballistics travel point of Figure 3. The total gap height for the annular flow region between cannon and projectile is 0.020 inch (0.5080 mm). The obturator protrudes 70% into that gap. The shaded bars indicate the range of values obtained by the solver, normalized to the reference values. Maximum pressure in the field is shown aft of the projectile, representing boundary condition, P_b = 10,250 psi, in a reservoir that extends 6.7 inches aft of the projectile base. Other flow quantities pictured include compressibility effects at the base. Flow expansion over the ogive cools the gas rapidly to the isothermal value, T = 300°K, on the surface; but at the resolution of the figure, the gas state (p, ρ, T) appears indistinguishable from that which was imparted by the precursor shock wave. Magnifications of the axial velocity confirm the boundary no-slip condition for viscous flow. Nearly equal magnifications of the pressure field, Figure 6, show a shock expansion on the corner of the obturator (Figure 6a) with pressure exceeding the reservoir value on the cannon wall. Downstream there are subsequent expansion and compression waves, first over the obturator, then farther downstream over the rotating band (Figure 6b). The maximum flow velocities over the ogive are nearly five times the sound speed at maximum expansion.

CONCLUSIONS

Figure 7 presents pressure distributions on the projectile for the case of no-obturator or band, at ballistic travel points, (a) 2.212 meters, and (b) 5.256 meters. Approximate integration of the distribution (b) over the projected lateral surface of the projectile gives an estimated side force of 500,000 pounds through the projectile center of pressure as it enters the brake section of the tube. In a yawed attitude, such forces become unbalanced and effect inertial instabilities on the projectile that contribute to balloting and mechanical wear of the tube.

For a projectile with obturator and band, Figure 8 gives the local heat transfer flux to the barrel wall, relative to the wall heat flux in the boundary layer 6.7 inches upstream of the projectile base. This ratio peaked at 2040 for the projectile at 2.212 meters from the origin-of-rifling, and then dropped more than an order of magnitude for the projectile at 5.256 meters from the origin-of-rifling. Although the larger peak might seem to be more accurate because convergence was carried out to 30 restarts, the low-peak solution was converged with the 18th restart file. Given that, the explanation is that the temperature gradient is dropping off faster than total enthalpy does as the projectile approaches the muzzle. To illustrate the solution convergence in terms of the heat transfer output, Figure 9 shows how the heat transfer evolves from initial restart to final restart for a projectile without obturator at the first travel point. (The x-axis coordinate is normalized by the gap height, HO = 0.020 inch.)

Another example is important. Results are presented at two points on the ballistics trajectory, 2.212 and 5.256 meters from the rifle origin. Local heat transfer to the barrel wall was obtained for projectiles with and without obturator and band. At the 2.212 meter location, the latter (see Figure 9) yielded maximum local heat transfer rates on the barrel surface that exceed 30 times the heat transfer computed 1.7 inches upstream of the projectile's base (i.e., in the projectile's wake boundary layer). With the obturator and band, and at the same travel point (see Figure 8a), the heat transfer ratio peaked at 2040, with the wake heat transfer computed at 6.7 inches upstream of the projectile's base. Other than the expectation of much higher temperature gradients, obtained with the much smaller gap for the obturator and band, the normalizing factor was prevalent farther upstream of the base where the wake had thinned out and the heat transfer was less. Hence, these two results cannot be used for comparison.

In addition to computation of the Navier-Stokes blow-by flow solution, the overall scope of this work included computation of pressure forces and heat transfer rates on the cannon wall. Heat transfer on the projectile and its components is available from the saved data. The perfect-gas solutions reported here represent 850 CPU hours. This work is considered baseline to the methodology that requires laboratory measurements to determine the degree of turbulence that can modify and validate predictive models of the blow-by flow. It is the basis for future three-dimensional, time-dependent, models for prediction of wear and erosion of barrel surfaces effected by a balloting projectile in a multi-component gas flow that reacts with the substrate.

RECOMMENDATIONS

The extension of this work for time-dependency and for three-dimensional modeling, and including chemical equilibrium, is estimated at 4500 CPU hours using one Origin 2000 processor. The work would be performed best at high performance computing facilities to take full advantage of the speed-up offered by parallelization techniques. New versions of NPARC will treat reacting gas flows. Chemical reactions require additional equations for the production and annihilation of each species considered. The NPARC Alliance has developed a new code for finite-rate chemically reacting flows, called WIND. We recommend its eventual use for subsequent blow-by flow work.

REFERENCES

1. Schmidt, E.M., and Shear, D.D., "Optical Measurements of Muzzle Blast," *AIAA Journal*, Vol.13, No. 8, August 1975, pp. 1086-1091.

2. Schmidt. E.M., Set of Photos, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1984.

3. Hasenbein, R.G., "BACK TO THE FUTURE: A Twenty Year Perspective on Artillery Wear and Erosion," *Proceedings of the Sagamore Workshop on Gun Barrel Wear and Erosion*, Sponsored by the U.S. Army Research Laboratory, 29-31 July 1996; see also "155-mm XM198 Howitzer Muzzle Wear," Technical Report WVT-TR-75024, Benet Laboratories, Watervliet, NY, 1975.

4. Sopok, S., Pflegl, G., O'Hara, P., Dunn, S., and Coats, D., "Thermochemical Erosion Modeling of Original M242/M919 Gun System," Technical Report ARCCB-TR-97005, Benet Laboratories, Watervliet, NY, February 1997.

5. Seiler, F., Zimmermann, K., Raupp, J., and Zettler, G., "Bore Erosion and Heat Transfer Measurements in 20 and 60-mm-Caliber Compared with Predictions of Model Calculations," *Proceedings of the Eighth U.S. Army Symposium on Gun Dynamics*, (G. Albert Pflegl, Ed.), ARCCB-SP-96032, Benet Laboratories, Watervliet, NY, November 1996.

6. Conroy, P.J., Weinacht, P., and Nusca, M.J.,"ARL Tube Erosion Code (ATEC)," *Proceedings of the 32nd JANNAF Combustion Subcommittee Meeting*, Huntsville, AL, June 1995; see also "Surface Chemistry Effects on Erosion in High Performance Tank Ammunition," *Proceedings of the Eighth U.S. Army Symposium on Gun Dynamics*, (G. Albert Pflegl, Ed.), ARCCB-SP-96032 Benet Laboratories, Watervliet, NY, November 1996.

7. Lawton, B., "Heat Transfer and Erosion in Gun Barrels," Royal Military College of Science, Cranfield University, UK, June 1994.

8. Hasenbein, R.G., "Analysis of Wear Data for the 155-mm XM198," Technical Report WVT-TR-75023, Benet Laboratories, Watervliet, NY, May 1975.

9. Ahmad, I., "The Problem of Gun Barrel Erosion: An Overview," *Gun Propulsion Technology*, Vol. 109, (Ludwig Stiefel, Ed.), American Institute of Aeronautics and Astronautics Series, 1984.

10. Buckingham, A.C., "Modeling Additive and Hostile Particulate Influences in Gun Combustion Turbulent Erosion," Lawrence Livermore Laboratory Report UCRL-82756, 27 September 1979.

11. Lawton, B., and Laird, M.P.B, "Influence of Gas Leakage on Heat Transfer and Wear in Gun Barrels," Royal Military College of Science, Cranfield University, UK, *Proceedings of the 16th International Ballistics Symposium and Exhibition*, San Francisco, CA, 23-27 September 1996.

12. Sirbaugh, J.R., Cooper, G.K., Smith, C.F., Jones, R.R., Towne, C.E., and Power, G.D., "A User's Guide to NPARC," Versions 2 and 3, Arnold Engineering Development Center; see Internet home page at http://info.arnold/af.mil/nparc/index.html, November 1994.

13. Messitt, D.G., Nagamatsu, H.T., and Myrabo, L.N., "Numerical Simulation of High Pressure, High Temperature Flow Through Bore Evacuator Seals and Blow-by Past Projectiles," Final Report for Army Contract DAAA22-96-M-0570, Rensselaer Polytechnic Institute, Troy, NY, December 1996.

14. Anderson, R.D., and Fickie, K.D., "IBHVG2–A User's Guide," Technical Report ARBRL-TR-2829, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1987.

15. Messitt, D.G., "Computational and Experimental Investigation of 2- and 3-D Scramjet Inlets and Flow Over a Sharp Flat Plate at Mach Numbers from 10 to 25 in a Hypersonic Shock Tunnel," Ph.D. Thesis, Rensselaer Polytechnic Institute, Troy, NY, May 1998.

16. Beam, R.M., and Warming, R.F., "An Implicit Finite-Difference Algorithm for Hyperbolic Systems in Conservation-Law Form," *Journal of Computational Physics*, Vol. 22, No. 1, September 1976, pp. 87-110.

17. Andrade, C.A., Nagamatsu, H.T., Messitt, D.G., and Myrabo, L.N., "Shock Tube Investigation of Bore Surface Heating and Related Erosion Chemistry in the Blow-by Region," *Proceedings of the Sagamore Workshop on Gun Barrel Wear and Erosion*, Sponsored by the U.S. Army Research Laboratory, 29-31 July 1996.

M16 Muzzle Blast

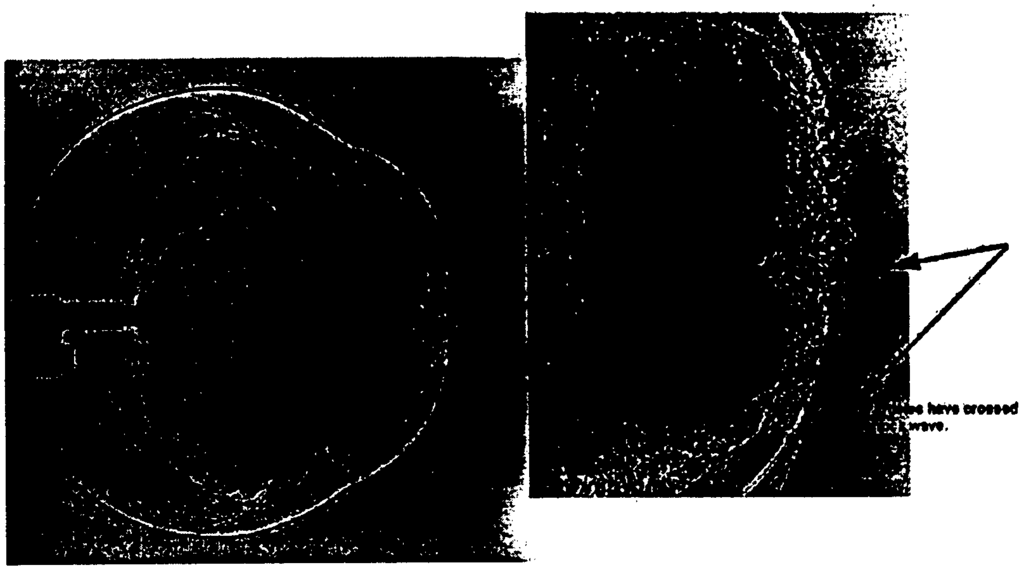

Figure 1. Shadowgraph of M16 muzzle blast flow, in-bore particles crossing blast wave (ref 2).

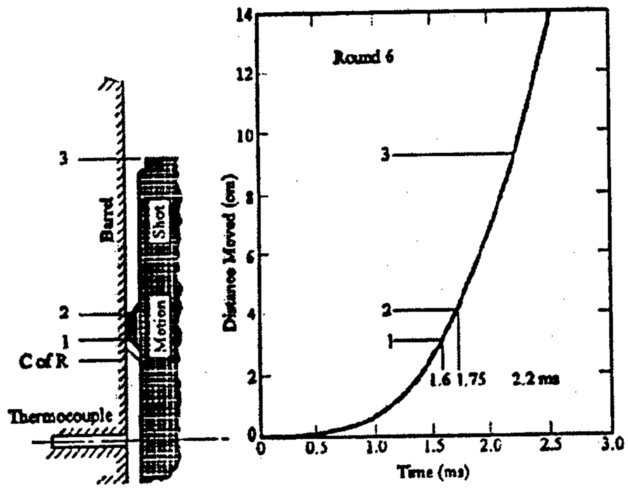

Figure 2a. Shot travel for a 40-mm Bofors gun computed from the measured pressure-time curve (ref 11).

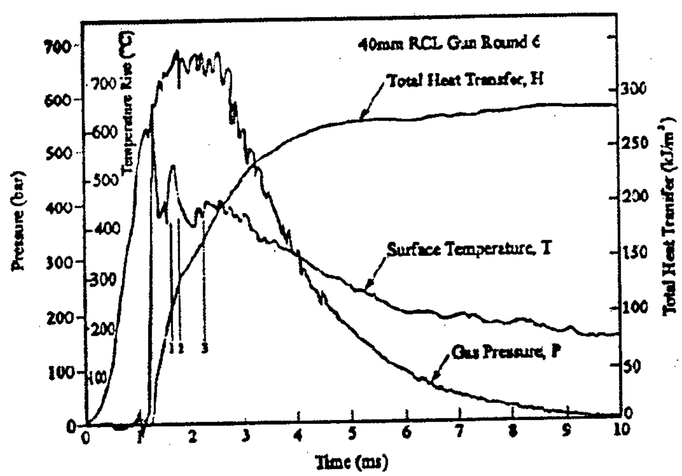

Figure 2b. Relation of 40-mm Bofors gun to pressure, surface temperature, heat transfer, and shot position (ref 11).

Interior Ballistics

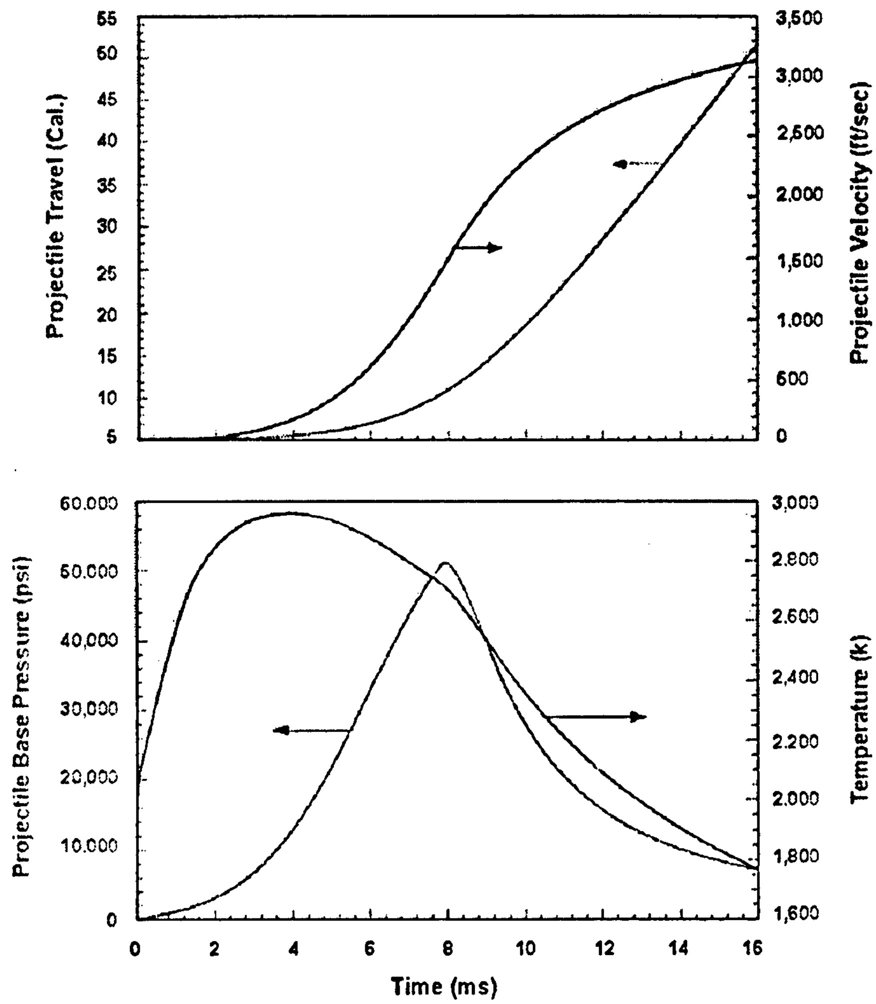

Figure 3. Simulation of inflow boundary conditions for M549A1/XM230/Zone 6.

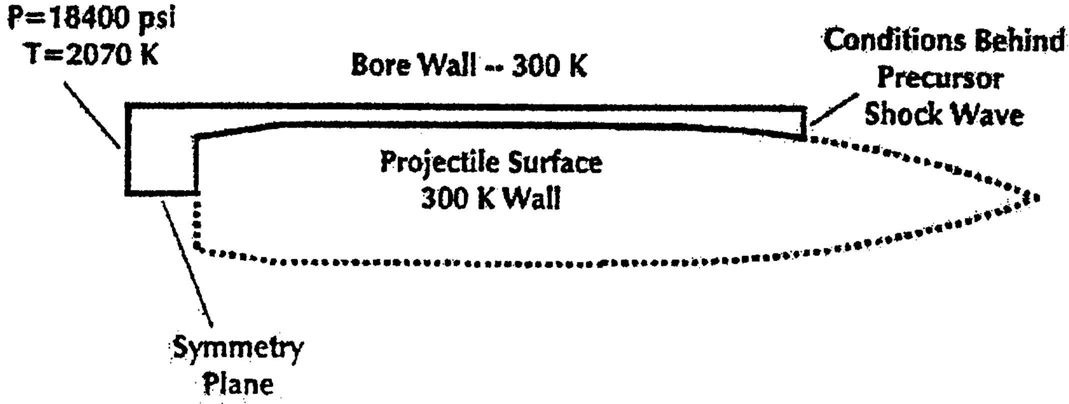

Figure 4. Boundary conditions for blow-by flow over projectile at 2.212 meters from the origin-of-rifling.

M549A1 at 5.256 m Travel

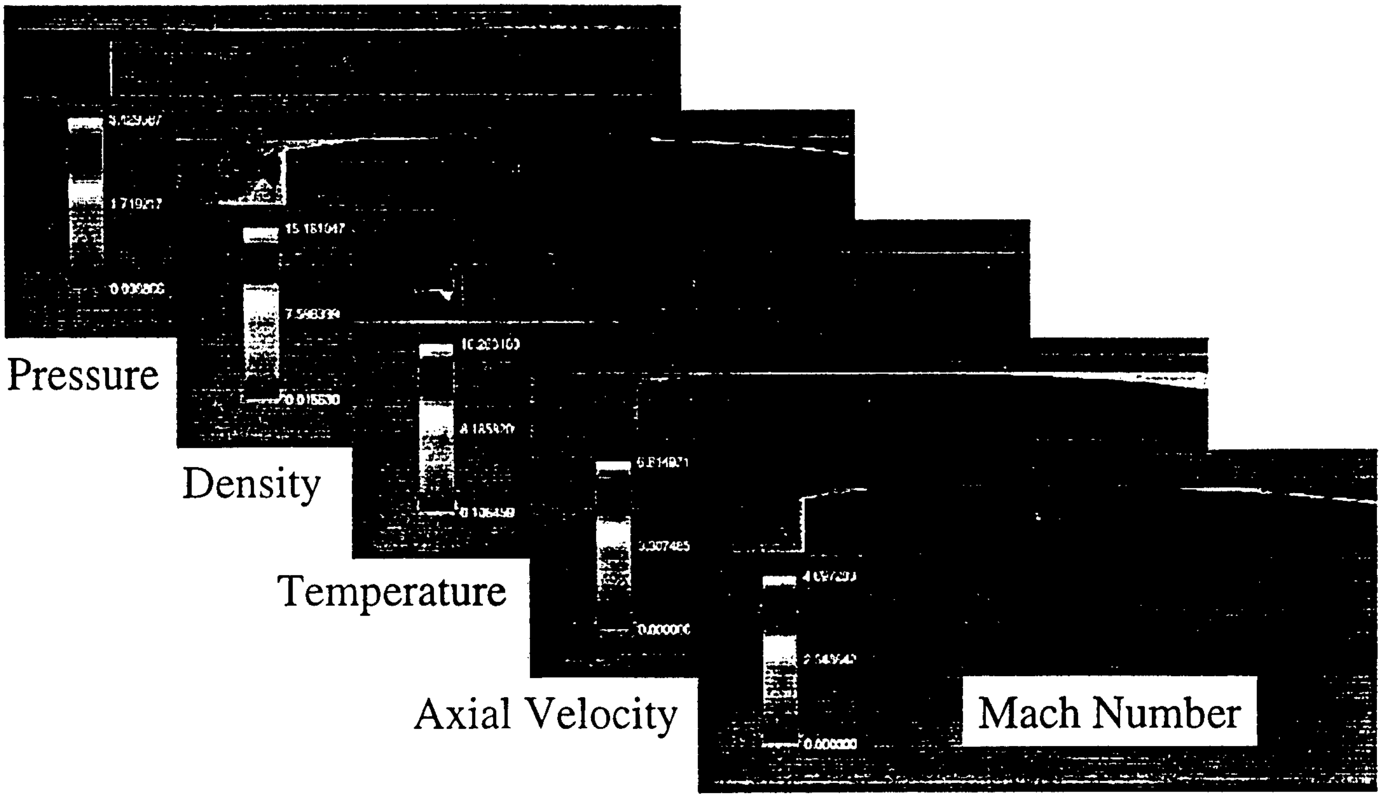

Figure 5. Composite blow-by flow field, 155-mm projectile
at 5.256 meters from the origin-of-rifling, 0.5 mm gap.

M549A1 at 5.256 m Travel

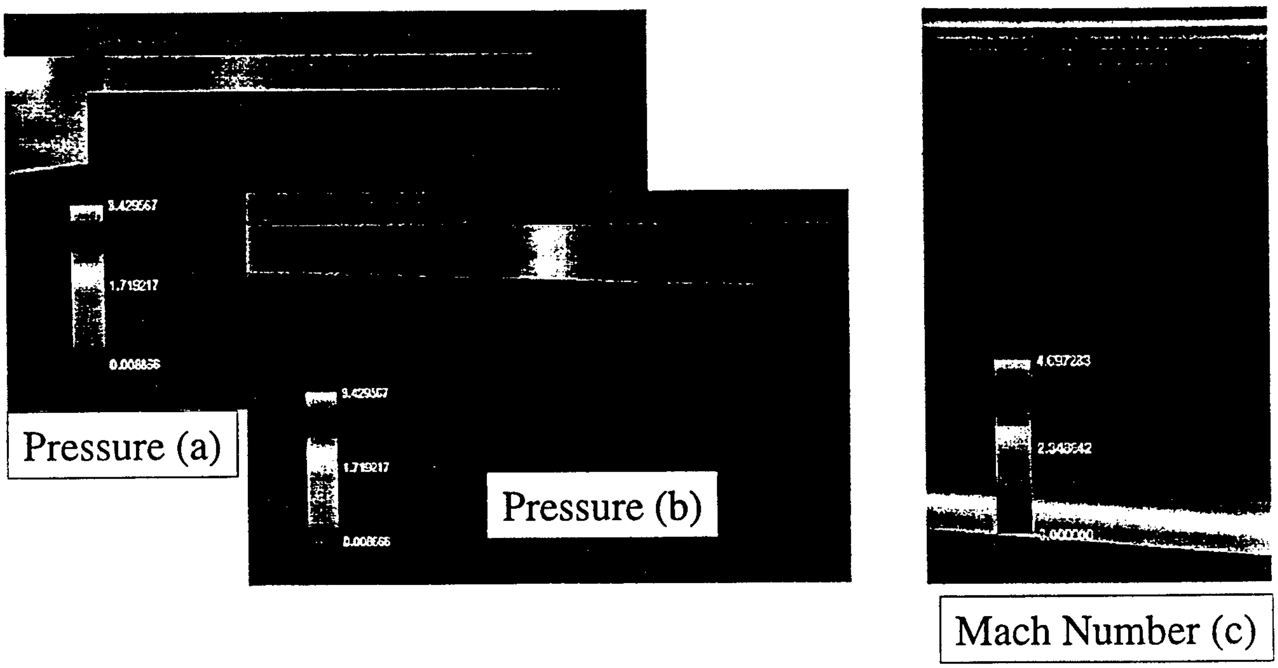

Figure 6. Magnified pressure field and Mach number of Figure 5 indicating shock structure: (a) zoom over obturator, (b) over the rotating band, and (c) ogive section.

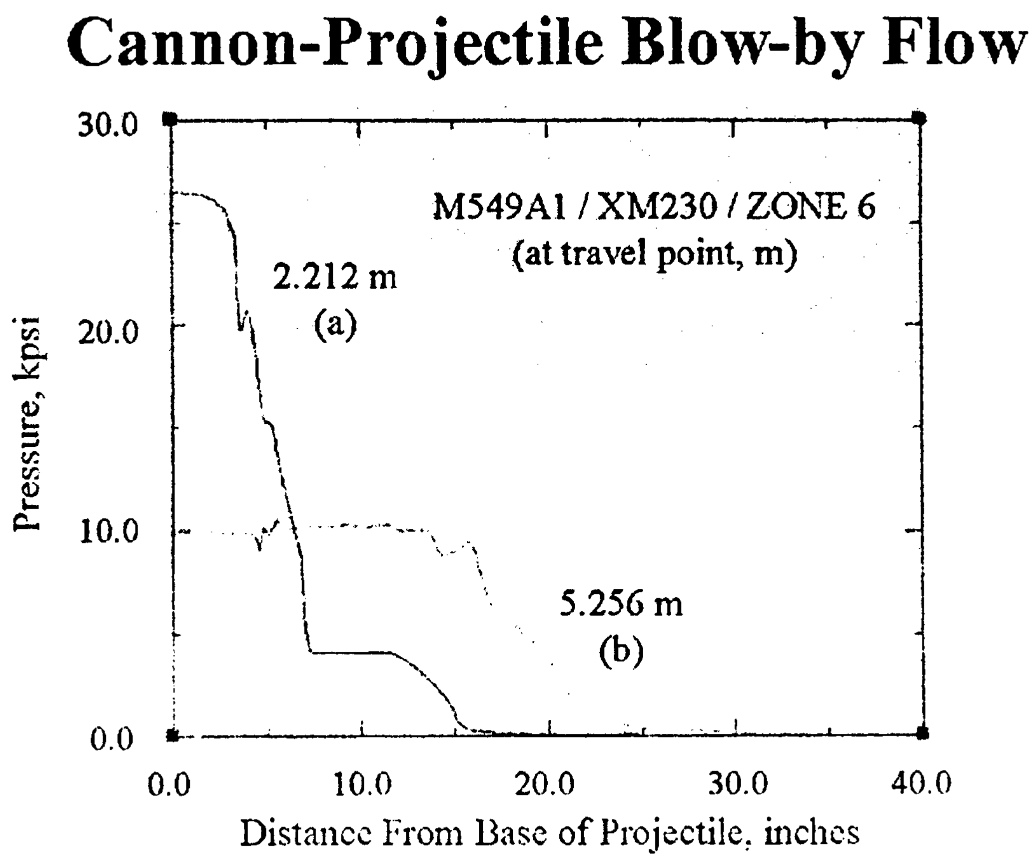

Figure 7. Pressure distributions on the projectile, no-obturator or band: (a) at 2.212 meters, and (b) at 5.256 meters.

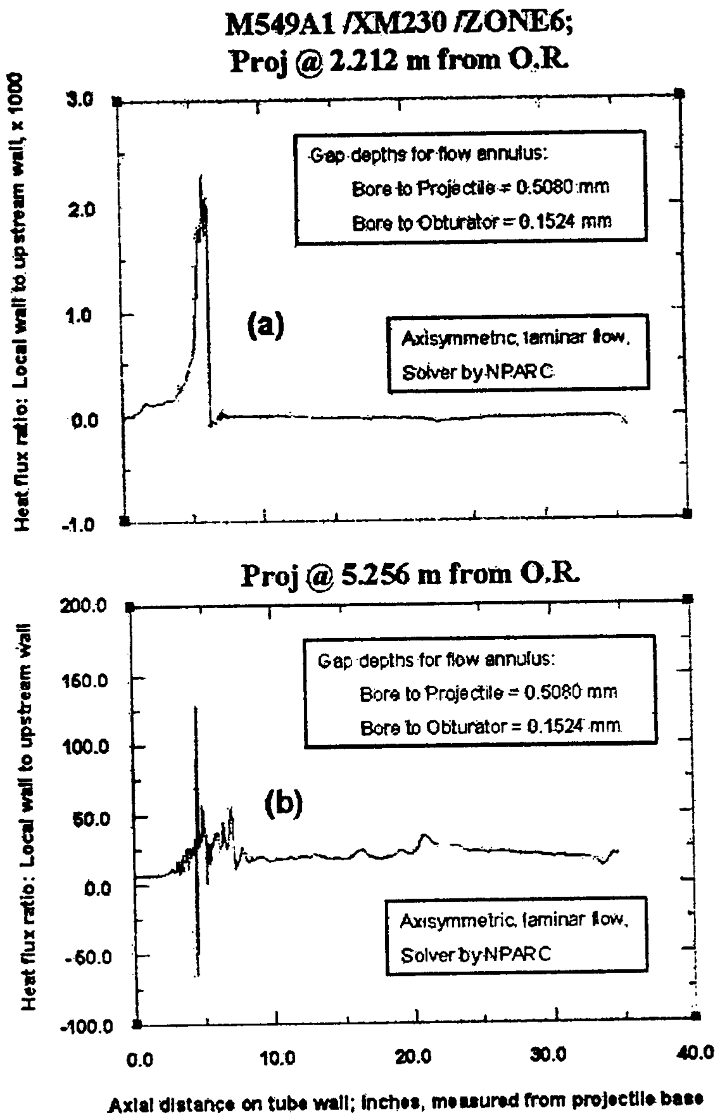

Figure 8. Heat transfer Stanton number ratio, bore wall to projectile wake boundary layer: (a) at 2.212 meters, and (b) at 5.256 meters.

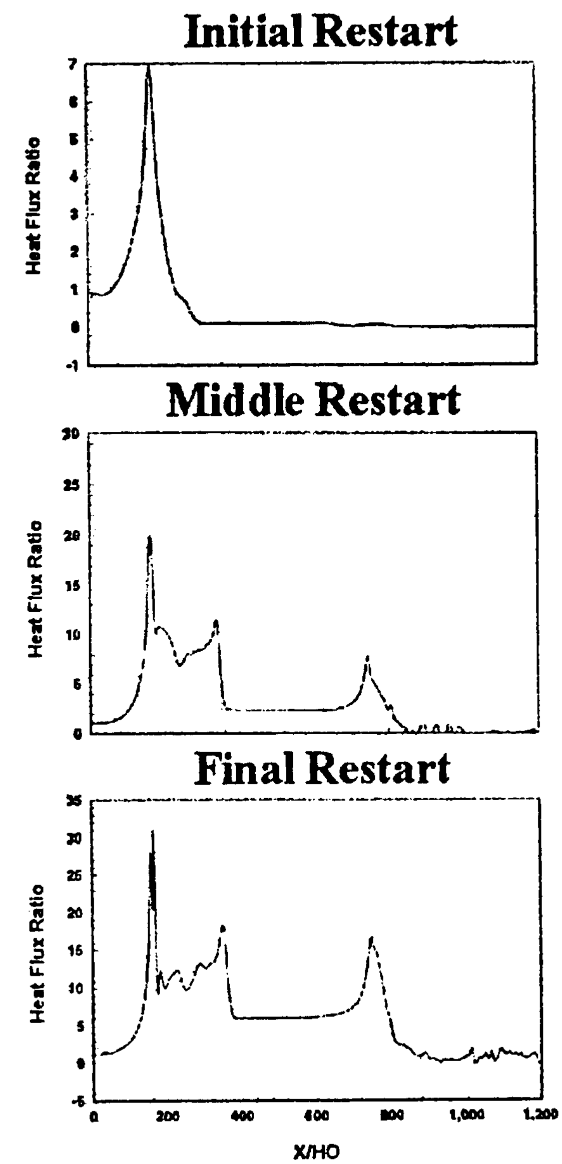

Figure 9. Illustration of convergence on heat transfer calculation, projectile at 2.212 meters from origin-of-rifling.

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