The development of the technology of ballistics as applied to gun launched Army weapon systems is the main objective of research at the US Army Ballistic Research Laboratory. The primary research programs at the BRL consist of three major ballistics disciplines: exterior, interior and terminal. The work done at the BRL in these areas has traditionally been highly dependent on experimental testing. A considerable emphasis has been placed on the development of computational modeling to augment the experimental testing in the development cycle; however, the impact of the computational modeling to this date has been modest. With the availability of supercomputer computational resources recently installed at the BRL, a new emphasis on the application of computational modeling to ballistics technology is taking place. The intent of this paper is to outline the major application areas which are receiving considerable attention at the BRL at present and to indicate the modeling approaches involved. An attempt has been made to give some information as to the degree of success achieved and indicate the areas of greatest need.

INTRODUCTION

The development of ballistics technology as applied to gun launched Army weapons systems is the main objective of research at the US Army Ballistic Research Laboratory. The primary research programs at the BRL consist of three major ballistics disciplines: exterior, interior and terminal. The work done at the BRL in these areas has traditionally been highly dependent on experimental testing. A considerable emphasis has been placed on the development of computational modeling to augment the experimental testing in the development cycle; however, the impact of the computational modeling to this date has been modest. This has been primarily caused by the lack of adequate computational resources at the BRL which has relied on a CDC 7600 computer since 1975. The CDC 7600 computer was replaced by a Cray XMP/48 computer in December 1986.

With the considerable increase in computational capability provided by this computer, a new emphasis on the application of computational modeling to ballistics technology is taking place. The intent of this paper is to outline the major application areas which are receiving considerable attention at the BRL at present and to indicate the modeling approaches involved. An attempt has been made to give some information as to the degree of success achieved and indicate the areas of greatest need.

Since the three ballistic disciplines represent well defined work areas, each discipline is discussed separately in the paper in the order: exterior, interior and terminal.
ties. Figure 6 shows the results achieved on a CPU using 2 million words of memory. The peak value of the pitching moment is about right; however, the trend of the coefficient with Mach number is unsatisfactory. Our latest attempt, which has not yet been published, was recently completed on the X-MP/48 at the NASA Ames Research Center. This computation took a year to complete due to problems of remote access, file storage and CPU availability. In order to carry out the full computation in which the entire projectile with the base region and the effect of surface spin are included, we expect to require at least eight million words of memory. The CPU time on an X-MP/48 using a fully vectorized code is expected to be of the order of 45 hours. This is the time using a single processor. It is obvious that to achieve improved turnaround time, the ability to perform computations on multiple processors is important.

Base Flow Modeling

Base region flowfield computations at zero angle of attack have been performed at BRL for several years. The results of these computational studies have been reported in References 6 and 8. The technique uses the thin-layer, time-marching Navier-Stokes computational code as reported by Nietubicz, Pulliam and Steger. An important feature of the technique is the ability to preserve the sharp corner at the base of the projectile. This is achieved using a zonal gridding approach.

An example of the application of this predictive capability to current projectile development concerns is shown in Figure 7 where two examples of irregular base region configurations are shown. These base configurations are currently being considered as modifications for fielded Army shell. The configurations are known to have measurable effects on the flight performance of the shell. Computational studies are underway to predict the total drag of the shell using the axisymmetric Navier-Stokes computational code. Using the X-MP class of machine, a substantial matrix of results can be developed over the speed range of interest, 1.8 < M < 2.5. An example of recent results achieved is shown in Figure 8 where the total drag for the standard and modified base geometries are plotted versus Mach number. Full 3D simulations are desired in order to provide the complete aerodynamic performance; however, the scope of results needed and the timeframe involved make this achievement unattainable.

The base flow modeling has been also been extended to include mass injection into the base region. This capability is desired to predict the performance of rocket base bleed and base bleed shell. The current configuration of the XM64A base bleed shell is shown in Figure 10 as an example. Recent results achieved in the modeling of this type of flow is shown in Figure 9 where the mass injected is modeled as a perfect gas. This figure compares the computation to an experiment conducted for the US Army Missile Command at AEDC. The results show comparisons of surface pressures at the base of the model. These results are encouraging; however, the real problem includes effects of multi-phase flow with combustion. The modeling of these effects is of considerable interest and research in this area is in progress.

Finned Projectiles

Kinetic energy penetrator projectiles are of considerable development interest within the Army. These are long L/D, finned projectiles which are launched at high supersonic velocities (M > 4.5) and have a very short time-of-flight (3-4 seconds maximum). A simplified drawing of a typical finned round (M735) is shown in Figure 10. A spark shadowgraph taken in the BRL Transonic Range of this projectile in flight at Mach = 4.5 is shown in Figure 12.

A series of computational studies for this type of projectile have been carried out using the PNS computational technique and are reported in Reference 9 and 10. Figure 13 shows the development of particle traces at the surface of the projectile in the vicinity of the fins. A comparison between the computations and free flight measurements of pitching moment is shown in Figure 14. In an attempt to achieve better comparisons with the experimental measurements, computations have been made with highly dense grids in the vicinity of the fins by coupling solutions from PNS and time-marching techniques. The results achieved indicate some improvement; however, further improvement in the ability to predict the aerodynamics of these shapes await the impact of greater computational resources than has been used to this date. This is especially true since current interest is in projectiles with L/D's greater than 20.

Interior Ballistic Modeling

The interior ballistic cycle involves the combustion of solid propellant in a gun tube which creates the high pressure required to propel the projectile out of the gun tube into free flight. The time of the cycle is of the order of 10-15 milliseconds. The maximum pressures reached are of the order of 50,000 psi and the flame temperature of the burning gases is of the order of 2500 °R. The configuration of the propellant consists of rods or sticks which are packaged together to form a loosely packed bundle or multiple bags of material.

The ignition of the propellant is a very important aspect of the burning since the pressure-time behavior of the combustion process can, if too violent, result in the destruction of the breech of the gun. Thus, the interior ballistic problem has the following characteristics: (1) time dependent; (2) multi-phase flow (solid and gaseous); (3) combustion; (4) high temperature; (5) high pressure; (6) real gas effects; (7) chemically reacting gas.
Due to the highly complex nature of the interior ballistic problem, current computational modeling techniques are far from being able to adequately model the full physical processes of interest. Thus, current computational modeling makes use of a combination of lumped parameter, two-dimensional phase flow, quasi-one-dimensional flow modeling and modified constitutive laws for chemical energy release, frictional losses, heat loss to the gun tube and erosive burning. A schematic illustration of a bagged charge inside of a gun chamber is shown in Figure 15. This drawing shows the basic configuration of the interior ballistic problem prior to ignition. A schematic illustration of the configuration for a multi-increment charge is shown in Figure 16. The presence of considerable ullage (or empty space) is illustrated and is an important factor in the performance of the propellant. The combination of modeling techniques used to model this multi-increment configuration is shown in Figure 17.

**Armor Penetration**

There are a number of penetration and impact codes which have been developed. Eight such codes are surveyed in Reference 13. EPIC-3 is a finite element code in a Lagrangian formulation. Models for material properties and equations of state to account for high energy impact are an important part of the computational technique. An example of an EPIC-3 computation for impact of a steel ball onto an aluminum plate is shown in Figure 18. Excellent agreement with experiment has been obtained for this case.

Another code used extensively at BRL for armor penetration modeling is the EPIC-2 code. An example of the application of this code to predict the penetration of single plate armor by a long rod is shown in Figure 19. In this figure, examples are shown of the time-dependent armor penetration process for two angles of impact, normal and oblique to the surface. The modeling of the armor penetration process is accomplished by a combination of Lagrangian and Eulerian techniques. Modeling of the dynamic response of the target material to the high energy release is an important aspect of this computational technique. The full problem of interest requires the capability to model penetration of multiple armor plates at high angles of obliquity. Fully three-dimensional computations require considerable computer resources in terms of CPU time and storage capacity.

**Incident Blast Wave Effects**

Blast effects are of concern in the ability of military vehicles and command post structures to withstand the effects of incident blast/thermal waves caused by nuclear bursts. The computational modeling of these effects utilizes time-dependent Euler and Navier-Stokes techniques. A typical example of the problem of interest is depicted schematically in Figure 20 where a vehicle is shown being struck by an incident blast wave. Reference 17 reported the application of an inviscid, finite-difference code to predict the time-dependent flow over several objects of generic interest. An example of the resulting sequence of density contours for the flow over the truck is shown in Figure 21. Fully three-dimensional viscous computations coupled with the effect of the thermal pulse are required to properly model the complex shapes and flowfield conditions of interest.

**Closing Remarks**

A brief overview has been presented of the computational modeling applications and activities at the US Army Ballistic Research Laboratory. The topics covered are by no means complete. Several additional areas of active research are in progress. The scope of this paper was not intended to provide a complete coverage, only a partial coverage within the allowed constraints. Given the supercomputer resources now available at the BRL, the impact of computational modeling on weapon system design and development is certain to become significant.

**References**


Figure 1. Aerodynamic Forces on a Spinning Shell

Figure 2. Critical Aerodynamic Behavior of a Boat-tailed Artillery Shell

Figure 3. Simplified Geometry of the M483 Artillery Shell

Figure 4. Spark Shadowgraph of a Shell in Flight at M = .96
Figure 5. Spark Shadowgraph of a Shell in Flight at M = 2.3

Figure 6. Pitching Moment Versus Mach Number for M549 Shell

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Figure 8. Total Drag Versus Mach Number for the Standard and Domed Bases, M483

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Figure 16. Schematic Illustration of a Multi-Increment Charge
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Figure 19a. Penetration of a Single Plate by a Long Rod

Figure 19b. Penetration of a Single Plate by a Long Rod
Figure 20. Schematic Illustration of a Vehicle-Blast Wave Interaction

Figure 21. Density Contours for Blast Wave-Vehicle Interaction