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High-Performance Computing and Simulation for Advanced Armament Propulsion

by Michael J. Nusca

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14. ABSTRACT

The U.S. Army is exploring a variety of armament propulsion options for indirect- and direct-fire weapons to be employed in the legacy force and for the Future Combat System (FCS). Development of propelling charges for these weapons requires state-of-the-art physics-based modeling codes. The gun propulsion-modeling environment has traditionally been one in which independently developed and upgraded computer codes were used to analyze different propulsion techniques, with no single maintainable code able to evaluate several candidate systems. This situation rendered comparison of ballistic performance for various weapon options cumbersome and inconclusive. In direct response to this situation, the U.S. Army Research Laboratory (ARL) has developed a "next-generation," computer scaleable, three-dimensional, multiphase, computational fluid dynamics code for armament propulsion (interior ballistics) modeling. ARL's NGEN3 code represents the sole Department of Defense (DOD) computer tool that is able to simulate the highly complex physics associated with indirect- and direct-fire guns. NGEN3 code development and application to the FCS was a 2001–2002 DOD high-performance computing challenge project and was being greatly advanced by priority access to the DOD Major Shared Resource Centers.

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1. Introduction

The U.S. Army is exploring a variety of armament propulsion options for indirect- and direct-fire weapons (guns) for the legacy force and the Future Combat System (FCS). As it transforms, the U.S. Army has identified requirements for hypervelocity projectile launch systems for strategic U.S. Army missions. Among these systems are those that use solid propellant—granular form loaded in modules (indirect-fire) or disk and strip form for high loading density (HLD) cartridges (direct fire)—augmented by electrothermal-chemical (ETC) technology. Two such armament propulsion systems are the U.S. Army's Modular Artillery Charge System (MACS) and HLD charges for the FCS. The MACS is being developed for indirect fire cannon on current 155-mm systems (e.g., M109A6 Paladin and M198 Towed Howitzer). The efficiency of the MACS charge is dependent on proper flamespreading through the propellant modules—a process that has been repeatedly demonstrated in gun firings, successfully photographed using the U.S. Army Research Laboratory (ARL) 155-mm ballistics simulator, and numerically modeled using the ARL NGEN3 code. The FCS requires weapons systems exhibiting increased range, accuracy, and highly repeatable projectile launch performance. One of the technologies under investigation to achieve these goals is the ETC concept, in which electrically generated plasma is injected into the gun chamber in order to efficiently and repeatedly ignite the high-energy and HLD solid propellant charge.

As modular and HLD propelling charges are being developed, optimized, and ultimately mated to systems such as indirect fire cannon and the continually evolving FCS, there is a critical need to have a single, validated, maintainable computer code based on state-of-the-art computational fluid dynamics (CFD), as an evaluation and performance analysis tool. It has long been recognized that the availability of such a tool would provide the U.S. Army with the unique capability to simulate current and emerging gun propulsion systems using computer simulations. These simulations would serve to both streamline testing and aid in the optimization of weapon performance. Indeed, such a tool would dovetail nicely with the U.S. Army's initiative in the creation of national high-performance computing (HPC) facilities. However, the gun propulsion-modeling environment has historically been one in which separate codes (some one-dimensional [1-D], some two-dimensional [2-D]) are used, with no single multidimensional code able to address the truly three-dimensional (3-D) details of all of these weapons systems. This unfortunate situation renders comparison of ballistic performance cumbersome and inconclusive. In contrast, the multiphase continuum equations that represent the physics of gun propulsion comprise a set of general equations universally applicable to all solid propellant armament propulsion systems.

In direct response to this situation, ARL began a development program ~8 years ago to revolutionize the U.S. Army's ability to use HPC to simulate propelling charges. The current author at ARL, with consultation from noted industry/academic experts, has worked on the project. The result is the U.S. Army's "Next Generation" computer scaleable 3-D multiphase CFD code for armament propulsion modeling. The ARL's NGEN3 code represents the sole Department of Defense (DOD) computer tool that is able to simulate the highly complex physics associated with indirect and direct fire guns. NGEN3 code development and application to the FCS was a 2001–2002 DOD HPC Challenge Project and was being exercised regularly with priority access to the DOD Major Shared Resource Centers (MSRCs).

2. Complex Physics Requiring HPC

A brief description of the physics of armament propulsion demonstrates the nature of this computing challenge and the necessity of state-of-the-art computer tools for use by the Army weapon system designers.

A solid propellant gun system consists of a reaction chamber connected to a gun tube through which a projectile is guided once propelled by pressurization of the chamber. Chamber pressurization is accomplished by placing a solid propellant (SP) charge in the chamber and igniting it by various means. Current SP charges are generally complex structures consisting of hundreds or even thousands of distinct regularly formed (e.g., spherical and cylindrical) grains, which may be loaded in either regular or random arrangements. In addition to small-scale voidage between grains (i.e., porosity), many charges also contain large-scale voidage (i.e., ullage), which surrounds the entire charge (such as when the charge does not fill the entire chamber volume) or separates distinct subcharges (i.e., increments or modules) that together comprise the whole charge. The addition of energy to the chamber, usually near the gun breech, or rearmost end of the chamber, and in some cases through a tube extending along the centerline of the chamber, ignites the SP. In general, all of the grains are not ignited simultaneously, but an ignition flame spreads from the breech to the projectile base.

The burning of the SP transforms chemical energy into heat as hot gases evolve from the surface of each grain of propellant. Initially the projectile resists movement allowing the pressure in the chamber to climb rapidly. Because the burn rate of the propellant is proportional to the pressure, hot gases are produced at an accelerated rate until peak pressure is reached in the chamber. Movement of the projectile down the gun tube, usually slight before peak pressure and much more significant afterwards, causes the chamber volume to increase and generates rarefaction waves that lower the pressure and thus the burn rate of the propellant. Upon ignition and burning, the gas dynamic flowfield in the gun chamber takes on a highly complex structure that includes the dynamics of propellant motion and combustion and various gas dynamic flow phenomena such as turbulent mixing, highly transient pressure waves, steep gradients in porosity and temperature, nonideal thermodynamics, and gas generation.

As a direct result of the complexity of the interior ballistic event, previously described, numerical simulation of the multiphase gas dynamics and propellant combustion in a gun chamber is critically important to gun charge design. In some cases, a new charge design is not performing as planned and numerical simulations are used to elucidate the important physics involved during flamespreading in the SP and augment experimental data gathering during gun firings. These efforts commonly lead to subtle charge design changes that increase the efficiency of the new design. In other cases, a new charge design can generate pressure waves of dangerously high levels that inappropriately stress the gun system. A central goal in computer modeling of the interior ballistics event is to predict the maximum pressure in the chamber and the projectile's gun tube muzzle velocity.

For some SP charges, successful modeling can be accomplished using 1-D, single-phase, “lumped parameter” models, which are based on the assumption that grains and the products of combustion constitute a well-stirred mixture. However, it has long been recognized that many charges, especially those involving multiple increments and complex distributions of ullage—the effects of which are nonuniformities in certain interior ballistic events (e.g., ignition) can only be simulated on the basis of a multidimensional multiphase flow model. In an ETC gun, the plasma injection event and the resulting plasma convection, diffusion and participation in ignition and flamespreading, through the SP, is also most accurately simulated using a multidimensional multiphase flow model.

Multidimensional, multiphase flow modeling of a single armament launch scenario proceeds from propellant and projectile loading (initial conditions) to propellant consumption and projectile launch. Each detailed simulation necessarily requires large amounts of computer memory (10–50 Gb) and time (10–130 CPU hr). As a result, the HPC resources made available by the DOD are being utilized by ARL when employing the NGEN3 code, as discussed in the following section.

3. The Emergence of a New Computing Tool for the U.S. Army

As the U.S. Army transforms, there is a renewed interest in armament propulsion systems wherein the projectile is of greater complexity and larger size, with an afterbody that extends into the gun chamber and a solid propellant charge that is contained in a smaller volume, and is therefore necessarily of high energy and HLD. Design and optimization of such systems requires a “next generation” of computer modeling tools. The ARL NGEN3 code is a direct response to this need, having been in development, testing, and validation for the last eight years. In this section, the truly unique features of the NGEN3 code are reviewed including the first use of a coupled Eulerian/Lagrangian solution scheme in multiphase CFD propulsion codes. This original modeling feature enables the NGEN3 code to resolve system details not attainable from other models.

The NGEN3 code has been documented elsewhere (*1–3*) The governing equations, state equations, and constitutive relations have been detailed in other papers (*1*, *4*, *5*). The 2-D version of the code (physical and numerical models) is briefly described herein. Extensions to 3-D are described elsewhere (*2*).

3.1 Generalized Governing Equations

A modeling code capable of treating a wide variety of gun propulsion systems must be based on a solution of the conservation equations for a multiphase, turbulent reacting flow. Two phases are considered: a continuous phase (multicomponent mixture of gases and liquids in local mechanical equilibrium) and a discrete phase (aggregate of particles made up of solid/liquid propellant reactants and combustion products as well as wear-reducing additives and pieces of the propellant container). The continuous phase is characterized by single local values for the dependent variables: density (ρ), velocity (**u**), pressure (p), temperature (T), shear stress (τ), and internal energy (e). It is assumed to comprise N_C species (e.g., air, plasma, and solid propellant gaseous products) with local values of the mass fraction, Y_i, and molar fraction, X_i. Each component, i, is characterized by a diffusion velocity, $\mathbf{v}_i$, relative to **u**, the mass weighted average velocity of each of the components. The discrete phase consists of N_d components (e.g., unburned/burning propellant), each characterized by values for the dependent variables, number density (n_d), volume (V_d), and surface area (S_d).

On a sufficiently small scale of resolution in both space and time, the continuous phase is represented by the balance equations for a multicomponent mixture cast in conservation form (*1*, *4*, *5*). These equations describe the conservation of mass (global and for each species), momentum, and energy. For example, the balance equation for the energy is

$$\frac{\partial}{\partial t}\left[\rho\left(e+\frac{u^2}{2}\right)\right]+\nabla\bullet\left[\rho\,\mathbf{u}\left(e+\frac{u^2}{2}\right)-\mathbf{u}\bullet\sigma+\mathbf{q}\right]=0\,, \tag{1}$$

where the stress tensor is σ = –p **I** + τ, with **I** as the unit tensor. Heat flux, **q**, includes radiative transport as well as mass and thermal diffusion. The presence of a dispersed phase makes the governing equations computationally intractable. In order to achieve more reasonable computer times, a macroscopic representation of the governing equations is adopted based on properties of the flow over length scales whose size is large compared to the length scale of the individual particles. A detailed derivation of the macroscopic balance equations is presented elsewhere (*4*). Mass and momentum are conserved in the discrete phase. A porosity variable (α) is defined to map variables from the discrete to the continuous phase

$$\alpha=1-\sum_{i}^{N_d}\alpha_{di}=1-\sum_{i}^{N_{di}}n_{di}\,V_{di}\ , \tag{2}$$

where α_{di} denotes the volume fraction of the i-th discrete phase consisting of n_{di} particles per unit volume, and the volume of a particle, V_{di}. No provision is made for transformation of one discrete phase into another. If the solid phase is considered to be incompressible (or nearly so, such that the solid phase is not thermally excited), the energy equation is not required. The macroscopic balance equations require a number of constitutive laws for closure. These include laws governing the molecular and turbulent transport terms, the equation of state for continuous and discrete phases, chemical reaction rates, intergranular stresses, and interphase transfer of energy, momentum, and mass. In addition, the morphology of the discrete phases is required and is typically expressed as a surface area per unit volume of each particle.

3.2 Boundary Conditions for Propelling Charges

Boundary conditions for the governing equations are divided into external and internal types. The external boundaries, i.e., those outside the numerical domain, usually include the gun breech face, the gun tube wall, and the base of the projectile. On these surfaces, conditions are derived that prescribe tangential slip of both phases. Flux conditions can be prescribed for reactive walls (e.g., a center core igniter tube or the plasma moderator tube). If wall boundary layers are to be resolved on inert surfaces, no-slip conditions are prescribed for the continuum phase. A flux condition is used for surfaces where propellant or plasma is injected. Internal boundaries (i.e., those within the numerical domain) usually separate two distinct regions and require a coupling formulation. A type of internal boundary is used in the MACS charge simulation. Boundary cells are placed around each module that are impermeable to flow until a prescribed pressure loading is attained. Once this threshold is exceeded and a prescribed rupture delay time interval has elapsed, flux into and out of the charge is unimpeded (partial flow is permitted when the pressure criteria is satisfied, but the time interval has not elapsed). A rigid body analysis is enforced up to the instant of container burst. In addition, the separation of a container end wall (or cap) due to overpressure can be modeled without relaxation of the rigid body treatment for the remainder of the container. The temperature of the cases, initially at an ambient value, is raised via convective heat transfer from the surrounding hot gases (generated by components that are ignited). The cases ignite producing hot gases in accordance with specified material properties.

3.3 Coupled Eulerian/Lagrangian Solution Schemes

The balance equations constitute a system of coupled partial differential equations that can be solved using a finite-difference technique. The derivatives in these equations are converted to algebraic expressions that pertain to a rectangular mesh of discrete, ordered points distributed about the geometry. Nonorthogonal geometric surfaces are handled using partially occluded cells (i.e., partially within geometric surfaces). Values of the dependent variables are determined at the cell centers using an iterative numerical method in space and time. An explicit method is chosen because the resolution of boundary layers (either on chamber walls or particle surfaces) is not considered. The numerical time step is limited by characteristic cell dimension and the fastest wave speed (Courant condition), except near the mesh boundaries where numerical stability is ensured by a Method-of-Characteristics based technique (*5*). The Courant condition is not overly restrictive for the present class of gas dynamic problems because the need for wave tracking is apparent, and thereby integration using Courant numbers larger than unity is not desirable.

Particularly unique and original to the NGEN3 code are the Continuum Flow Solver (CFS) and the Large Particle Integrator (LPI). The spatial values of the dependent variables at each time step are determined by a numerical integration method, denoting the CFS, which treats the continuous phase and certain of the discrete phases in an Eulerian fashion. The Flux-Corrected Transport scheme (*1*) is a suitable basis for the CFS because the method is explicit and has been shown to adapt easily to HPC systems. The discrete phases are treated by a Lagrangian formulation, denoting the LPI, which tracks the particles explicitly and smoothes discontinuities associated with boundaries between propellants, yielding a continuous distribution of porosity over the entire domain. The manner of coupling between the CFS and the LPI is through the attribution of properties (e.g., porosity). The size of the grid as well as the number of Lagrangian particles is user prescribed. For the simulations of novel solid propellant configurations, such as slabs (disks) stacked axially along the chamber centerline and/or thin annular concentric layers (wraps), the NGEN3 code takes a macroscopic approach. These solid propellant media are modeled using Lagrange particles that regress, produce combustion product gases, and respond to gas dynamic and physical forces. Individual grains, sticks, slabs, and wrap layers are not resolved; rather, each medium is distributed within a specified region in the gun chamber. The constitutive laws that describe interphase drag, form-function, etc., assigned to these various media, determine preferred gas flow paths through the media and responses of the media to forces.

4. Recent Accomplishments

4.1 Description of the MACS

The U.S. Army's MACS is the propulsion system for all fielded 155-mm guns, including the M109A6 Paladin and the M198 Towed Howitzer. The MACS charges are designed to both significantly increase muzzle energy and to be suitable for application in automated loading systems. As a result of the modular charge design there is a physical barrier (i.e., the case) at the interface between two adjacent charge increments. Because direct ignition transfer is therefore impeded, charge ignition may not proceed in the order in which the charges are loaded into the gun chamber without a highly effective ignition system. These system-specific details (such as the propellant module cases and igniters) must be modeled as part of the overall numerical simulation and cannot be accurately treated with less than a multidimensional CFD code (i.e., 1-D "lumped-parameter" models cannot properly model the MACS). The efficiency of the MACS charge is highly dependent on proper flame spreading through the modules, which can only be modeled using the NGEN3 code because ignition and flame spreading in the MACS charge are largely three-dimensional. Data from experimental pressure taps located on the gun chamber wall and photographs/movies of the MACS in the ARL's clear tube simulator do not provide enough detail to diagnose the performance of the MACS charge.

The NGEN3 code was used to analyze the M231 and M232 charges that have been recently developed and type classified at the U.S. Army's Armament Research, Development, and Engineering Center in a typical 155-mm cannon. Three significant accomplishments using the NGEN3 code are as follows:

1. NGEN3 simulations for the M231, low-zone MACS charge, displayed the importance of nonsequential center core charge ignition, module movement and case ignition/burn-through, 2-D and 3-D propellant flame spreading behavior within the modules, module cap separation, and nonsequential module bursting (*1*).

2. The NGEN3 code was used to uncover a heretofore-unknown physical phenomenon for the M232 high-zone MACS charge that only occurs during charge fallback in an elevated gun tube (*6*). NGEN3 simulations of these charges proved that a prevailing gas dynamic process, when the modular charges are positioned adjacent to the gun chamber breech face, would cause the rigid charge modules to be displaced forward. This displacement mitigates any pressure wave formation that would have occurred had the charges remained on the breech face during flame spreading and rupture. Laboratory fixture tests, conducted at ARL, validated the code. Subsequently, the NGEN3 simulations for the M232 were used to plan range testing of the XM297 cannon. These gun tests confirmed that M232 increments at zones 4–6, positioned adjacent to the wedge face, support predictions by the NGEN3 code; the ballistic cycle is virtually unchanged, except for slight differences in timing.

3. NGEN3 code simulations for the M232 charge uncovered a heretofore-unknown physical phenomenon involving the importance of case combustion (*7*). It was found that case combustion is clearly a significant contributor to chamber pressure and a significant factor in the generation of pressure differentials in the gun chamber. NGEN3 simulations indicate that the prediction of pressure differentials that are similar to those measured in the gun firings are not possible without first achieving good agreement with measured pressure data early in the ballistic cycle and including case combustion effects.

Unfortunately, graphical results of the simulations leading to these accomplishments cannot be provided in this public-release report. As both a substitute and as a means of demonstrating the NGEN3 code, this section does include several illustrative examples of both MACS-type charges. These results represent a unique examination of the MACS charge not achievable without the NGEN3 code and heretofore not available to the charge design community.

4.2 Results for a Typical Modular Charge

Figure 1a shows a schematic of the gun chamber filled with propellant. Because the configuration is axisymmetric, only one radial plane is displayed that extends from the chamber

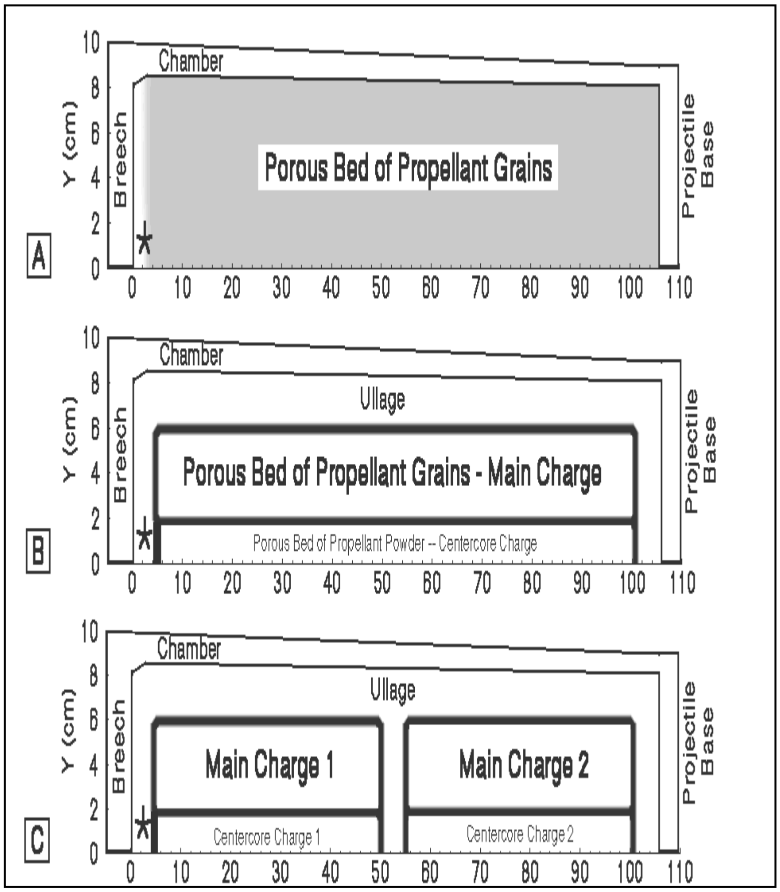

Figure 1. Schematics of gun charge configurations: (a) loose charge, (b) packaged charge in single module, and (c) packaged charge in two modules. Ignition source indicated by (*).

centerline (y = 0) to the outer wall (sloped from 8.4 to 8.1 cm). The axial extent, from the breech to the projectile base, is 106 cm (the gun tube extends beyond this point for an additional 594 cm). The projectile mass is 44 kg and resists movement for the first 5 cm of travel. The granular propellant is cylindrical. The porosity of the propellant bed is 0.63.

Figures 1b and 1c show alternate arrangements in which the granular propellant is packaged in either one or two cylindrical modules. These modules are assumed to be aligned along the centerline of the chamber and to consist of a main charge section (porosity of 0.63) and a center core that is filled with ball propellant with properties that are distinct from the granular propellant (porosity of 0.4). The module is sealed with walls that are rigid but permeable, admitting flow (or “leaking”) only after a significant gas pressure differential has been reached. Subsequently, these walls are allowed to break or “burst” after a fixed time interval has elapsed since over pressurizing. A rigid body analysis is enforced up to the instant of container burst. These walls can resist substantial pressure loading except for the radial wall separating the main charge from the center core (i.e., an internal wall) and the axial wall that represents a module cap that is used to fill the modules. This cap is located at the module end closest to the chamber breech. However, breakage of the internal wall or the module cap does not relax the rigid body treatment of the remaining module components. In each case, the charge is ignited at the breech end, near the chamber centerline over 2 cm of length, 3 cm in radius, and during the first 6 ms.

Figure 2 summarizes the computed results for the packaged charge of two modules (figure 1c). The breech-end igniter starts an ignition wave or flame that quickly opens and ignites the first pressure waves, traveling though the radial ullage and into the region near the projectile base, over-pressurizing and bursting the second center core at its far axial end (figure 2e). As a result, main charge flame spreading in the second module begins nearest to the projectile base (figure 2h). By 11 ms, the main charge of the first module is fully ignited, causing increased pressure that bursts the end cap, causing high-velocity flow against the breech face (figure 2g) and a sudden forward movement of the first module. This movement increases the pressure against the end cap of the second module and causes it to burst (figure 2i). These events cause the second module to move forward and impact the projectile base (figure 2j).

The pressure history of the events described in figure 2 is shown in figure 3a. For this case of two modules, the breech pressure is slowly increasing and is nearly coincident with projectile base pressure (zero pressure differential) until ~10 ms. Subsequently, the base pressure increases rapidly (negative 1.5-MPa pressure differential) in response to pressure waves caused by the initial disintegration of the first module and the igniting of the second. Between 11 and 18 ms, a series of three pressure waves (repeating positive, +1 MPa, and negative, –1 MPa, differentials) is caused by the movement and breakup of the modules. Another negative pressure differential (–2.5 MPa) occurs at 21 ms due to the impact of the second module upon the projectile base. Negative pressure differentials (i.e., pressure at the projectile base is larger than that at the chamber breech) are potentially dangerous to the structure of the gun chamber and the projectile payload. Such waves are generally absent from unconfined (i.e., nonpackaged) propellant charges. After this time, the now-loose propellant is free to move within the chamber, and these waves subside (note positive differential after 22 ms in figure 3a). Even though the case of a single module would seem to be less complex, the pressure history for this case (figure 3b) shows a larger negative pressure differential that is fortunately short lived. Detailed results from the NGEN3 code (omitted in this report due to space limitations) show similar events as reported in figure 2.

4.3 Description of HLD Charges and ETC Technology for the FCS

The FCS requires weapons systems exhibiting increased range, accuracy, and highly repeatable projectile launch performance. Several technologies are under investigation in order to achieve these goals. HLD charges consist of SP cast in several media types (e.g., grains, sticks, and disks) combined into a single charge. These combinations along with small-scale gaps between SP media and large-scale ullage around the projectile after body create special concerns for efficient ignition and flame spreading in the HLD charge. A promising ignition technology for HLD charges is the ETC concept. In the ETC concept, energy, which is stored either in batteries or in a rotating device, is converted on demand into an electrically generated plasma (resulting from the ablation of polyethylene material in a capillary) that is injected into the chamber of a gun. This plasma energy is used to ignite the chemical charge as well as to enhance gun

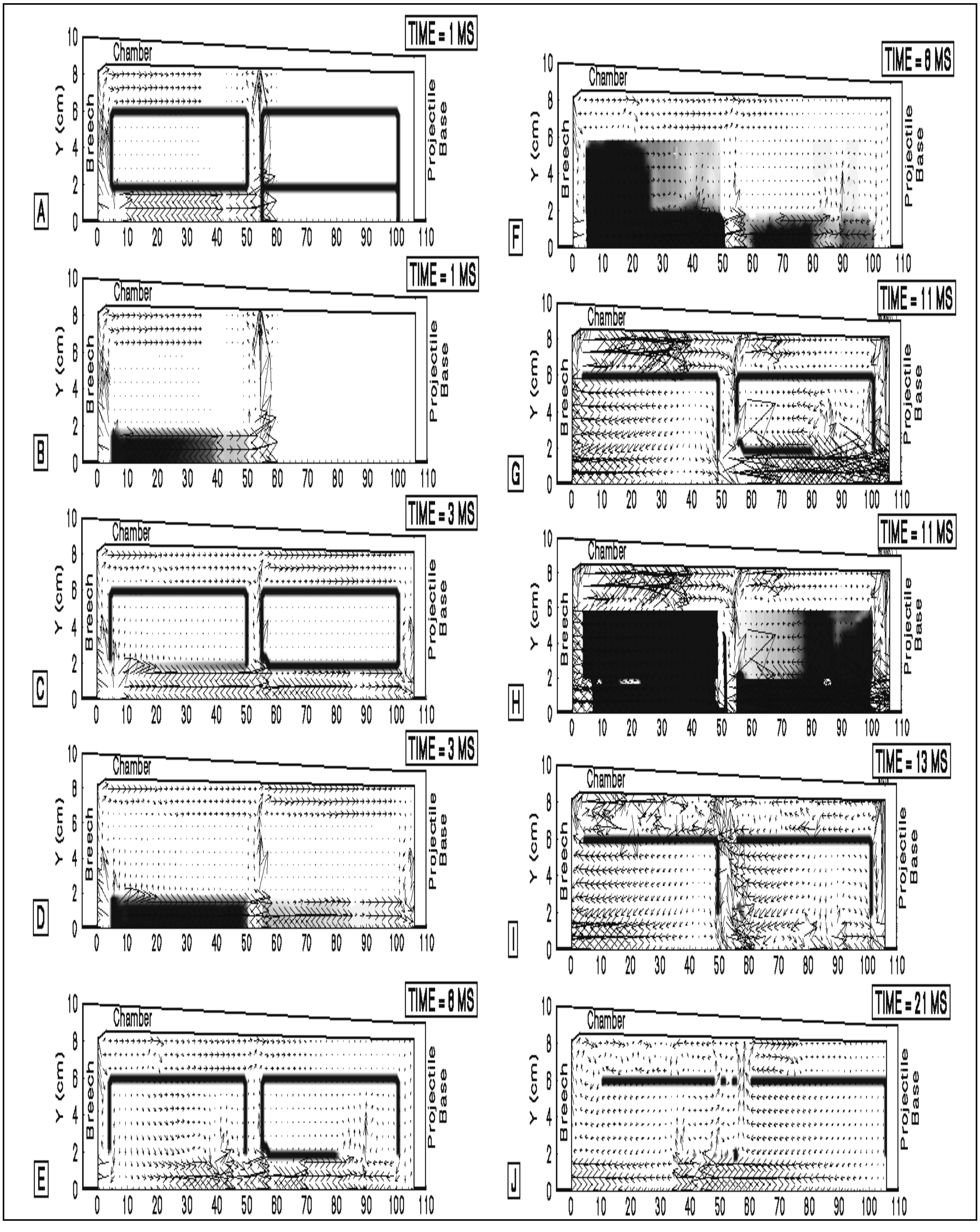

Figure 2. Computed results for packaged charge (two modules): (a, b) time = 1-ms, (c, d) time = 3-ms, (e, f) time = 8-ms, and (g, h) time = 11-ms gas velocity vectors along with module boundaries (a, c, e, and g) and propellant temperature contours (b, d, f, and h) from 294 K (white) to 440 K (black). Computed results for packaged charge (2 modules): (i) time = 13-ms and (j) time = 21-ms gas velocity vectors along with module boundaries.

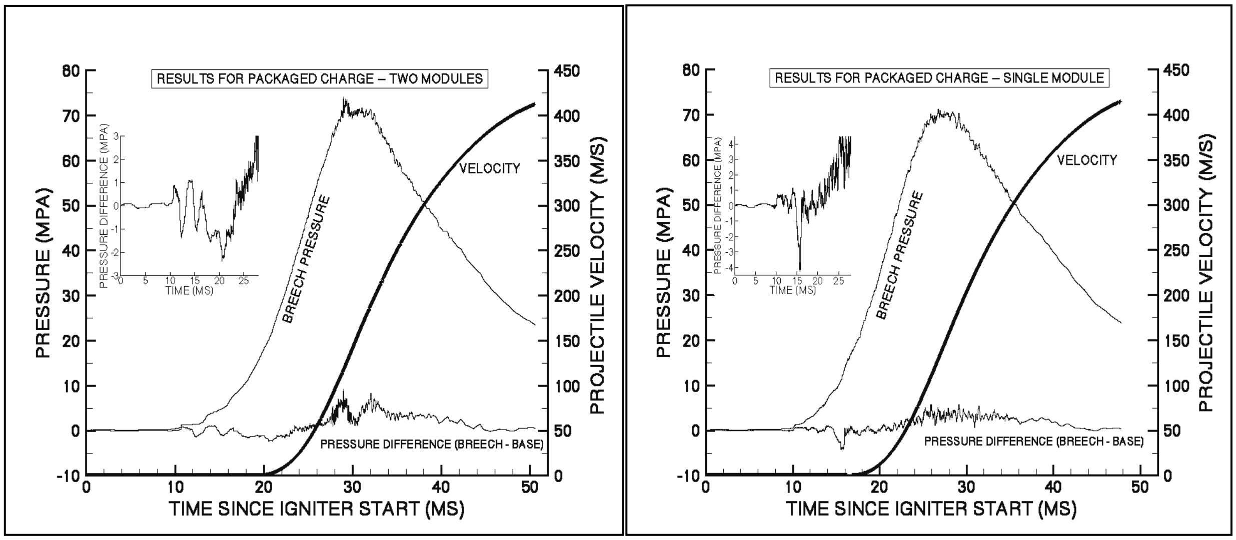

Figure 3. Computed results for (a) packaged charge (two modules): projectile velocity, breech pressure, and pressure difference (breech pressure minus pressure at chamber end) vs. time and (b) computed results for one module.

performance by taking advantage of a number of unique plasma characteristics. For example, a low-density plasma jet can efficiently ignite charges of HLD, can control propellant mass generation rates, can reduce propellant charge temperature sensitivity (i.e., the variation of gun performance with changing ambient temperature), and can shorten ignition delay (i.e., the time interval between firing of the igniter and ignition of the propellant). Plasma igniters also eliminate the conventional chemical igniter and can thus enhance the safety aspects of the overall gun propulsion system. All of these observations have a significant effect on the ballistics of ETC gun systems and can lead to a useful improvement in gun performance.

Unfortunately, graphical results of the specific FCS simulations cannot be provided in this public-release report. As both a substitute and as a means of demonstrating the NGEN3 code, this section does include an illustrative example of HLD charges.

4.4 Results for a Typical Direct-Fire Gun Chamber

Figure 4 shows the computed porosity contours (white to black: open space to nearly solid material) and propellant temperature contours (white to black: ambient to 440 K) for a 120-mm HLD charge consisting of separate regions of disk and granular propellant. The propellant disks are stacked axially in the chamber; each disk has an inner radius that provides space for the igniter and the projectile after body and outer radius that is smaller than the radius of the chamber (shown from centerline to chamber wall). Figure 4a shows the initial condition of the charge (i.e., before the igniter is activated). Figures 4b and 4c show the condition after 6 ms (note that the projectile has moved into the gun tube and out of view). It can be noted that the granular propellant has been consumed and that the stack of disks has been pushed forward but is not fully ignited (figure 4c). This compressed region of disks (from 50 to 55 cm in figure 4b) lacks the interstitial gaps that have been closed, preventing convective heat transfer. When this simulation is repeated using an ETC igniter, plasma convection is accomplished between all

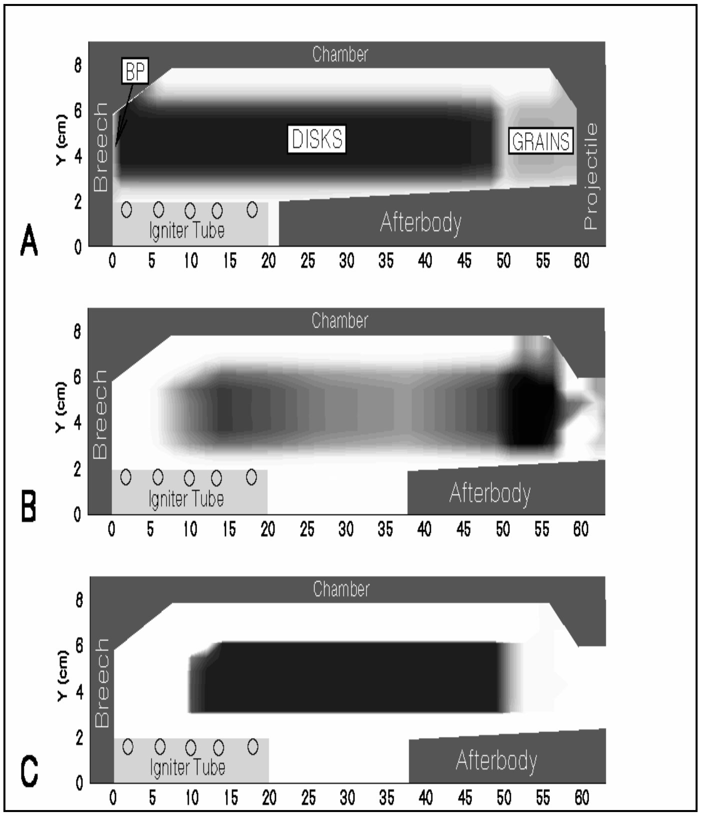

Figure 4. Computed results for 120-mm HLD charge (SP disks and grains): (a) porosity contours (black is dense material) at initial time, (b) porosity contours at 6 ms, and (c) propellant temperature contours (black is ignited propellant at 440 K) at 6 ms.

disks before significant disk compression, and as a result the entire stack of disk propellant is efficiently ignited (*3*). Thus, the low molecular weight plasma, generated by an ETC igniter, could circumvent this problem by establishing a convectively driven flame that propagates faster than the material compression wave in the disk propellant, thereby permitting an even ignition of the charge. A basic design tenet for using HLD charges was established, namely pressure waves in the chamber generated by the conventional igniter, when paired with the disk propellant charge, were avoided by using an ETC igniter. This conclusion, heretofore undocumented, is of critical importance to the design process for the FCS weapon.

5. Summary

In direct response to the immediate need for a reliable computer modeling tool to assist in the design and optimization of armament propulsion systems for both the legacy force and the FCS, ARL has developed a next generation computer-scaleable 3-D multiphase CFD code. ARL's NGEN3 code represents the sole DOD computer tool that is able to simulate the highly complex physics associated with indirect and direct fire guns. The NGEN3 code, which incorporates general continuum equations along with auxiliary relations into a modular code structure, is transportable between computer architectures and is applicable to a wide variety of gun propulsion systems. Two such systems are the U.S. Army's MACS and the FCS. NGEN3 code development and application to the MACS and the FCS is currently a DOD HPC Challenge Project. Significant progress has been made in optimizing both these systems—progress that was heretofore not attainable without a computer model and progress that has been greatly advanced by priority access to the DOD MSRC.

6. References

1. Nusca, M. J.; Gough, P. S. Numerical Model of Multiphase Flows Applied to Solid Propellant Combustion in Gun Systems. *Proceedings of the 34th AIAA Joint Propulsion Conference*, 13–15 July 1998; AIAA 98-3695.

2. Nusca, M. Computational Fluid Dynamics Model of Multiphase Flows Applied to Solid Propellant Combustion in Guns. *Proceedings of the 18th International Symposium on Ballistics*, San Antonio, TX, 1999, pp 252–261.

3. Nusca, M.; Conroy, P. Multiphase CFD Simulations of Solid Propellant Combustion in Gun Systems, *Proceedings of the 2001 Users Group Meeting*, sponsored by the DOD High Performance Computing Modernization Office, Biloxi, MS, 18–21 June 2001; see also Nusca, M.; Conroy, P. *Progress in the Modeling of High-Loading Density Direct-Fire Charges Using the NGEN Multiphase (CFD Code)*; ARL-TR-2934; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2003.

4. Gough, P. S. *Modeling Two-Phase Flow in Guns, Interior Ballistics of Guns*; Krier, H., Ed.; American Institute of Aeronautics and Astronautics: New York, NY, 1979.

5. Gough, P. S.; Zwarts, F. J. Modeling Heterogeneous Two-Phase Reacting Flow. *AIAA Journal*, **1979**, *17* (1), 17–25.

6. Nusca, M. J. Investigation of Ignition and Flame Spreading Dynamics in the Modular Artillery Change System Using the NGEN Multiphase CFD Code. *Proceedings of the 36th JANNAF Combustion Subcommittee Meeting*; CPIA Publication 1999, *691* (3), 137–154.

7. Nusca, M. J. Numerical Modeling of the Modular Artillery Change System Using the NGEN Multiphase CFD Code-Effects of Case Combustion. *Proceedings of the 37th JANNAF Combustion Subcommittee Meeting*; CPIA Publication 2000, *701* (2), 87–101.

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