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The Charge Designer's Workbench: A Range of Interior Ballistic Modeling Tools

by Albert W. Horst and Michael J. Nusca

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Weapons and Materials Research Directorate, ARL

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Gun and ammunition designers typically employ various models initially to evaluate preliminary design concepts and ultimately to make specific decisions regarding the design and optimization of both individual components and all-up weapon systems. A wide range of computerized models exists today to address virtually every aspect of this process; in particular, the propelling charge designer has available several levels of interior ballistic models. These range from rather simple lumped-parameter models, providing basic performance data such as muzzle velocity and peak pressure and which run quickly on personal computers, to very complex multidimensional, multiphase flow models capable of describing the details of flamespreading, grain motion, and the formation of pressure waves, but employ specialized and occasionally unavailable input for propellant, charge, and gun parameters and require many hours on a workstation or supercomputer to complete the simulation. This report addresses the increasing level of physics and thus range of applicability to problems of increasing sophistication associated with three of today's most popular interior ballistic models: the lumped-parameter IBHVG2 code, the one-dimensional, two-phase flow XKTC code, and the state-of-the-art multidimensional, multiphase flow NGEN3 code. Recommendations are made with respect to the appropriate use of each of these highly useful tools, as well as the transferability of input data and comparability of results so obtained.</td></tr>
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1. Introduction

There exists a wide range of motivations for modeling gun interior ballistics. Computer modeling can provide a fast and economical means of evaluating the performance potential for new gun concepts or configurations, or alternatively, the use of new propellant compositions or geometries in existing guns. Modeling also provides an ideal approach to automation of parametric analysis and design optimization of gun and ammunition characteristics. On a somewhat more physically sophisticated level, high-level models can be used to address the causes and possible solutions for undesirable ballistic behaviors. Specifically, past efforts (*1–3*) employing state-of-the-art interior ballistic codes in conjunction with transparent (plastic) chambered gun-chamber simulators have facilitated the detailed comparison of simulated and measured results, with emphasis on identifying causes and controls for flamespreading anomalies and ensuing deleterious pressure waves in large caliber guns.

With many interior ballistic models of varying complexity, both in terms of underlying physical representations and numerical features, selection of the appropriate model to address a given problem of interest can be of critical importance, both in terms of the level of difficulty associated with the model used and the value of the results so obtained. In this report, we will consider simulation of a sample, generic gun/propelling charge configuration using a range of interior ballistic models, assessing the type and level of problems addressable within the physical basis of each, the significant differences in the requirement for input data, and the computational burdens and numerical difficulties associated with each.

2. A Range of Modeling Approaches

Three levels of interior ballistic models, representative of broad classes characterized by various levels of physics underpinning the representations, are considered in this report. Specifically, the models employed are the IBHVG2 lumped-parameter interior ballistic code; the XKTC one-dimensional (1-D) (with area change), two-phase flow interior ballistic code; and the NGEN3 multidimensional, two-phase flow interior ballistic code.

Briefly, IBHVG2 (*4*) provides a simple but useful lumped-parameter representation of the interior ballistic cycle, embodying such assumptions as uniform and simultaneous ignition of the entire propellant charge, with combustion assumed to take place in a smoothly-varying, well-stirred mixture, the burning rate being determined by the instantaneous, space-mean chamber pressure. An assumed, longitudinal pressure gradient is superimposed on the solution at each instant in time to appropriately reduce the pressure on the base of the projectile. While an excellent tool for estimating overall performance of a gun, the study of ignition-induced pressure waves (a major concern of this study) is clearly outside the physical scope of this model.

Next, the XKTC code (*5*) provides a quasi-1-D, macroscopic (with respect to individual grains), two-phase description of flow in the gun chamber, with the conservation laws formulated to neglect the effects of viscosity and heat conduction in the gas phase. Most important, however, gas and solid phases are coupled through heat transfer, combustion, and interphase drag, these processes being modeled using empirical correlations that relate the microphenomena to the average flow properties described by the governing equations. The igniter is either modeled explicitly or treated as a predetermined mass-injection profile, and flamespreading follows primarily according to convection, until the ignition temperature is reached and combustion follows at a rate determined by the local pressure. Formulated as a 1-D-with-area-change representation, XKTC provides a first-level capability for treating the dynamics of the axial pressure field and its potential for causing potentially damaging overpressures.

Finally the NGEN3 code (*6*–*8*) is a multidimensional, multiphase computational fluid dynamics (CFD) code that incorporates three-dimensional (3-D) continuum equations along with auxiliary relations into a modular code structure. On a sufficiently small scale of resolution in both space and time, the components of the interior ballistic flow are represented by the 3-D balance equations for a multicomponent reacting mixture describing the conservation of mass, momentum, and energy. A macroscopic representation of the flow is adopted using these equations derived by a formal averaging technique applied to the microscopic flow. These equations require a number of constitutive laws for closure including state equations, intergranular stresses, and interphase transfer (similar to those employed in the XKTC code). The numerical representation of these equations as well as the numerical solution thereof is based on a finite-volume discretization and high-order accurate, conservative numerical solution schemes. The spatial values of the dependent variables at each time step are determined by a numerical integration method denoted the Continuum Flow Solver (CFS), which treats the continuous phase and certain of the discrete phases in an Eulerian fashion. The Flux-Corrected Transport scheme (*9*) is a suitable basis for the CFS since the method is explicit and has been shown to adapt easily to massively parallel computer systems. The discrete phases are treated by a Lagrangian formulation, denoted the Large Particle Integrator (LPI), which tracks the particles (described below) explicitly and smoothes discontinuities associated with boundaries between propellants yielding a nearly 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 and mass generation). The size of the grid as well as the number of Lagrangian particles is user prescribed. The solid propellant is modeled using Lagrange particles that regress, produce combustion product gases, and respond to gasdynamic and physical forces. Individual grains, sticks, slab, and wrap layers are not resolved; rather, each propellant 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 (e.g., radial for disks and axial for sticks) and responses of the media to gasdynamic forces. Media regions that are encased in impermeable boundaries, which only yield to gasdynamic flow after a prescribed pressure differential and/or surface temperature is reached, act as rigid bodies within the chamber. The use of computational particles to represent the propellant charge permits a host of other modeling features that enhanced the representation of charge details (*8*).

3. A Generic Problem Treated at All Three Levels

To elucidate the benefits and burdens associated with using higher-level interior ballistic models, we address a generic gun/propelling charge configuration based loosely on a 155-mm howitzer firing a single-bag, top zone propelling charge previously employed by the U.S. Army. In short, a 46.7-kg projectile is launched by an 11.8-kg charge of granular M30A1 propellant from a 155-mm bore cannon with a 20.1-L chamber volume and 5.1 m of travel. Figure 1 displays the configurational representations available with each of the codes.

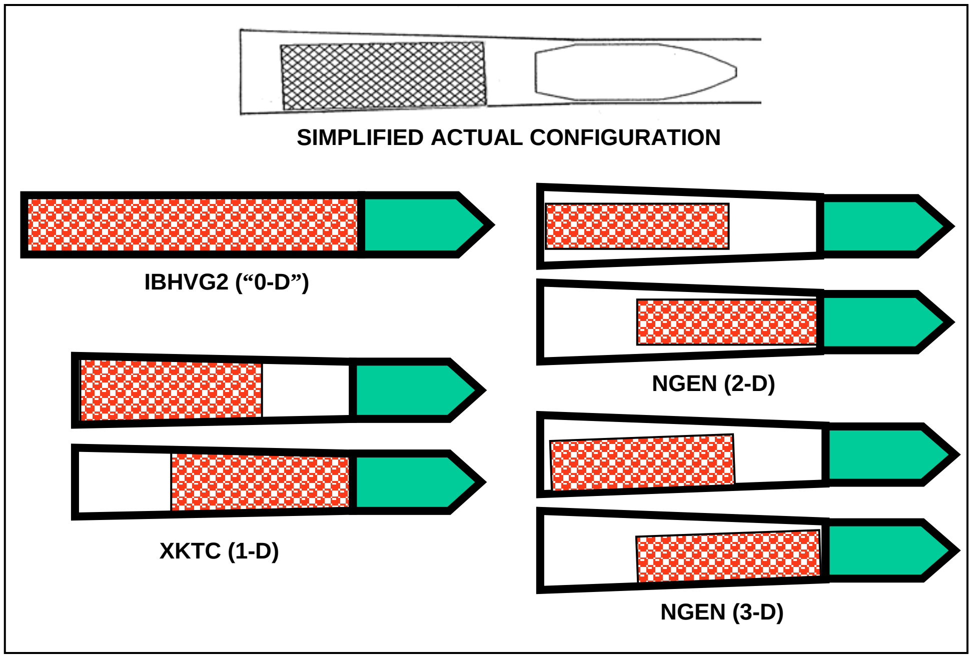

Figure 1. Generic artillery charge and representations provided by the three interior ballistic models.

4. IBHVG2 Simulation

Consistent with the lumped-parameter description assuming a uniformly distributed, instantaneously and uniformly ignited propellant charge, as previously described, input data required for an IBHVG2 simulation can be as simple as gun chamber volume and tube diameter; projectile mass and travel; barrel resistance profile; igniter mass and thermochemical properties; and main charge propellant mass, dimensions, thermochemical properties, and burning rates. No information on the specific location of the propellant charge or the manner in which it is ignited (other than just the initial pressurization supplied by the igniter, assumed to be all burned at time zero, with all surfaces of the main propellant charge ignited) is admitted, with modeling results correspondingly limited. Figure 2 presents pressure-time profiles for chamber and projectile base for the single solution definable by this set of input data. The curves are necessarily smooth and reflect none of the details of flamespreading and possible pressure-wave formation. Predicted performance is 796 m/s with a peak chamber pressure of 323 MPa.

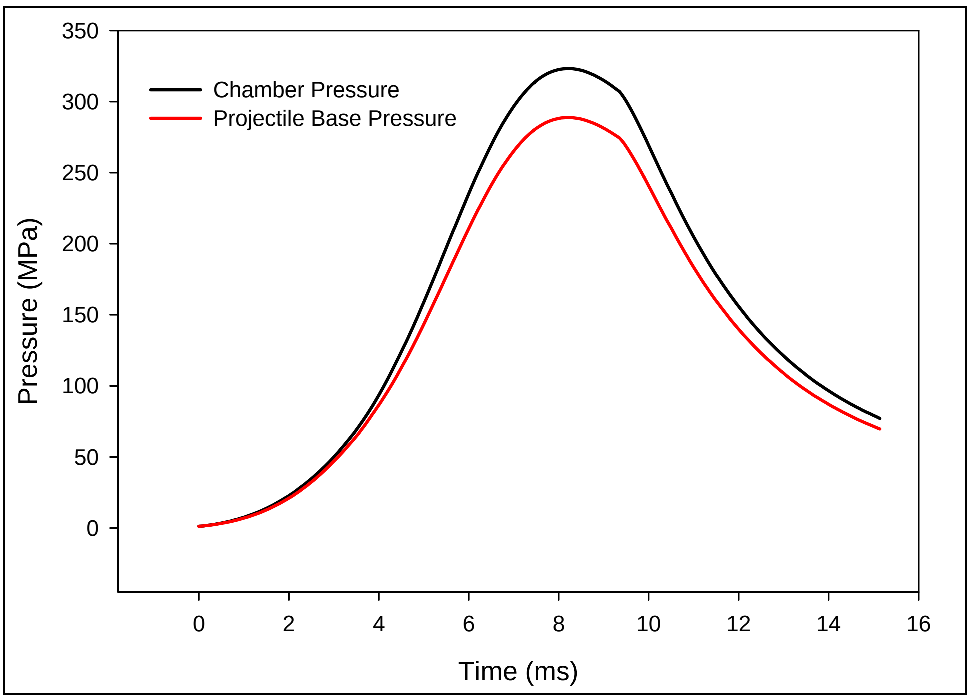

Figure 2. Pressure-vs.-time curves at breech and projectile base as predicted by IBHGV2.

5. XKTC Simulations

As depicted in figure 1, XKTC allows assignment of the axial delimiters of the propellant charge within the gun chamber, as well as a tabular description of ignition system output, capable of influencing axial flamespreading and pressurization within the gun chamber. In addition, the 1-D-with-area-change representation provides a first level of recognition of the chambrage and tapering of the gun chamber. Input data beyond those required for IBHVG2 thus include chamber dimensions, axial boundaries of the propellant charge, and thermal properties, including an ignition temperature, for the propellant, as well as parameters describing propellant bed compressibility. These last two categories of input are often unavailable for specific propellants and estimated based on related data.

Figures 3 and 4 present XKTC results for two charge-loading conditions, as displayed in figure 1 (termed minimum and maximum standoff from the breech face) and two ignition system output profiles (located either at the rear or the forward end of the propellant charge). We note the interplay of the initial distribution of axial ullage and the site of ignition on the ensuing path of flamespreading and pressurization on the development of potentially deleterious pressure waves. Indeed, it is easy to imagine that initial conditions might lead to large, longitudinal pressure waves, accompanying solid-phase (unburned propellant) motion, possible grain fracture upon impact against the breech or projectile base, generation of unintended burning surface, and damaging overpressures. This sequence of events is, in fact, the prescription for breechblows (*10*, *11*). Predicted velocities for these conditions range from 799 to 810 m/s, with peak pressures from 316 to 330 MPa and initial negative differential pressures from 22 to 67 MPa.

One must remember, however, that the 1-D representation prohibits consideration of the influence of radial flow on these processes, either to exacerbate or mitigate undesirable ignition-phase dynamics. In particular, the potential for equilibration of longitudinal pressures early in the cycle via the high permeability path radially external to the propellant package is beyond treatment by such codes.

6. NGEN3 Simulations

The primary feature to be exploited through application of the NGEN3 code was clearly its capability to provide a multidimensional representation of the problem: both two-dimensional (2-D) axisymmetric and fully 3-D treatments, as shown once again in figure 1. Three sets of calculations were thus performed to investigate the role of multidimensional flow for the given generic problem: (1) a direct transfer of the XKTC databases for minimum and maximum

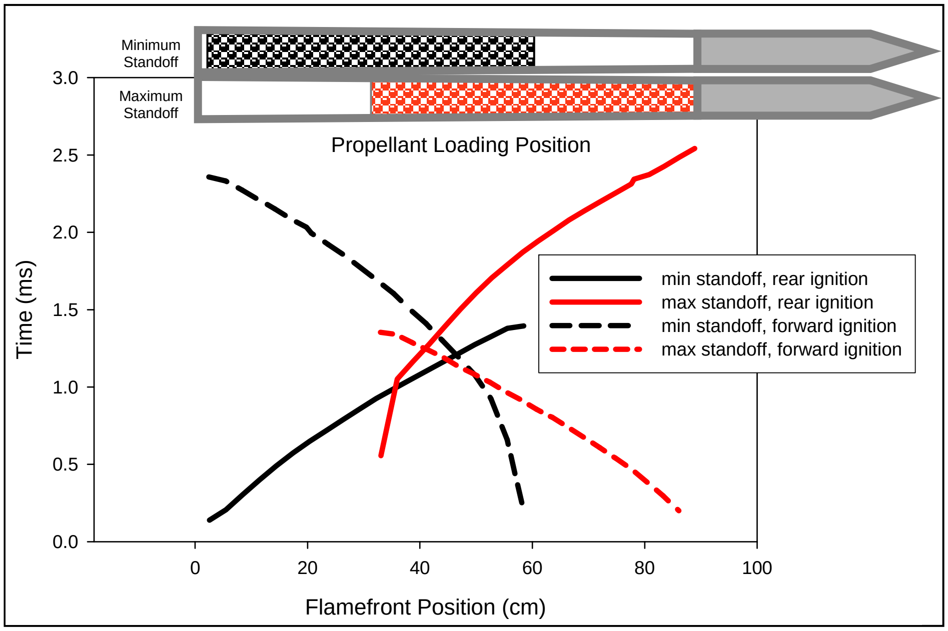

Figure 3. Flamespreading profiles for four charge location/ignition profile combinations as predicted by XKTC.

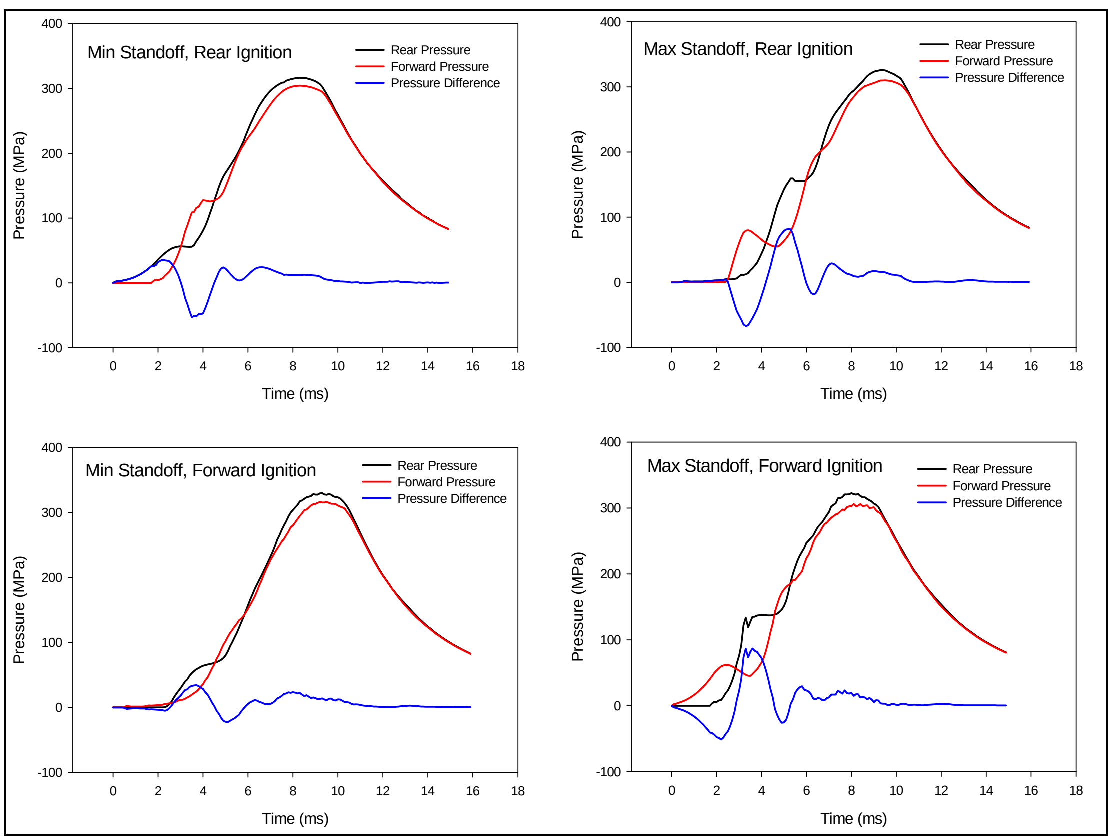

Figure 4. Pressure-vs.-time data for four charge location/ignition profile combinations as predicted by XKTC.

standoff, with the propellant assumed to occupy the full radial extent of the chamber from rear to forward boundaries of the charge; (2) these same two configurations but with the diameter of the charges reduced to about 90% of the average diameter of the chamber; and (3) the same propellant charge package (reduced diameter charge at minimum standoff), but this time, lying on the bottom of the chamber as in real life rather than the simplified version with co-axial propellant charge and gun chamber.

Figures 5–7 display pressure-vs.-time and pressure-difference-vs.-time data for these three sets of calculations: the first virtually duplicates the XKTC rear ignition results; the second reveals the equilibrating effect with respect to longitudinal pressure waves of the high permeability path external to the charge (a reduction in the initial negative differential pressure of 48 to 13 MPa for the minimum standoff configuration, but only from 78 to 65 MPa for maximum standoff, where the lack of forward ullage limits the effectiveness of flow in the high permeability region of circumferential ullage); and the final of these figures demonstrates that three-dimensionality provides only a minor perturbation to the longitudinal pressure fields calculated in the second set. However, when we examine propellant temperature contours and velocity vectors for axisymmetric and fully 3-D representations of the minimum standoff, rear ignition, reduced diameter configurations (figures 8 and 9), recognizable differences in the early flow and path of flamespreading become evident. Such differences, while likely inconsequential with respect to evolution of the overall pressurization of the gun chamber and net interior ballistic performance, could indeed alter transient inputs to the projectile base, perhaps exciting undesirable material responses in the projectile body or payload. Indeed, the coupling of such interior ballistic results from the NGEN3 code to various projectile material response codes is the subject of related studies (*12–14*).

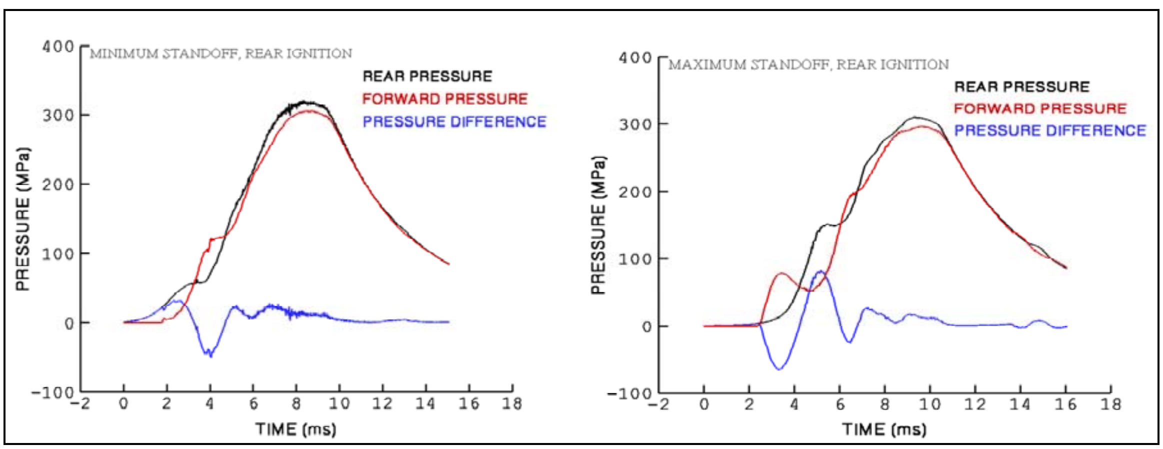

Figure 5. Pressure-vs.-time data for minimum and maximum standoff, rear ignition, full-bore charges as predicted by NGEN3.

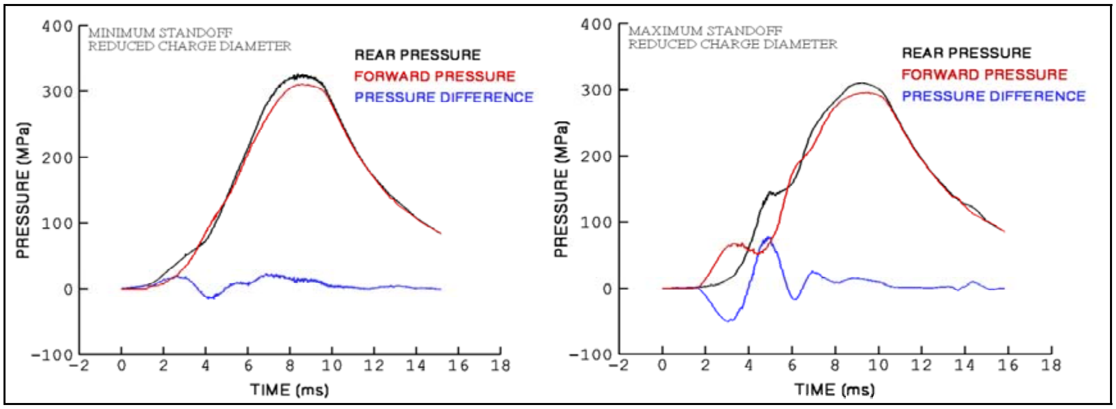

Figure 6. Pressure-vs.-time data for minimum and maximum standoff, rear ignition, reduced diameter charges (axisymmetric representation) as predicted by NGEN3.

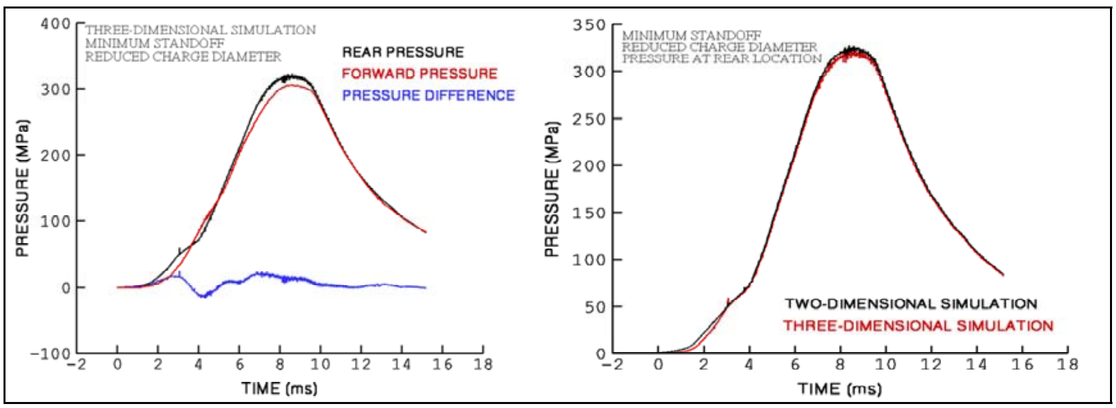

Figure 7. (a) Pressure-vs.-time data for minimum standoff, rear ignition, reduced diameter charge (fully three-dimensional representation) as predicted by NGEN3 and (b) direct comparison of with these results to those of the axisymmetric representation of figure 6.

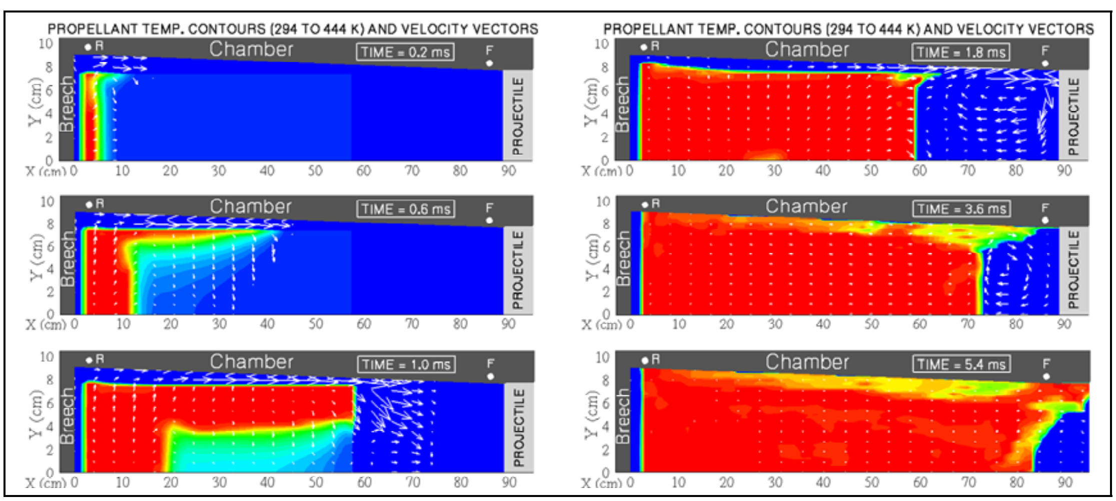

Figure 8. Propellant temperature contours and selected velocity vectors for minimum standoff, rear ignition, reduced diameter charges (axisymmetric representations) as predicted by NGEN3.

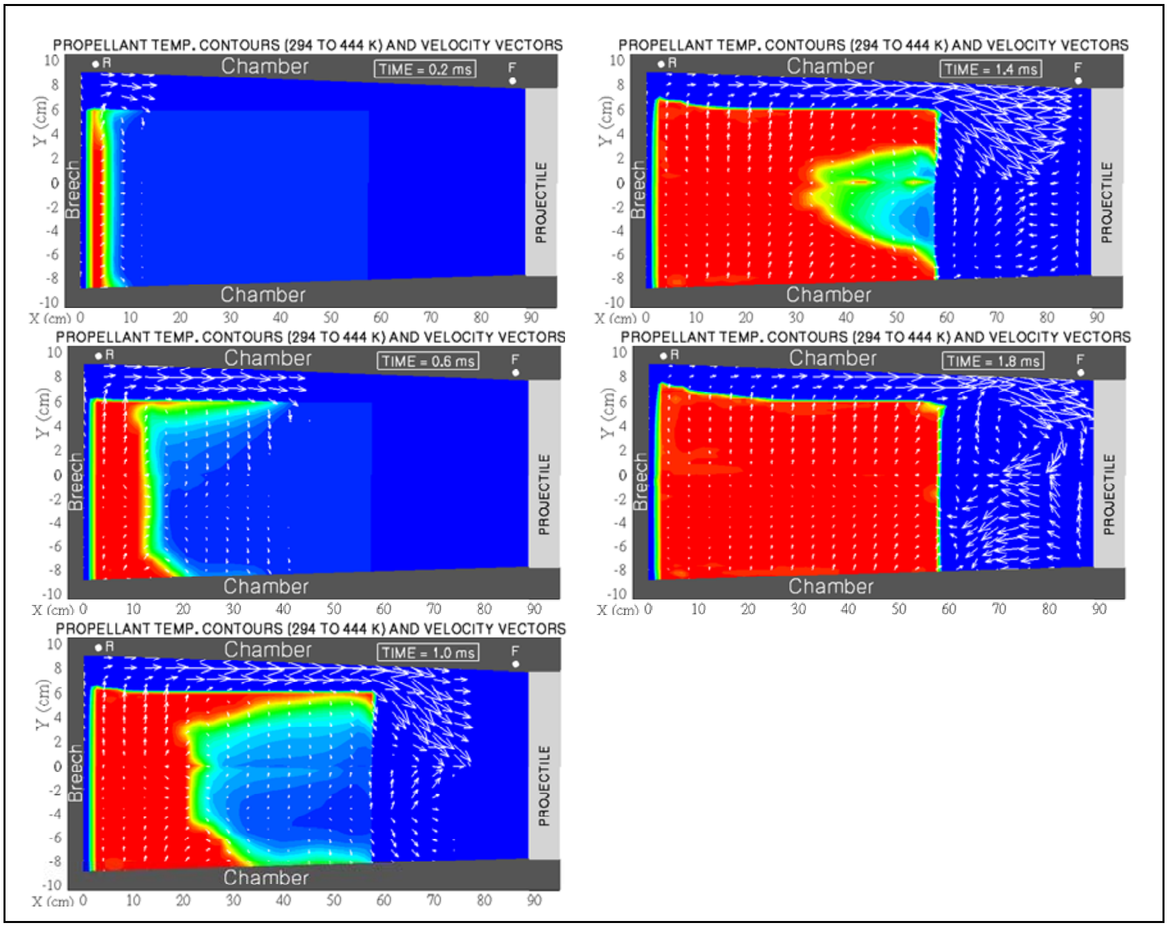

Figure 9. Propellant temperature contours and selected velocity vectors for minimum standoff, rear ignition, reduced diameter charges (fully 3-D representation) as predicted by NGEN3.

7. Conclusions and Recommendations

Let us now make some specific recommendations regarding the use of interior ballistic models in each of these three categories. Lumped-parameter models are appropriate, and indeed usually the best choice, for the following types of analyses: overall gun envelope performance limits, determination of maximum performance benefits from various propellant formulations or configurations, grain geometry optimization, determination of the influence of temperature-dependant burning rates on performance, performance sensitivity analyses, and the study of idealized interior ballistic concepts (e.g., delayed ignition of grain perforations). Computer runs usually take at most a few seconds per in-bore trajectory on a personal computer.

The use of multiphase flow codes becomes necessary when ignition and flamespreading are important to the problem of interest: typically environments characterized by substantial longitudinal pressure waves, with possible deleterious effects, such as performance excursions and even breechblows. Moreover, such codes are required when the primary interest is simply the sensitivity of performance, including pressure waves, to ignition stimulus and location; propellant geometry, combustion, and mechanical property characteristics; and overall charge-loading density and location. When the ignition stimulus and charge distribution are consistent with a 1-D representation, codes such as XKTC are appropriate. Even with the added complexity of such codes, computer times of well under a minute on a personal computer are typical. Successful application of such codes to propelling charge design and diagnostics problems throughout recent decades is widely documented (*15–17*).

Multidimensional, multiphase flow codes must be used, however, when either the ignition stimulus or the initial distribution of the propellant in the gun chamber cannot reasonably be assumed to be adequately treated as 1-D (or 1-D with area change). In particular, when the early flow of ignition or propellant gases cannot be expected to flow primarily in the longitudinal direction through the propellant bed or regions of primarily axial ullage, a 1-D code will be unable to capture critical two-phase flow processes whereby alternate paths may significantly alter the structure of flow. Should the propellant charge be initially contained in an inert or combustible package that allows longitudinal flow both within the charge and external to it in a region of circumferential ullage surrounding the charge, the path of flamespreading and the overall development of pressure waves can be substantially altered, in a fashion possibly critically dependent on the persistence of such ullage as determined by the strength and permeability of the case itself. Only multidimensional codes such as NGEN3 are capable of addressing such issues (*2*, *18*). Moreover, we need to reiterate that the success of current efforts in the community to couple interior ballistic codes to projectile dynamic response codes for transient structural analysis will be highly dependent on the level of representation provided by the interior ballistic code which drives the overall analysis—a multidimensional, multiphase flow code may well be required to provide a full description of the transient, multidimensional, gas, and solid-phase inputs to the projectile base (*14*). Burdens associated with the use of multiphase flow interior ballistic codes fall into two major categories. The first is the requirement for specific input data not typically available to the charge developer (e.g., propellant bed rheology, needed regardless of the dimensionality of representation, and case permeability and strength characteristics, required to take full advantage of multidimensional representation of cased charges). The second, of course, is the computational burden. The NGEN simulations reported herein were run on an SGI Octane2 with dual 400-MHz processors and 8 Gb of memory. The 2-D runs required about 3 hr and the 3-D about 55 hr, with modest meshes appropriate to this notional charge configuration (for 2-D: 2015 grid cells in the Eulerian mesh and 375 particles in the Lagrangian mesh with ten-times larger meshes for 3-D). Again, documentation on successful application of this code is abundant (*18–20*).

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