Flame-Spreading Processes in a Small-Caliber Gun

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by Albert W. Horst and Paul J. Conroy

ARL-TR-4181 **July 2007**

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ARL-TR-4181 **July 2007**

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* July 2007

2. REPORT TYPE Final

3. DATES COVERED (From - To) June 2006 to May 2007

4. TITLE AND SUBTITLE Flame-Spreading Processes in a Small-Caliber Gun

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER 622618H8000

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S) Albert W. Horst (AS) and Paul J. Conroy (ARL)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Weapons and Materials Research Directorate
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-4181

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The interior ballistic cycle of small guns (40 mm and below) has in the past been typically modeled with the use of lumped parameter codes that assume instantaneous ignition of the entire propelling charge followed by uniform combustion throughout the chamber at each instant in time, with the burning rate governed by an instantaneous space-mean pressure. In this study, a two-phase flow approach is employed to model the interior ballistics of a generic 5.56-mm gun, focusing on the ignition and flame-spreading dynamics in the gun chamber, the formation of gas and intergranular stress waves, and the ultimate effect of these processes on gun performance. Results suggest that the flame-spreading portion of the cycle plays a significant role in the overall phenomenology occurring within such guns, outside the scope of lumped parameter analysis. Approaches for exploiting this improved understanding of small-caliber interior ballistic phenomenology are identified, with respect to improved performance and safety.

15. SUBJECT TERMS

flame spreading; interior ballistics; small caliber

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Paul J. Conroy
Unclassified	Unclassified	Unclassified	SAR	23	19b. TELEPHONE NUMBER (*Include area code*) 410-278-6114

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

The influence of ignition stimulus, the influence of parasitic components, and the distribution of initial ullage on the formation of pressure waves in large-caliber guns has been studied for more than 30 years and is the subject of numerous theoretical and experimental investigations *(early examples, 1-7)*. These enlightening efforts were in direct response to the occurrence of a series of malfunctions, sometimes catastrophic, in large-caliber Navy and Army guns *(8-11)*, which accompanied substantial longitudinal pressure waves, the causes for which were ultimately tied to the features mentioned, all of which can lead to local pressurization of the gun chamber with substantial and undesirable ensuing two-phase flow dynamics. Without similar motivation, small and medium caliber interior ballistics and cartridge design have, in most cases, proceeded without the benefit of such a detailed investigation.

Over the past several years, however, U.S. involvement in Iraq and Afghanistan has understandingly stimulated significant interest in developing an increased level of technical understanding of the detailed phenomenology of small-caliber ballistics with the goal of increasing the performance and reliability of such weapons. The study reported herein addresses the detailed interior ballistics phenomenology of a generic 5.56-mm round. The code employed is known as XKTC *(12)* and provides a quasi-one-dimensional, macroscopic (with respect to individual grains), two-phase description of flow in the gun chamber. The gas and solid phases are coupled through heat transfer, combustion, and interphase drag; these processes are modeled with the use of empirical correlations that relate the microphenomena to the average flow properties described by the governing equations. The igniter is typically treated as a predetermined mass injection profile, and flame spreading follows primarily according to convection, until the ignition temperature is reached and combustion follows at a rate determined by the local pressure. Regions of axial ullage (i.e., free space) or compactable filler elements (e.g., propellant packing spacers, case closure plugs) are recognized as boundary conditions on the two-phase region occupied by the propellant. With these features, XKTC[1], despite the limitation of its one-dimensional-with-area-change representation, provides a first-level capability for treating the dynamics of the axial pressure field and its potential for causing potentially damaging overpressures. Input to the code includes gun chamber and tube internal dimensions; projectile mass and travel; a barrel resistance profile; igniter mass and thermochemical properties; and main charge propellant mass, axial boundaries, grain dimensions, thermochemical properties, burning rates, thermal properties, ignition temperature, and bed compressibility.

[1]not an acronym

2. Baseline Calculation

The baseline data for the series of calculations discussed herein, as reported previously *(13)*, are based on physical and chemical characteristics of a generic 5.56-mm round with a deterred, rolled ball propellant. Gun, cartridge case, and projectile dimensions are approximately those of the M855 cartridge, with case debulleting force[2] and barrel resistance assigned values consistent with ex-perience and dimensional properties of the case and tube. Thermochemical properties for the primer (FA956) and propellant (WC844) compositions were determined through the use of the BLAKE[3] code *(14)*. The primer output profile was based initially on high speed photo-graphic studies *(15)* and subsequently varied to determine its influence. Distribution of deterrent in the main charge, as well as accompanying burning rates, followed historical data provided by the manufacturer *(16)*. Propellant thermal conductivity and diffusivity, rheological data, and ignition temperature were not specifically known for this propellant and were assumed to be consistent with those typically assigned to gun propellants.

An XKTC calculation employing these data yields the results shown in figure 1. Pressure-time curves for breech and projectile base locations are depicted, along with projectile acceleration versus time and a curve depicting the progress of flame spread in the propellant bed. The pressure-time curves exhibit a moderate level of pressure waves, as expected for a base-ignited granular propellant charge. Of particular note, however, is the acceleration curve, which should mimic (if appropriately scaled) the base pressure curve (minus the barrel resistance); rather, it reveals a sharp spike before the gas pressure reaches the base of the projectile, which suggests that intergranular stress is driving the projectile motion during this period of time. Further, the flame-spreading curve reveals that although ignition at the base of the charge is very prompt, ignition at the forward end is delayed until the assumed stress-driven acceleration spike has diminished.

To elucidate the underlying cause of this behavior, figure 2 displays gas pressure, propellant bed stress, and propellant surface temperature from breech to projectile base and at the time of 0.1 ms. Indeed, while the convectively driven flame front (and accompanying increase in gas pressure) has not yet reached the front of the propellant bed, a substantial increase in intergranular stress is present at the projectile base. Although both gas pressure and solid-phase stress lead to early projectile ac-celeration, subsequent calculations will show that the accompanying state of flame propagation and propellant combustion differ considerably with varying ignition stimuli and bed conditions, leading to not only differences in the magnitude of pressure waves but also maximum pressure and muzzle velocity! Specifically, we examine the effects of ignition stimulus, propellant bed rheology (i.e., stiffness), and the presence of forward ullage in the case.

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[2]That is, the force required to expel the projectile from the crimped cartridge case.
[3]Not an acronym

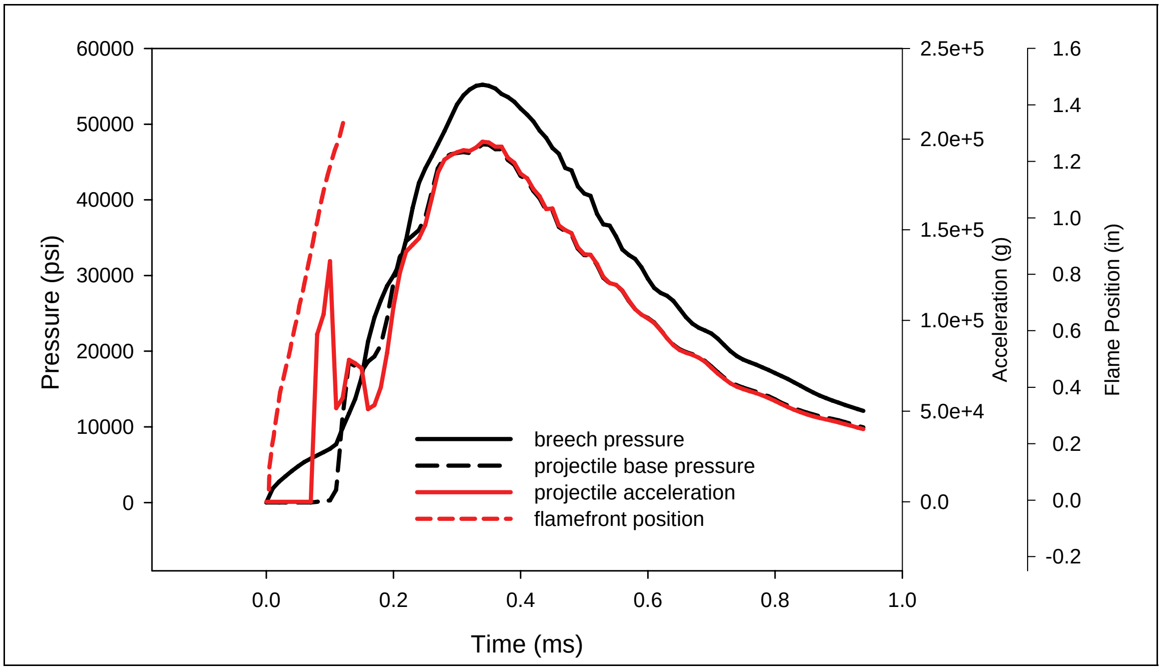

Figure 1. XKTC prediction of interior ballistic parameters for a baseline 5.56-mm cartridge.

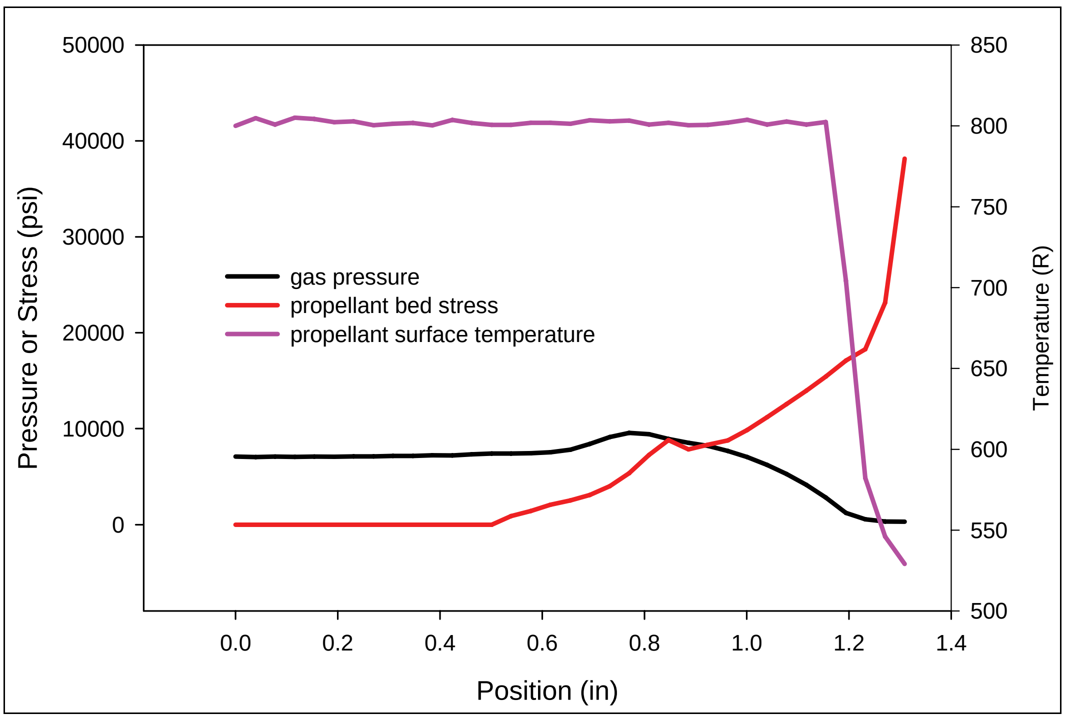

Figure 2. XKTC prediction of ignition phase profiles at 0.1 ms for a baseline 5.56-mm cartridge.

3. The Influence of Variation in Ignition Stimulus

For completeness, we recall the previous results looking at the effects of (a) uniform, instantaneous ignition (as one would assume in a lumped parameter calculation) and (b) an order of magnitude slower primer output profile than that used in the baseline calculation *(13)*. First, with the assumption that all propellant surfaces were initially ignited at time zero, no ignition-induced pressure waves are produced and no intergranular stress waves are formed. Since the entire propellant bed is burning at the time of first motion of the projectile, one might expect an increase in performance and indeed it does, with a resulting peak pressure of 72.5 kpsi and muzzle velocity 3,235 ft/s versus 55.2 kpsi and 3,023 ft/s for the baseline. Otherwise, the results are unremarkable and not displayed, with smooth pressure-time curves and the acceleration curve overlying the base pressure curve, minus retarding forces associated with the case crimp and the origin of rifling.

However, when primer function time was increased from 0.2 ms to 2.0 ms (and flux correspondingly adjusted to maintain the same total output), we obtain the initially surprising result that the predicted pressure is once again higher (this time only about 10 kpsi) than that for the baseline case. The first clue to an explanation is found in figure 3, with the absence of an early spike in the acceleration curve, indicating a significant reduction in bed stress at the projectile base. Figure 4 then tells the rest of the story. Although flame spreading is much slower than in the baseline, nearing completion at 0.3 ms versus 0.1 ms, the net effect, however, is not less propellant burning at the time of first projectile motion, but actually the opposite, as the reduced intensity of the igniter results in a much lower intergranular stress at the base of the projectile and thus a lower initial projectile acceleration. Significantly, peak pressure is attained at a reduced projectile travel (~8%) (and thus slightly smaller total available volume) and a slightly greater (~3%) quantity of propellant burned, which explains its increase.

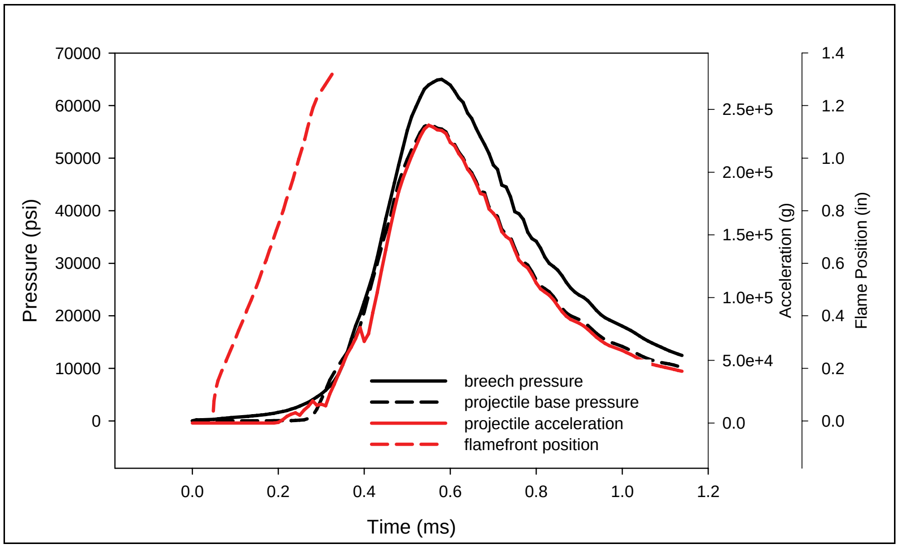

Figure 3. XKTC prediction of ballistic parameters of a 5.56-mm cartridge with a slow igniter.

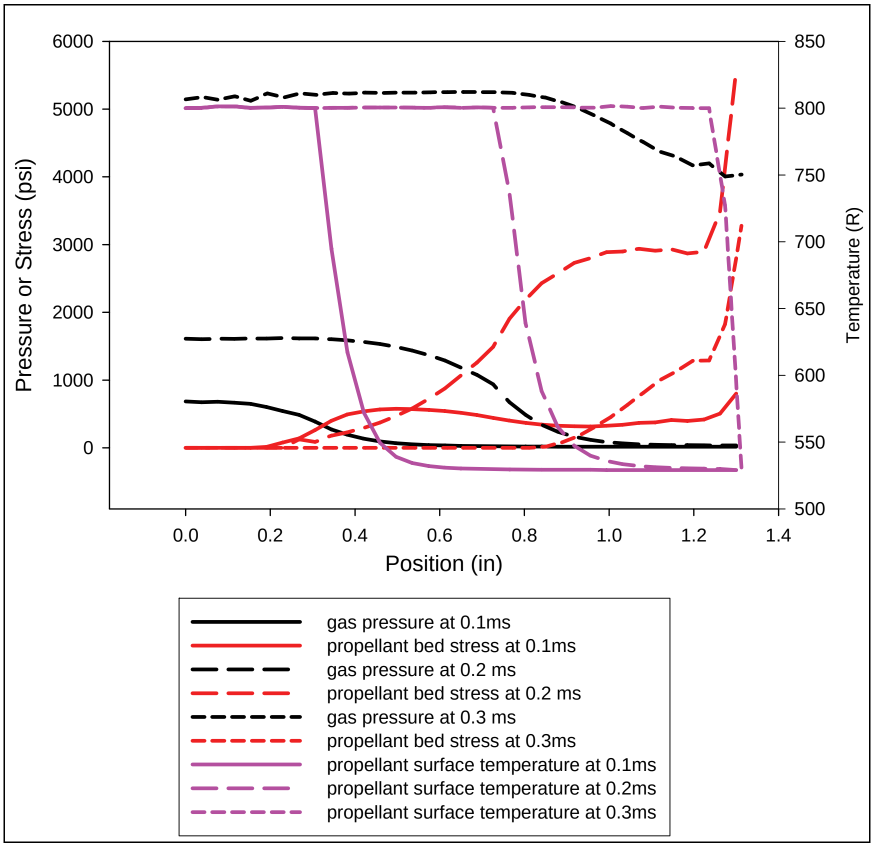

Figure 4. XKTC prediction of ignition phase profiles for a 5.56-mm cartridge with a slow igniter.

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4. The Influence of Variation in Propellant Bed Rheology

The granular propellant bed compaction law in XKTC is depicted graphically in figure 5. By convention, the bed porosity ε is defined as the ratio of free volume to the total volume in a given region (i.e., the fraction not occupied by the solid phase propellant). As the bed is compacted from its natural settling porosity, ε_o, to some lesser value, the local intergranular stress rises at a rate dependent on a_o (actually $a_o\varepsilon_o/\varepsilon$), where a_o is the rate of propagation of intergranular stress in a settled bed during loading. During unloading or reloading, a higher rate is assumed, as determined by the parameter a_1. The reader is directed to the reference *(12)* for a more complete discussion of this representation.

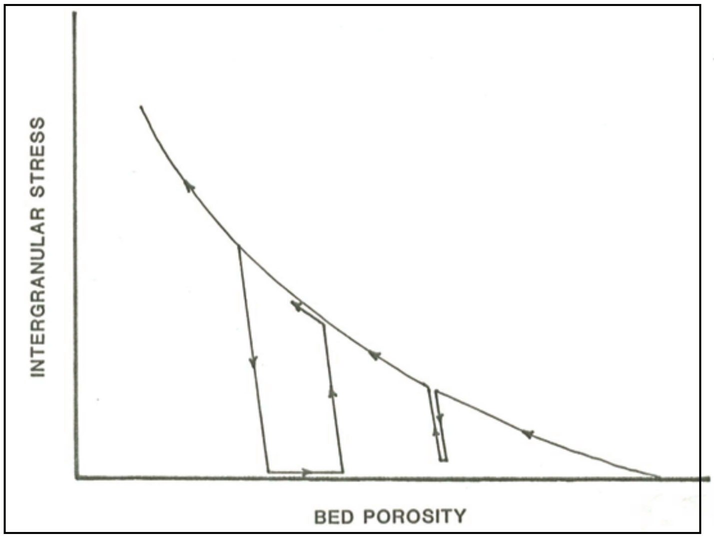

Figure 5. Granular stress law in XKTC code.

To examine the role of this property, a calculation was performed with the baseline database but the value of a_o reduced from 15,000 inches/second to 5,000 inches/second. This represents a change in bed "stiffness" from that of a single-base propellant such as the Navy's NACO[4] gun propellant to a much softer double-base propellant, such as the German JA2 formulation used by the U.S. Army in high performance tank guns. This particular datum is not currently available for WC844 propellant, but its value likely falls somewhere between these two extremes. The predicted pressure-time curves of figure 6 reveal substantial and continuing longitudinal waves until the time of peak pressure, with the acceleration profile essentially following the base pressure curve, which suggests little or no influence from intergranular stress. Further, although the large pressure waves somewhat mitigate the effectiveness of the maximum pressure (68.9 kpsi with a muzzle velocity of 3,148 ft/s), it is clear that bed compaction has not prevented early ignition of propellant grains in the forward portion of the bed. Indeed, figure 7 reveals an explanation for all, the rapid ignition of the bed preceding the intergranular stress wave, so that when compaction does occur, it does so in an already burning region of propellant, reducing local volume and increasing pressure and burn rates. A complicated interaction of processes during the ignition phase of small caliber rounds is clearly pictured. A closer examination of tabular results shows the continuation of pressure waves to be a result of actual flow reversals in the solid as well as gas phase, repeating bed compaction at both ends of the chamber and associated local pressurization and burning processes as described before.

[4]Navy cool

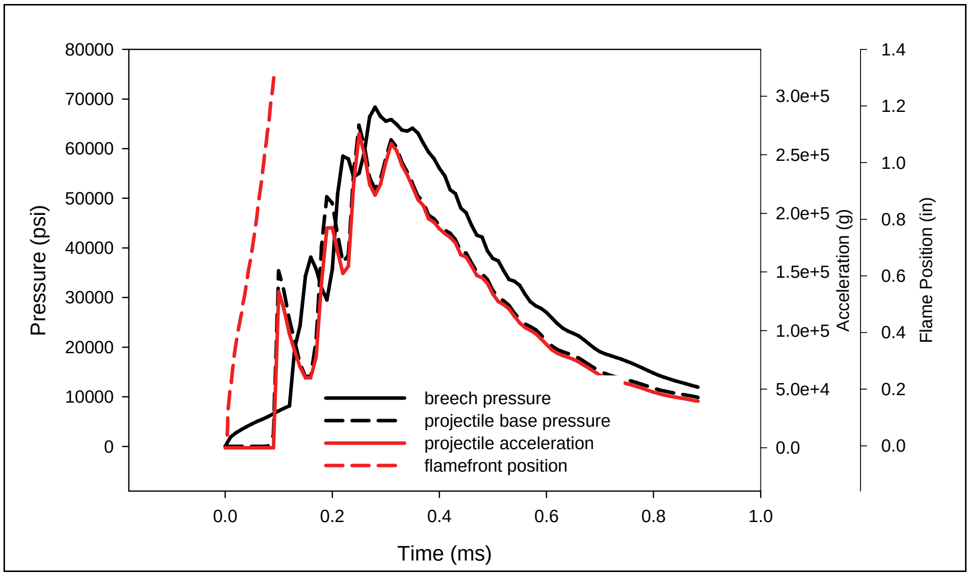

Figure 6. XKTC prediction of ballistic parameters for a 5.56-mm cartridge with "soft" propellant.

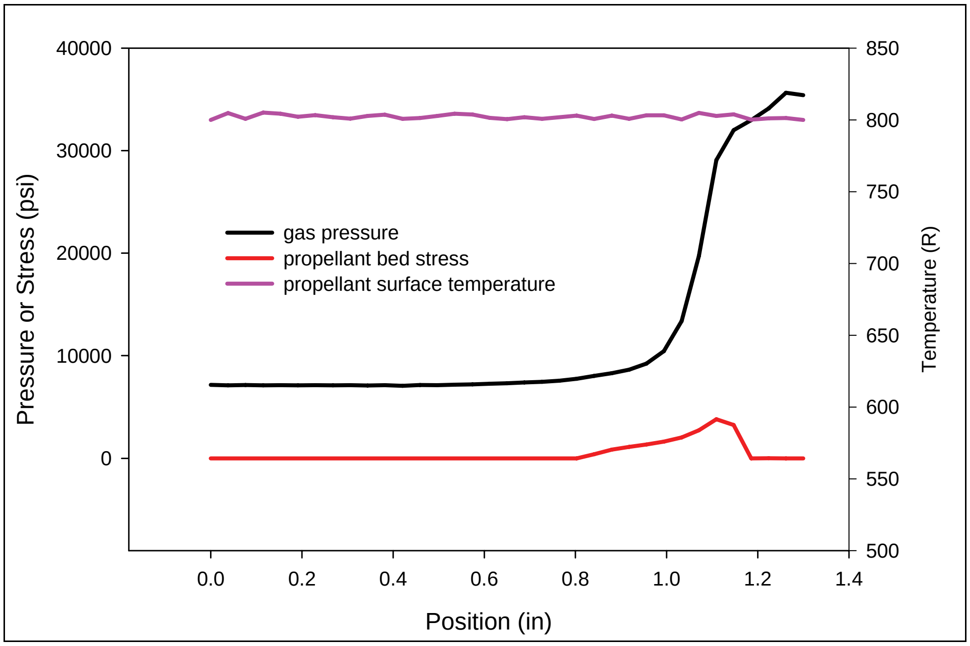

Figure 7. XKTC prediction of ignition phase profiles at 0.1 ms for a 5.56-mm cartridge with "soft" propellant.

5. The Influence of Initial Ullage

The presence of initial ullage in the gun chamber can greatly complicate the path of flame spreading, the localization of pressurization, and the subsequent equilibration of pressure gradients. In this very brief section, we look at just one aspect of this problem, namely, the presence of a small amount (5%) of longitudinal ullage at the forward end of the chamber between propellant bed and projectile base. Figure 8 displays the predicted influence of a region of forward ullage in the (otherwise) baseline configuration (compare to figure 1). Although there is very little influence on flame front propagation, peak pressure is increased from 55.2 kpsi to 57.9 kpsi, with a corresponding increase in muzzle velocity of 40 ft/s. However, the real change is in flow dynamics in both the gas and solid phases. Pressure waves are considerable larger and more persistant with the presence of ullage, with the initial differential pressure (not plotted separately in the figure but easily discernible) nearly doubled (15.2 kpsi versus 7.9 kpsi). Peak intergranular stress at the base of the projectile at the start of projectile motion (again, not displayed directly but clearly reflected in the acceleration profiles) is similarly increased by ~10 kpsi. The mechanism for these dynamics results from the shifting rearward of first combustion and pressurization, leading to an increase in the early forward flow of the gases, and via interphase drag and differential pressure forces, the propellant bed as well, leading to a stronger stagnation at the projectile base and increased subsequent two-phase flow dynamics. More complex distributions of ullage will lead to correspondingly more complex flow dynamics; the assessment of most will require the use of a multi-dimensional code such as NGEN3[5] (*17*). However, longitudinal flow dynamics will continue to be the dominant mode in solid-propellant guns, and this brief study confirms their importance even in small-caliber guns.

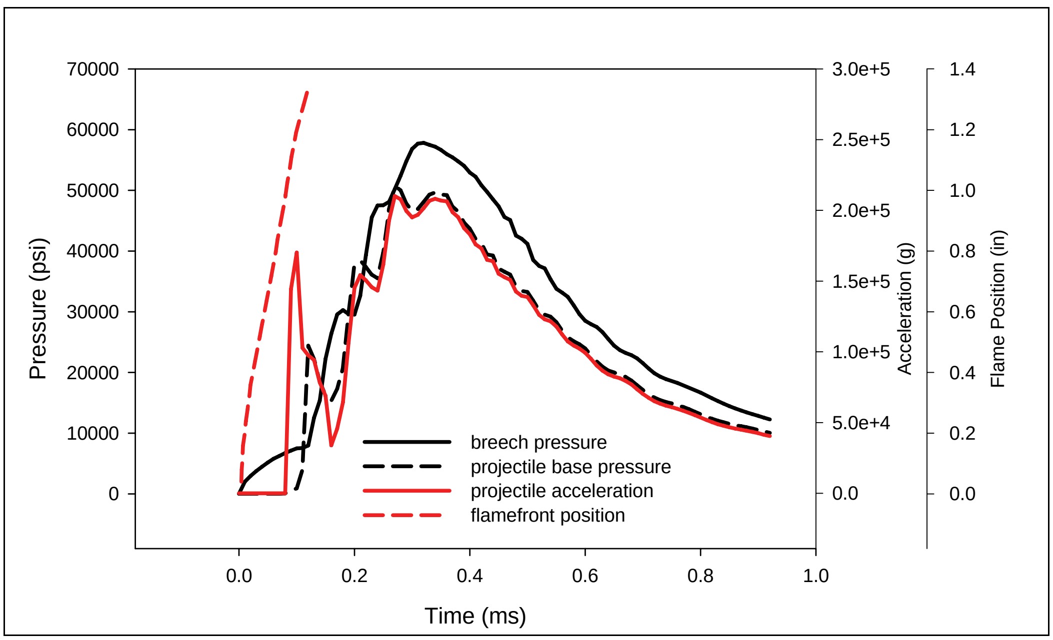

Figure 8. XKTC prediction of ballistic parameters for a 5.56-mm cartridge with a small region of ullage between the propellant bed and projectile base.

[5]Next generation three-dimensional interior ballistic code

6. Lessons Learned and The Way Forward

So what have we learned from this series of calculations? First, just as is the case for the large-caliber world, small-caliber ammunition configurations are not immune to problems associated with non-simultaneity of ignition. Not only is localized ignition likely to lead to strong longitudinal pressure gradients and ensuing pressure waves, but owing to the tight packing of the propellant grains, large intergranular stresses can result during the flame-spreading process. In particular, early bed stresses at the base of the projectile may actually be responsible for debulleting of the projectile from the cartridge case and early motion in some cartridges. Should this occur before complete ignition of the bed, a significant influence on performance (i.e., peak pressure and muzzle velocity) in terms of level and reproducibility could result.

We have seen that the assumption of uniform, instantaneous ignition eliminates such problems. Uniform ignition not being possible, it is expected that increased axial permeability of the charge to ignition and propellant gases will mitigate the problem of local pressurization and the described detrimental effects. Achieving either of these desired conditions, however, is difficult in a charge consisting of a tightly packed bed of small granular propellant. Alternate propellant configurations (very small sticks or slabs) with reduced resistance to axial gas flow might be successful but are likely to be extremely difficult to manufacture in the required small web size for small-caliber guns. Propel-lant mechanical properties, as they impact bed compressibility, are also worth investigating as an approach to maintain initial bed porosity and permeability to facilitate early ignition and (gas) pressurization of the front of the bed, adjacent to the base of the projectile. Alternatively, inno-vative techniques for transmitting ignition gases along the walls of the cartridge case (configurational or material) are worthy of consideration.

Our previous paper *(13)* described two vented center core concepts, one which was simply a hollow tube ("swizzle stick") and a second in which the tube was filled with propellant. Figure 9 provides a simple depiction of this arrangement for a 5.56-mm cartridge; not surprisingly, it looks very much like a center core or bayonet primer-ignited large-caliber round in miniature.

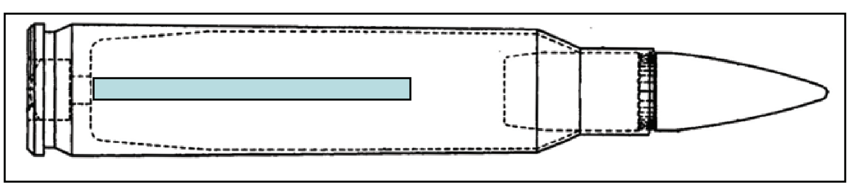

Figure 9. Example of small-caliber cartridge with center core igniter.

Although the earlier study revealed that the predicted curves for the empty swizzle stick exhibited undesirable longitudinal pressure waves, which is a likely result of a continued strong base ignition in the necessarily one-dimensional environment assumed by the XKTC code, a multidimensional analysis may reveal benefits if one can direct a majority of the primer output into the tube rather than into the rear of the propellant bed. The second concept, however, which for simplicity assumed no primer but the swizzle stick to be filled with uniformly ignited propellant, was quite successful in reducing pressure waves and associated bed stresses, presented here as figure 10. Although promising, the same caution as with alternate propellant geometries needs be offered: producibility of such an igniter that is effective, reliable, and durable presents a formidable challenge.

Ultimately, performance enhancement is desired for small arms cartridges. Improved interior ballistic performance can most directly be achieved if the weapon is modified to operate at a higher pressure; however, the ignition process becomes only more critical as pressures are increased. Clearly, any study to improve performance should include consideration of the complexity of the ignition process in such systems, with improvement of the ignition system considered an integral part of the effort. All in all, the challenge for nearly uniform ignition in small-caliber cartridges should be considered as important is in large-caliber rounds, with both performance and safety as benefits.

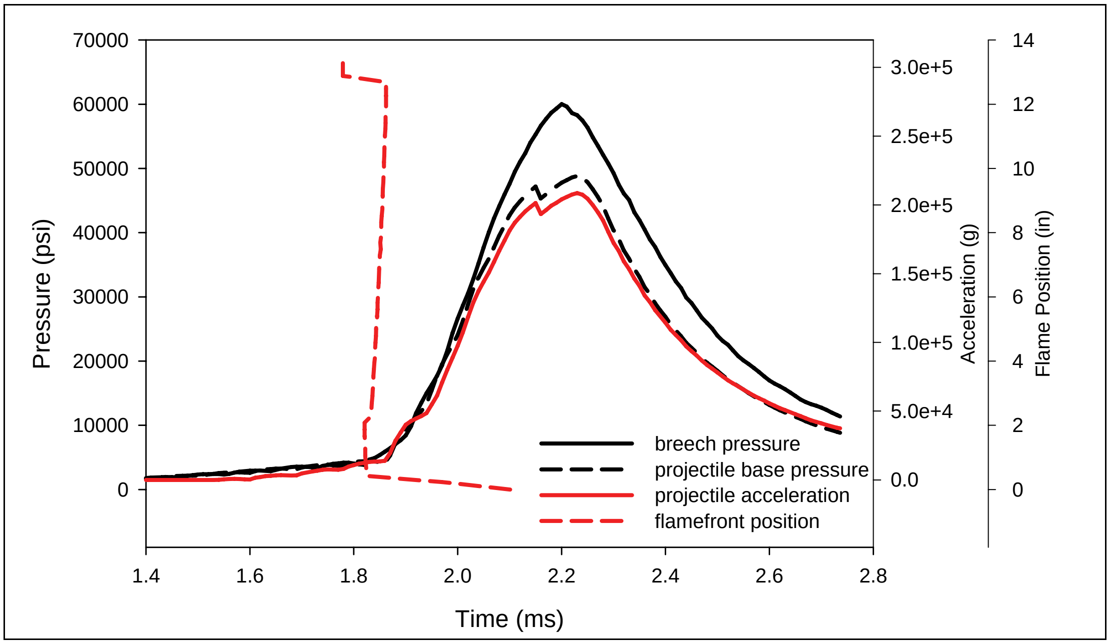

Figure 10. XKTC prediction of ballistic parameters for a 5.56-mm cartridge employing a vented center core tube containing pre-ignited propellant (based on data from reference 13).

7. Conclusions

A first attempt has been made to model the effect of igniter and propellant parameters on the interior ballistics of a small arms cartridge. In particular, the igniter output profile, the stiffness of the propellant bed, and the presence or axial ullage were varied to determine potential effects on flame spread, bed stress, early projectile motion, and ultimately gun performance. The XKTC one-dimensional, two-phase interior ballistic code was employed because of its capability to treat explicitly such features and its relative economy of use. Ultimately, a much more time-consuming analysis using a multidimensional code such as NGEN3 will be required to provide a complete understanding of processes involved, but since the specific features of the interior ballistic cycle undergoing investigation in this first study are largely one-dimensional, XKTC seemed to be a good choice.

We point out that many of the input values employed in these simulations are approximate or even conjectural, yet selections have been made to be at least representative of those for a small-caliber gun system such as 5.56 mm. Thus, the specific results may not be quantitatively accurate but are believed to be illuminating in their qualitative features. In addition to traditional charge design parameters (e.g., propellant type, quantity, and dimensions), we have clearly seen that other design parameters and characteristics can substantially affect early-time processes, even the sequencing of critical events, with significant overall ballistic effects. Not considered in this study were changes in the barrel resistance profile, which would affect early projectile motion, and the presence of circumferential ullage, which would likely influence the path of flame spreading and the magnitude of pressure waves. It is hoped that this initial, brief study will motivate sufficient interest to result in further theoretical and experimental efforts providing a more complete understanding of the details of interior ballistic processes in small-caliber guns.

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