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A COMPARISON OF BARREL-HEATING PROCESSES FOR GRANULAR AND STICK--ETC(U)
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MEMORANDUM REPORT ARBRL-MR-03193

A COMPARISON OF BARREL-HEATING PROCESSES FOR GRANULAR AND STICK PROPELLANT CHARGES

Albert W. Horst

August 1982

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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The natural flow channels offered by propelling charges composed of bundles of stick propellant significantly reduce the resistance to gas flow when compared to that of granular propellant charges, virtually eliminating potentially damaging pressure waves in the gun chamber. However, this same feature which reduces pressure waves may also result in more propellant remaining in the chamber, burning behind the origin of rifling, and perhaps increasing barrel erosion. In this study, a two-phase flow interior ballistic code (NOVA) is

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employed to compare propellant motion and heat transfer processes for ballistically-equivalent stick and granular propellant charges. A large difference in the motion of the solid phase during ignition and combustion is predicted for the two configurations, leading ultimately to an approximately 300 K higher maximum wall temperature for the stick propellant charge.

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NOMENCLATURE

D_p	particle diameter
D_h	hydraulic diameter
h	convective heat transfer coefficient
k_f	thermal conductivity of gas at film temperature
Pr	Prandtl number
q	heat transfer rate
R_T	tube radius
Re_D	Reynolds number
T_g	gas temperature in core flow
T_s	bore-surface temperature
u	gas velocity in core flow
ϵ	macroscopic bed (or bundle) porosity
μ_f	gas viscosity at film temperature
ρ_f	gas density at film temperature

I. INTRODUCTION

Stick propellant is finding increasing application in high-performance artillery charges. Currently employed in a number of European top-zone propelling charges, stick propellant is now being introduced into US artillery as a product improvement to the existing 155-mm, M203 (Zone 8S) Propelling Charge. Further, its use is all but assured in future Enhanced Self-Propelled Artillery Weapon Systems (ESPAWS) under consideration in the United States.

The current popularity enjoyed by stick propellant can be attributed to a number of very desirable ballistic advantages associated with its use, some of them only potential but others clearly demonstrated. The natural flow channels associated with bundles of sticks reduce the resistance offered to gas flow by several orders of magnitude when compared to that resulting from the tortuous path required of flow through a granular propellant bed[1]. Locally high pressure gradients cannot therefore be supported in a stick propellant charge, and potentially damaging longitudinal pressure waves are all but unseen. In addition, the regular packing of propellant sticks yields higher loading densities than for randomly packed granular propellant, allowing equivalent performance with stick propellant charges using a slightly increased mass of a lower energy, lower flame-temperature propellant formulation. It is widely purported, and not unreasonable to expect, that the lower flame temperature should lead to increased barrel life and perhaps reduced muzzle flash and blast. Alternatively, a larger possible charge mass of the existing formulation may allow performance increases in an otherwise volume-limited gun system. With such worthwhile benefits in the offing, exploitation of the stick propellant concept certainly appears well-motivated.

In this paper, we wish to raise concern in respect to one of these potential benefits - that of increased tube life with stick propellant charges. Under the assumption that heat transfer to the tube wall is the dominant mechanism for gun barrel erosion, the use of cooler propellant made possible by the higher packing density of propellant sticks has been deemed adequate to assure a reduction in barrel wear. However, an interior ballistic analysis scheme devised by Nordheim[2] during World War II purports heat transfer to the tube at the origin of rifling to be strongly affected by the distribution of burning propellant grains in the gun tube. According to this picture, heat transfer would be the greatest when the burning propellant remained in the chamber; the least when the propellant was uniformly distributed throughout the gun. Thus, the very feature of stick propellant which reduces pressure waves should also reduce motion of the

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[1] *F.W. Robbins, et al, "Experimental Determination of Stick Charge Flow Resistance," 17th JANNAF Combustion Meeting, CPIA Publication 329, Vol. II, pp. 97-118, November 1980.*

[2] *L.W. Nordheim, H. Soodak, and G. Nordheim, "Thermal Effects of Propellant Gases in Erosion Vents and Guns," NDRC Armor and Ordnance Report No. A-262, National Defense Research Committee, Washington, DC, March 1944.*

solid phase considerably, leading to increased heat transfer to the tube and perhaps increased erosion rates as well.

Indeed, recent calculations[3] based on Nordheim's hypothesis yielded an 18% higher heat input for a stick propellant charge assumed to remain in the chamber when compared to a granular propellant distributed throughout the gun. These calculations were performed using ballistically-equivalent candidate stick (XM208) and granular (XM203E2) propellant charge configurations for the US 155-mm, M198 Towed Howitzer. The same study reports limited experimental measurements of heat transfer for the two charges (without wear-reducing additives) to differ by 13%, the stick propellant charge again yielding the larger value. In fact, based on Nordheim's analysis, the flame temperature for a ballistically-equivalent stick propellant charge must be reduced by 300K to obtain comparable heat transfer to that of the granular propellant, top-zone, 155-mm howitzer charge. While Nordheim's analysis is admittedly crude and confirmatory experimental data sparse, further study of this problem appeared warranted in view of the major commitment to stick propellant under consideration by the US Army.

II. THEORY

Calculations reported in this paper were performed using the NOVA code[4], a two-phase, unsteady flow representation of the interior ballistic cycle. The balance equations describe the evolution of macroscopic flow properties accompanying changes in mass, momentum, and energy arising out of interactions associated with combustion, interphase drag, and heat transfer. Functioning of the igniter is included by specifying a predetermined mass injection rate as a function of position and time. Flamespreading then follows from axial convection, with grain surface temperature deduced from a heat transfer correlation and the unsteady heat conduction equation, and ignition based on a surface temperature criterion. Noteworthy features of NOVA pertinent to this study include mechanisms leading to motion of the solid phase (explicit description of igniter functioning, interphase drag forces, the gas pressure gradient, and intergranular stresses) and the processes of heat transfer to and conduction in the tube wall.

While the code remained unchanged except for input data for granular and stick propellant charge calculations, differences do exist in the forms of correlations employed within the code to relate those microprocesses responsible for interphase drag and intergranular stresses for the two propellant geometries to the overall governing equations for macroscopic

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[3] *J.R. Ward and I.C. Stobie, "On the Erosivity of Stick and Granular Propellant," USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD (report in preparation).*

[4] *P.S. Gough, "THE NOVA CODE: A User's Manual, Volume 1. Description and Use," IHCR 80-8, Naval Ordnance Station, Indian Head, MD, December 1980.*

flow in the gun. Reference is made to the empirical, steady-state correlations of Ergun[5] and Andersson[6] for resistance to flow through fixed and fluidized beds of granular propellant, while drag is deduced from heat transfer by means of a Reynolds analogy for stick propellant, where it is expected to be dominated by the boundary layer. Similarly, intergranular stress in a granular propellant bed is described as being an irreversible function of bed porosity, while a stick propellant bundle is treated as being elastic and capable of sustaining tension as well as compression. In both cases, individual grains/sticks are assumed incompressible.

Convective heat transfer to the tube is calculated using a simple turbulent pipe flow correlation[7] based on a hydraulic Reynolds number to account for the presence of the solid phase:

$$q = h\,(T_g - T_s)$$

$$h = \frac{k_f}{D_h}\left[0.023\ Re_D^{0.8} Pr^{0.4}\right]$$

where

$$Re_D = \rho_f u\ D_h/\mu_f$$

$$D_h = 2\varepsilon R_T/\left[1 + 2R_T \frac{\varepsilon}{D_p}\right]$$

The local temperature at the inside surface of the tube is then determined, as driven by the convective boundary condition, using an approximate cubic profile integral solution to the one-dimensional heat conduction equation. This approximation has been previously shown[8] to produce a 2% error in predicted temperature change for a constant heat flux and 6% for a linearly increasing flux.

Results presented are not to be interpreted as firm, quantitative predictions of wall temperature. Certainly such confidence awaits a considerably more detailed representation of the microprocesses occurring in the chemically-reacting, unsteady (and perhaps multiphase) boundary layer,

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[5] *S. Ergun, "Fluid Flow through Packed Columns,"* <u>*Chem. Eng. Progr.*</u>*, Vol. 48, pp. 89-95, 1952.*

[6] *K.E.B. Andersson, "Pressure Drop in Ideal Fluidization,"* <u>*Chem. Eng. Sci.*</u>*, Vol. 15, pp. 276-297, 1961.*

[7] *J.P. Holman, "Heat Transfer," McGraw-Hill, 1968.*

[8] *C.W. Nelson, "On Calculating Ignition of a Propellant Bed," ARBRL-MR-02864, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1978.* (AD A062266)

as well as processes occurring on the bore surface itself. Nevertheless, the NOVA code provides a phenomenologically much more complete picture of the interplay of charge motion and heat transfer than does Nordheim's procedure, and quantitative trends revealed during this study may warrant consideration by the charge design community.

III. RESULTS

Figure 1 presents bore-surface temperature histories at the origin of rifling calculated for ballistically-equivalent, top-zone, granular (M203) and stick (XM208) propellant charges for the 155-mm, M198 Howitzer. The M203 charge employs a conventional seven-perforation granulation, while the XM208 made use of charge-length, slotted, single-perforation sticks. Both charges employ the same M30A1 propellant formulation, yet significantly higher wall temperatures are predicted for the stick propellant charge. Loci of maximum wall temperatures as a function of axial position for the two charges are displayed in Figure 2, again indicating a more severe heating environment associated with the stick propellant.

If Nordheim's hypothesis is correct, the mechanism for this difference should involve a difference in the motion and distribution of the burning propellant, an integral part of the two-phase flow dynamics described by NOVA. Figure 3 depicts the distribution of solid propellant at various times during the interior ballistic cycle for the two propellant configurations. The granular propellant, indeed, becomes more widely dispersed in the gun tube during much of the combustion phase, resulting in a significant portion of the total charge burning ahead of the origin of rifling and hence not contributing to its erosion. Virtually all of the stick propellant, however, is predicted to remain in the chamber during the combustion cycle. While these distributions do not mimic precisely the limiting-case assumptions of Nordheim, the data of Figure 3 clearly identify the difference in granular and stick propellant motion as an important factor in barrel heating and perhaps erosion.

A logical extension to Nordheim's hypothesis might include the role of gas velocities in the heat transfer process. Figure 4 depicts gas velocities for the two charges at the moments of their respective maxima at the origin of rifling. While it must be cautioned that these figures represent core-flow velocities, we note again that the lowered resistance to flow offered by the stick propellant charge leads to a condition which exacerbates heat transfer to the tube.

To confirm this effect, an additional calculation was performed employing the granular propellant configuration, this time with the interphase-drag friction factor reduced to a value corresponding to stick propellant[1]. As expected, propellant motion was substantially less than that predicted for the unmodified granular propellant (also shown in Figure 3); further, the predicted maximum bore-surface temperature rose to nearly 1500K.

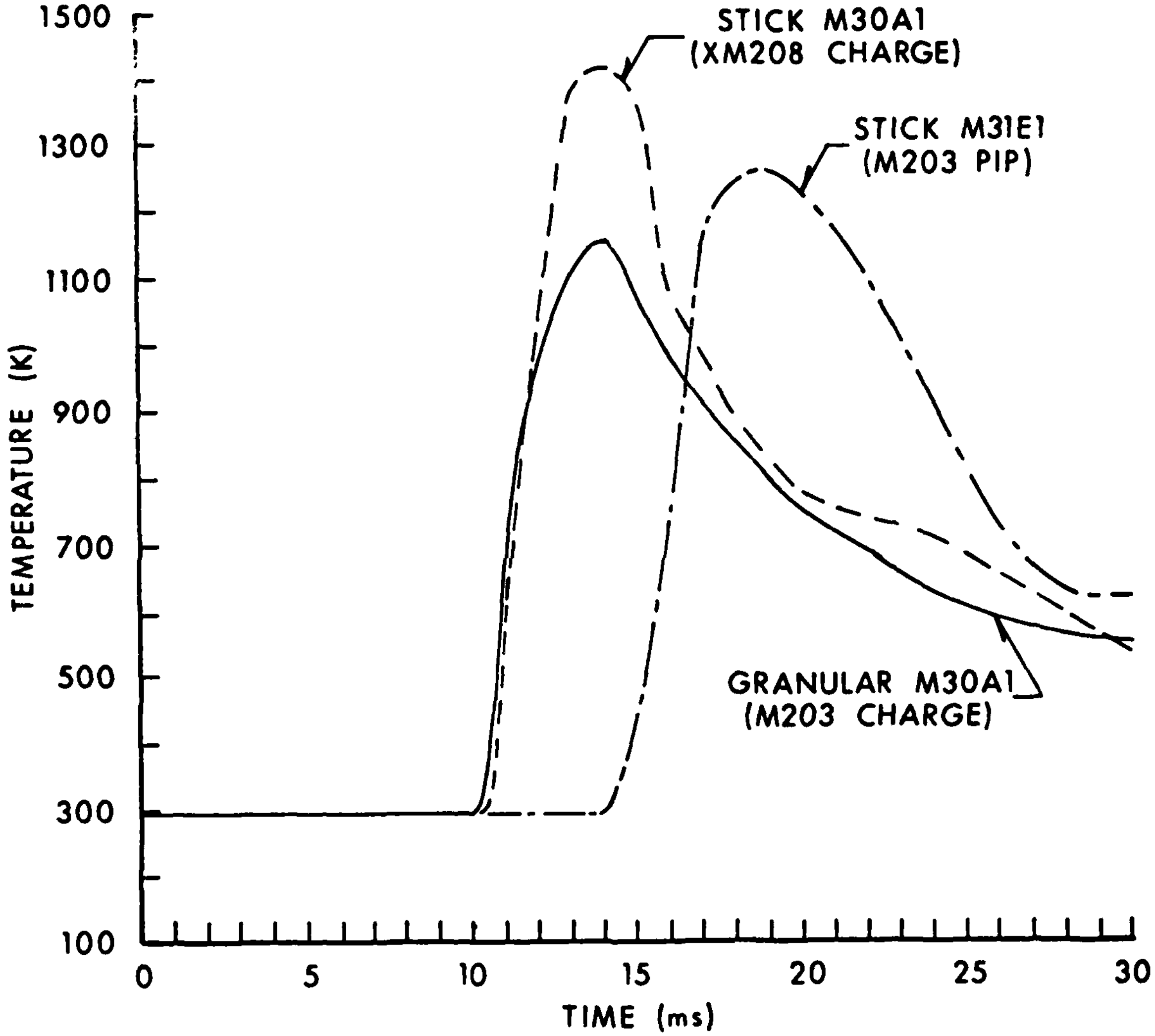

Figure 1. Predicted Bore-Surface Temperature Histories

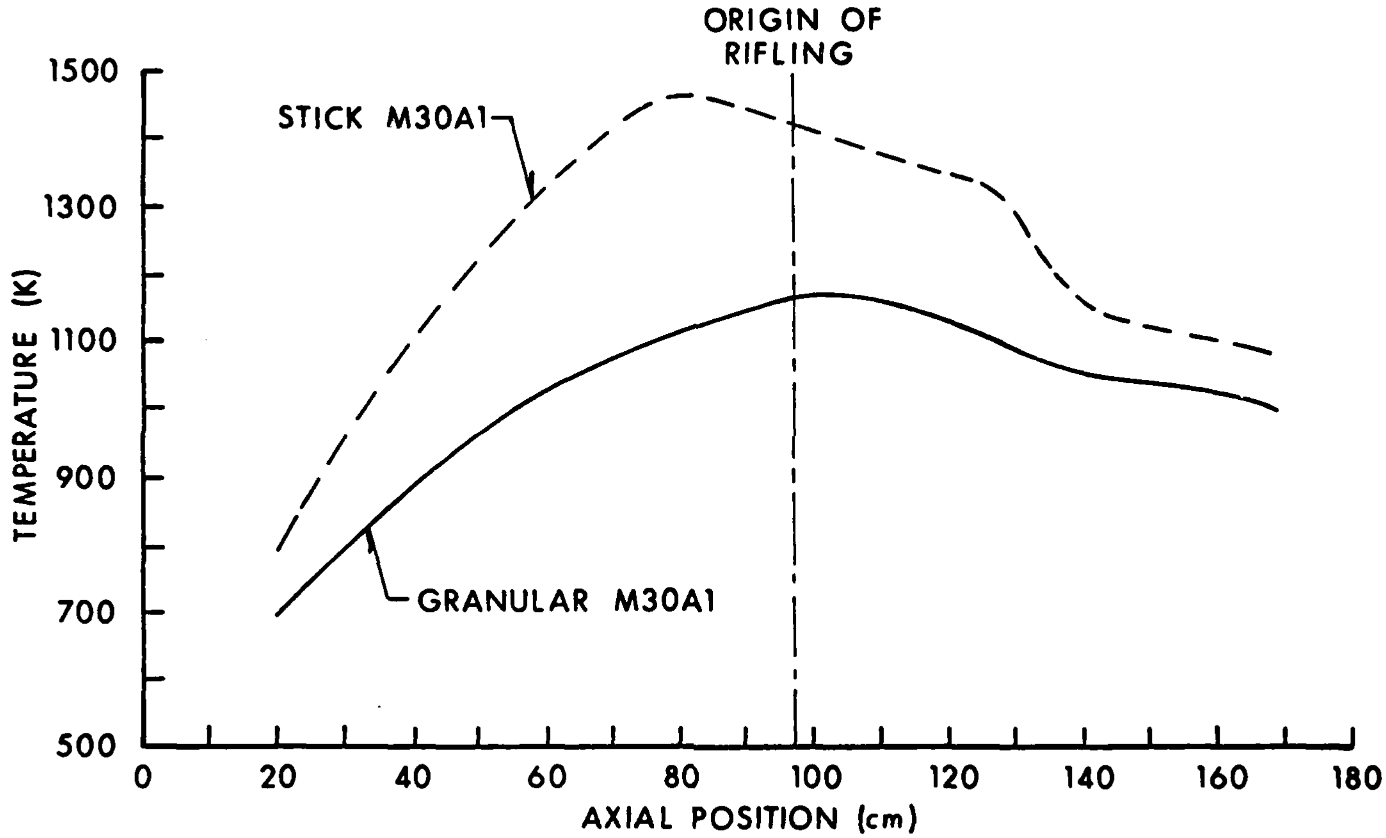

Figure 2. Maximum Predicted Wall Temperatures

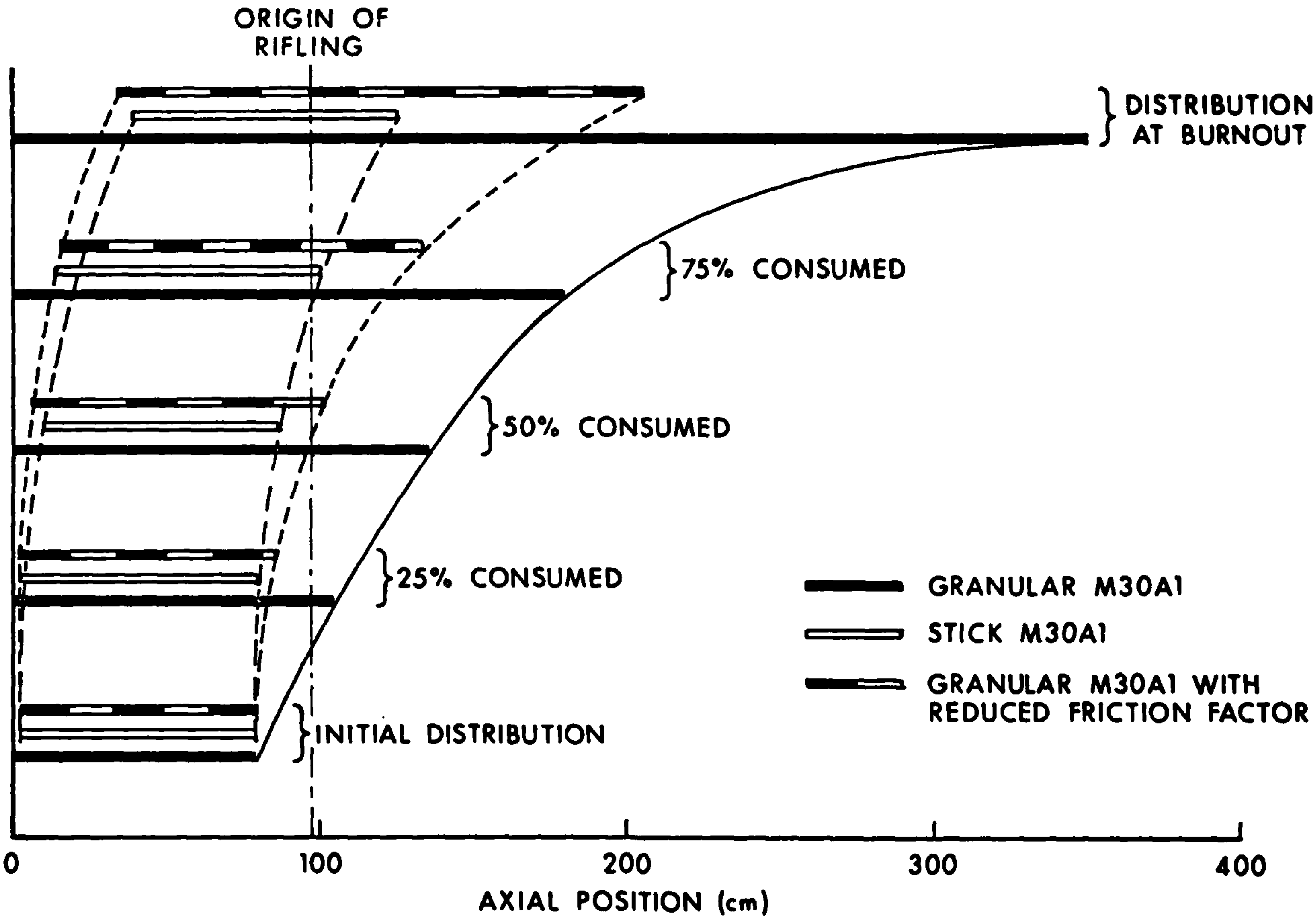

Figure 3. Calculated Distributions of Propellant

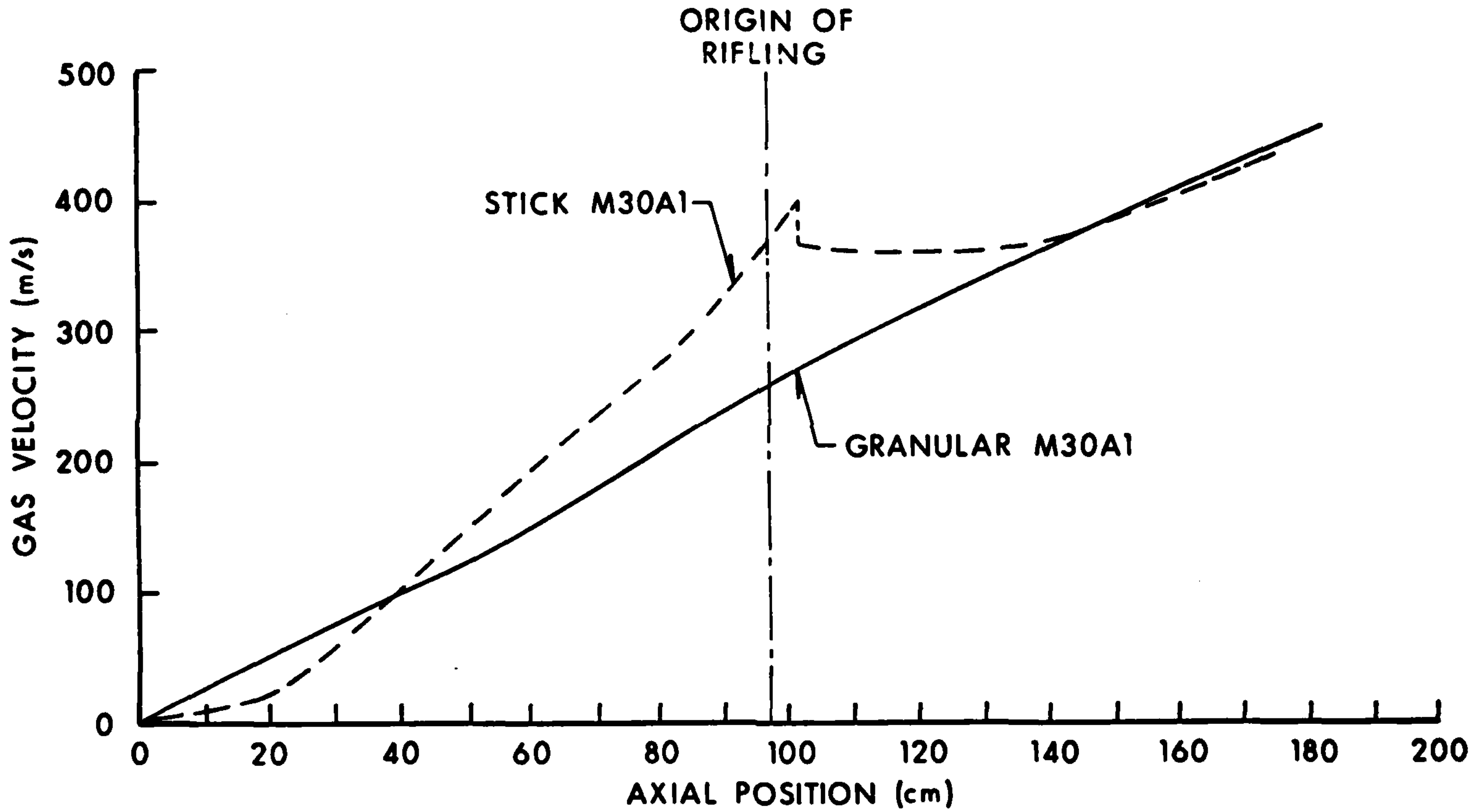

Figure 4. Predicted Gas-Velocity Profiles

Finally, we recognize the compensating effect associated with the use of a cooler propellant (i.e., lower flame temperature) made possible by the higher loadable charge weights of bundles of sticks. Specifically, the M203 Product Improvement Program (PIP) calls for replacement of M30A1 granular propellant with M31E1 stick propellant. However, based on computed results for this propellant formulation, also shown in Figure 1, the accompanying decrease in flame temperature of approximately 400K is not sufficient to compensate for the increase in bore-surface temperature at the origin of rifling associated with the stick geometry.

IV. CONCLUDING REMARKS

A phenomenologically reasonable hypothesis has been presented that suggests that stick propellant geometries may be inherently more erosive based on hydrodynamic considerations alone. Calculations employing the NOVA code substantiate earlier predictions to this effect based on the simple analysis of Nordheim. While quantitative predictions of bore-surface temperature provided by the current analysis must be viewed with some uncertainty, we have no justification for rejecting the basic message that stick propellant erosivity may not equate with granular propellant erosivity. Planned commitments to stick propellant charges warrant immediate experimental investigation of this problem. Perhaps the use of several tiers of shorter sticks being considered to facilitate propellant manufacture and blending may also be shown to promote distribution of the burning propellant throughout the gun tube. If this can be accomplished without the return of undesirable pressure waves, the problem of excessive heat transfer, if real, may be eliminated.

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