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**A BRIEF INVESTIGATION IN THE IMPROVEMENTS OF INTERIOR BALLISTIC
PERFORMANCE THROUGH THE CONTROL OF THE SURFACE AREA OF
SOLID PROPELLANTS**

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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT
COMMAND ARMAMENTS CENTER

Munitions Engineering Technology Center

Picatinny Arsenal, New Jersey

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INTRODUCTION

In conventional gun systems, stored chemical energy is converted into mechanical energy of the projectile through the combustion of solid propellants. This is done via the use of an ignition system that vents hot gas riddled with solid particulates into the bed of solid propellant. Through complex conductive, convective, and radiative heat transfer mechanisms, the temperature of the exposed surface area of the solid propellant quickly reaches its auto-ignition temperature due to the generally poor thermal diffusivity of the material. The solid propellant then begins to deflagrate, producing high pressure/temperature gases that work on the base of the projectile. When the pressure acting on the base of the projectile exceeds the projectile's shot start pressure (i.e., the pressure required to overcome projectile engraving and bore resistance), the projectile begins moving down bore causing the combustion gases to expand. In order to maximize the work done on the projectile as it travels down bore, high-pressure gases must be continually evolved from the solid propellant at a rate commensurate with the resulting volumetric expansion due to projectile transit. However, the aforementioned rate must be controlled such that the gun barrel does not over-pressurize and catastrophically fail.

The rate at which combustion gases are evolved from solid propellants is assumed to be the product of the density of the solid propellant, the burn rate, and the available total surface area. The burn rate is an empirical correlation that relates the rate at which the propellant is consumed with the pressure at which combustion takes place (i.e., confinement dependent). It is generally written in the form of St. Robert's Law (also commonly referred to as Vieille's law), which is a simple power-law relationship per reference 1 and is provided in equation 1.

$$\frac{dx}{dt} = \beta(P)^\alpha \quad (1)$$

Where,

$$\begin{aligned} \frac{dx}{dt} &= \text{The burn rate (m/s)} \\ P &= \text{Mean pressure of the combustion gas (MPa)} \\ \alpha &= \text{Exponent of Vieille's law} \\ \beta &= \text{Coefficient of Vieille's law [m/(s-MPa}^\alpha\text{)]} \end{aligned}$$

As mentioned previously, the burn rate dictates the consumption of the solid propellant. Thus, it is the magnitude of the surface regression velocity vector that is inward normal to the surface of the solid propellant. As the solid propellant is consumed, its effective surface area is altered. For conventionally extruded solid propellant grains, the available surface area can either decrease, remain neutral, or increase (until web burn out) with respect to the burn distance. These dynamic topological profiles are commonly termed regressive, neutral, or progressive, respectively.

With the advent of new manufacturing processes (e.g., additive manufacturing), the geometry of solid propellant grains can theoretically be designed to exhibit hybrid-like, surface-area regression profiles (e.g., initially regressive, then progressive). With such manufacturing processes, the charge designer can tailor the topological profile of the grains such that the gas generation rate maintains the system at peak operating pressure during the munition launch cycle. In doing so, the piezometric efficiency of the system (i.e., the ratio of mean pressure during the entire ballistic cycle to peak pressure per ref. 2) can be optimized, which will implicitly increase the total amount of pressure-volume work done on the base of the projectile and ultimately increase the projectile's muzzle velocity.

DISCUSSION

The purpose of this paper is to investigate how the ballistic performance of a given system can be optimized by controlling the surface area of solid propellant. For this study, the fictitious "AGARD gun," which stands for Advisory Group for Aerospace Research and Development, was used. It is important to note that the AGARD gun is assumed to have a constant bore diameter of 13.2 cm, use homogenous, cylindrical grains that have 7 perforations (colloquially known as a 7-perf cylinders), and is assumed to have negligible heat loss. A pictorial representation of the gun chamber is shown below in figure 1 and was obtained courtesy of reference 3. The interior ballistics modeling parameters pertaining to this gun were obtained from reference 3 and are provided in table 1.

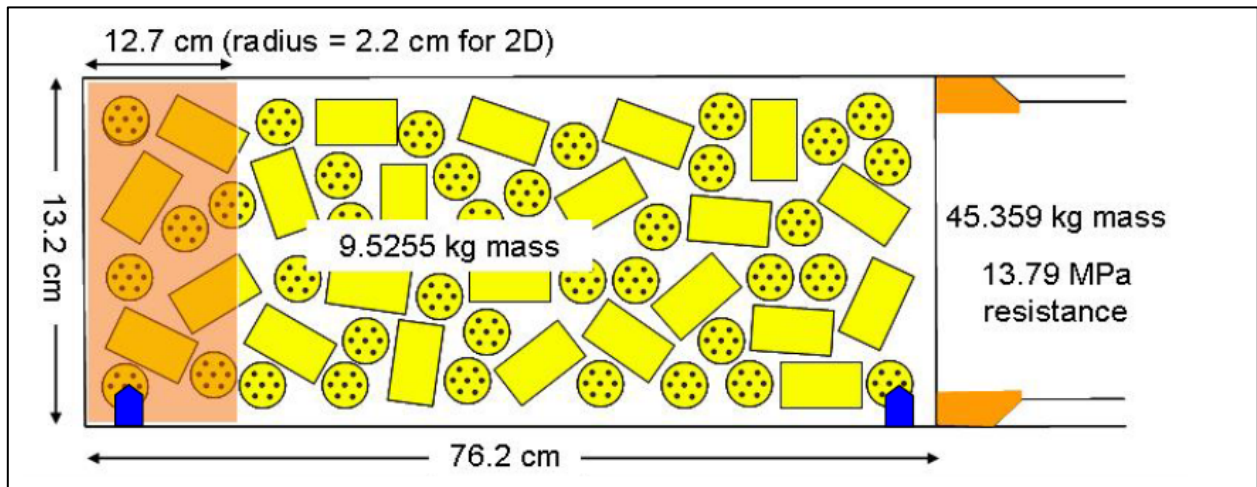


Figure 1
Pictorial representation of AGARD gun chamber

Table 1
Interior ballistics parameters of the AGARD gun system

Parameter	Value
Weapon specific	
Gun caliber	0.132 m
Initial position of projectile from breech face	0.762 m
Travel of projectile	4.318 m
Bore resistance (assumed constant along travel)	13.79 MPa
Projectile mass	45.359 kg
Propellant	
Mass	9.5255 kg
Solid density	1578 kg/m ³
Geometry	7-perf cylinder
Grain length	0.0254 m
Grain diameter	0.01143 m
Grain perf diameter	0.001143 m
Burn rate coefficient (β)	0.00078385 m/(s-MPa $^\alpha$)
Burn rate exponent (α)	0.9
Adiabatic flame temperature	2585 K
Specific heat ratio	1.27
Impetus	1.009E6 J/kg
Co-volume	0.0010838 m ³ /kg
Ignitor	
Mass	0.2268 kg
Adiabatic flame temperature	1706 K
Specific heat ratio	1.25
Impetus	0.3926E6 J/kg
Co-volume	0.001 m ³ /kg

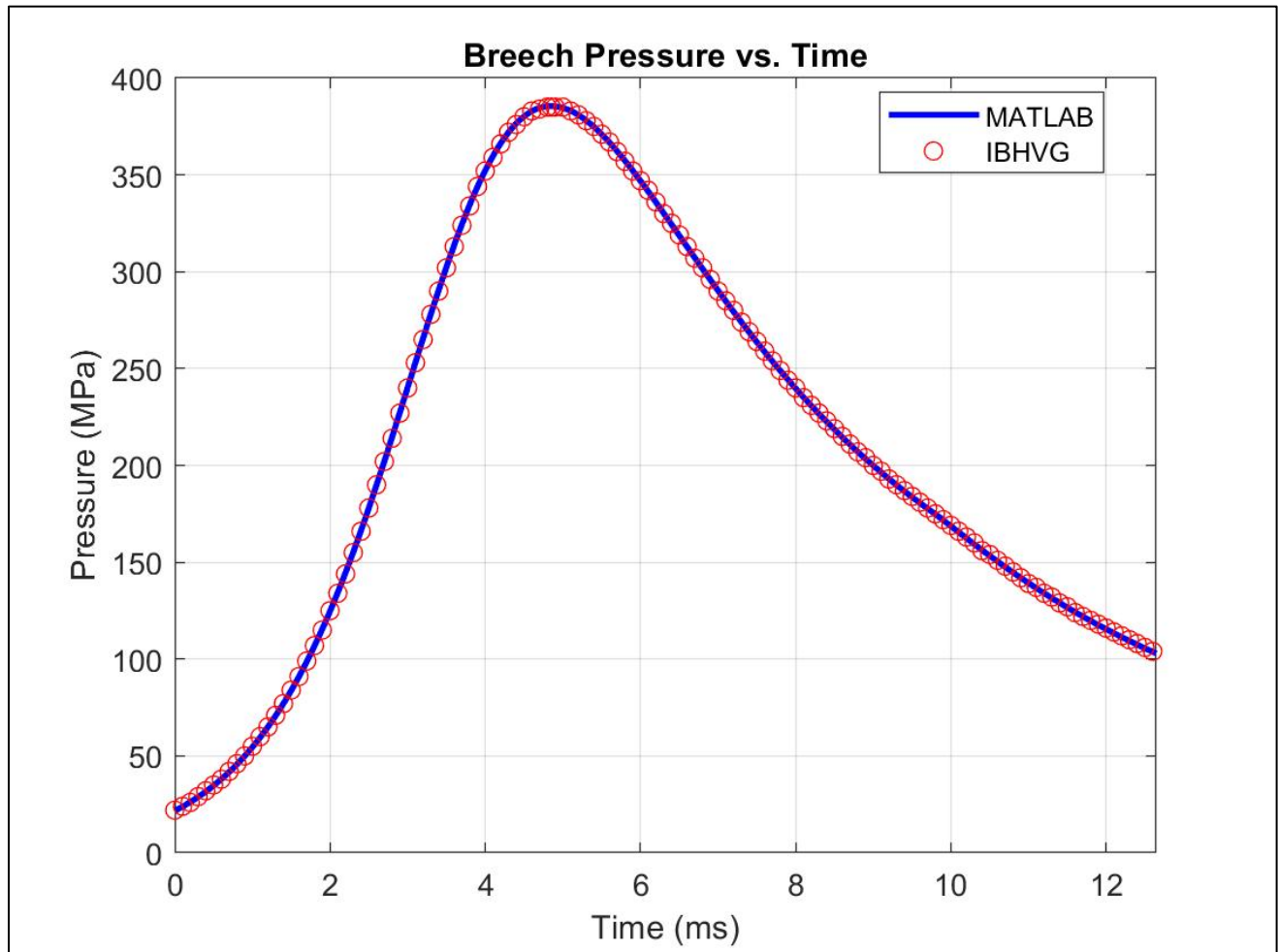
For this study, a lumped-parameter representation of the gun system was used, which is consistent with the Baer-Frankle model. For further information regarding the governing equations of the Baer-Frankle model, consult the Interior Ballistics of High Velocity Guns version 2 (IBHVG2) user manual per reference 4. For a lumped-parameter model, ideal launch assumptions are implemented to reduce the partial differential conservation equations governing two-phase, reactive flow into relatively simple algebraic and ordinary differential equations that can be easily integrated over time via numerical methods. For thoroughness, the aforementioned ideal launch assumptions used in the lumped-parameter model are as follows:

- All of the ignitor material is consumed at time zero
- The deflagration process follows the well-stirred reactor assumption (i.e., the gas and solid phases are treated as a uniform mixture)
- The bed of solid propellant is uniformly and instantaneously ignited (i.e., it is assumed that the speed of the ignitor flame spread is much greater than the initial propellant burn rate and the solid propellant reaches its auto-ignition temperature instantaneously)
- There is no spatial variation in the density of the combustion gas (i.e., $\frac{\partial \rho}{\partial x} = 0$)
- The pressure distribution within the gun can be characterized by a super-imposed, time dependent pressure gradient that is derived via the analytical solution to the

one-dimensional, inviscid equations of continuity and momentum (note this assumption precludes the onset of pressure waves in the model)

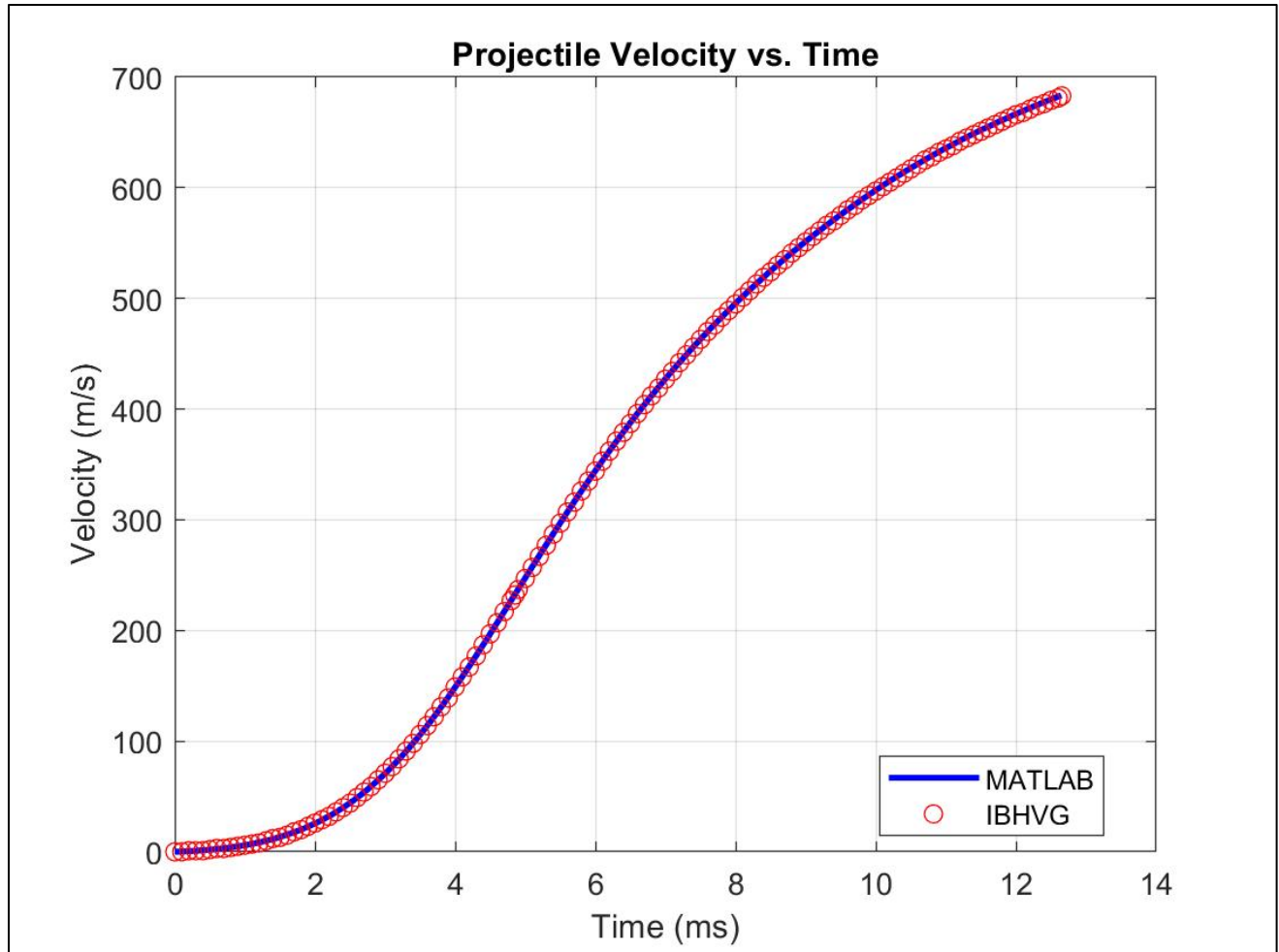
- There is no cracking or mechanical degradation of the propellant grains during the ignition and combustion processes

Via use of the assumptions and parameters identified previously, a MATLAB script was developed to integrate the governing equations, provided in reference 4, as a function of time. Note that for the lumped-parameter model used in this report, a classical fourth order Runge-Kutta numerical integration scheme was used to integrate the governing equations. More information on this integration scheme can be found in numerical methods textbooks such as reference 5. It is important to note that in lieu of using IBHVG3 for this paper, a user developed MATLAB script was created such that it could be easily customized by the author to optimize the surface area of the propellant grains. Prior to implementing this feature, the MATLAB model was validated against the results produced by IBHVG3 for a standard interior ballistics calculation of the previously identified system. As shown in figure 2, both codes are in excellent agreement with one another.



(a)
Breech pressure versus time

Figure 2
Comparison of lumped-parameter, interior ballistics models for AGARD gun



(b)
Velocity versus time

Figure 2
(continued)

Per the results shown in the figures, the conventional AGARD gun reaches a peak operating pressure of 385.5 MPa and results in a muzzle velocity and piezometric efficiency of 683 m/s and 53.3%, respectively. For this paper, it is assumed that 385.5 MPa is the maximum operating pressure of the AGARD gun. Thus, subsequent interior ballistics calculations used in this study will not allow the system to reach pressures beyond this limit.

Constant Pressure Interior Ballistics Model

The theoretical maximum muzzle velocity of the AGARD system can be determined by assuming that the munition launch cycle initiates at the maximum operating pressure and remains at this pressure as the projectile transits down bore. With this approach, the projectile experiences a constant rate of acceleration until all of the solid propellant is consumed, which then causes the system pressure to reduce as the propellant gas expands. If the AGARD system operated in such a manner at the aforementioned peak pressure of 385.5 MPa, the resulting muzzle velocity would be 788 m/s and the piezometric efficiency would be 80.1%. Figures 3 through 5 show the resulting

pressure versus time, velocity versus time, and solid propellant surface area versus depth burned profiles, respectively.

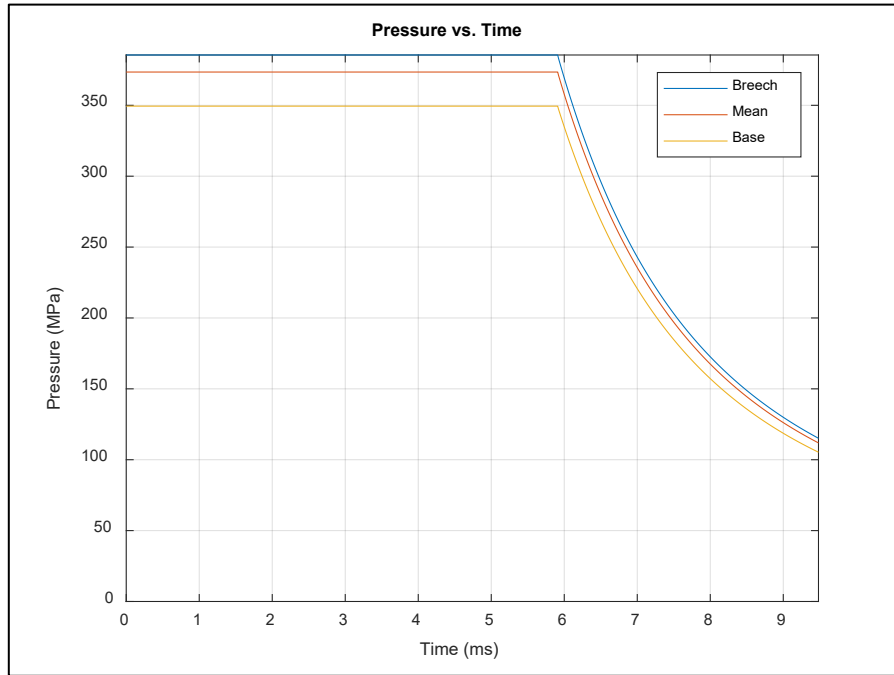


Figure 3
Pressure versus time profile for constant pressure analysis of AGARD gun

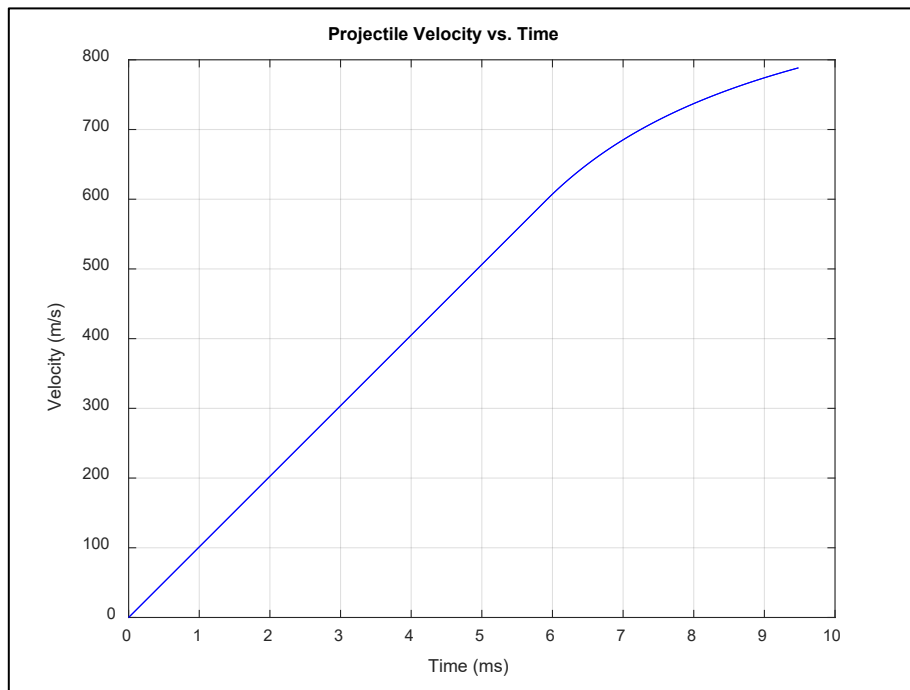


Figure 4
Velocity versus time profile for constant pressure analysis of AGARD gun

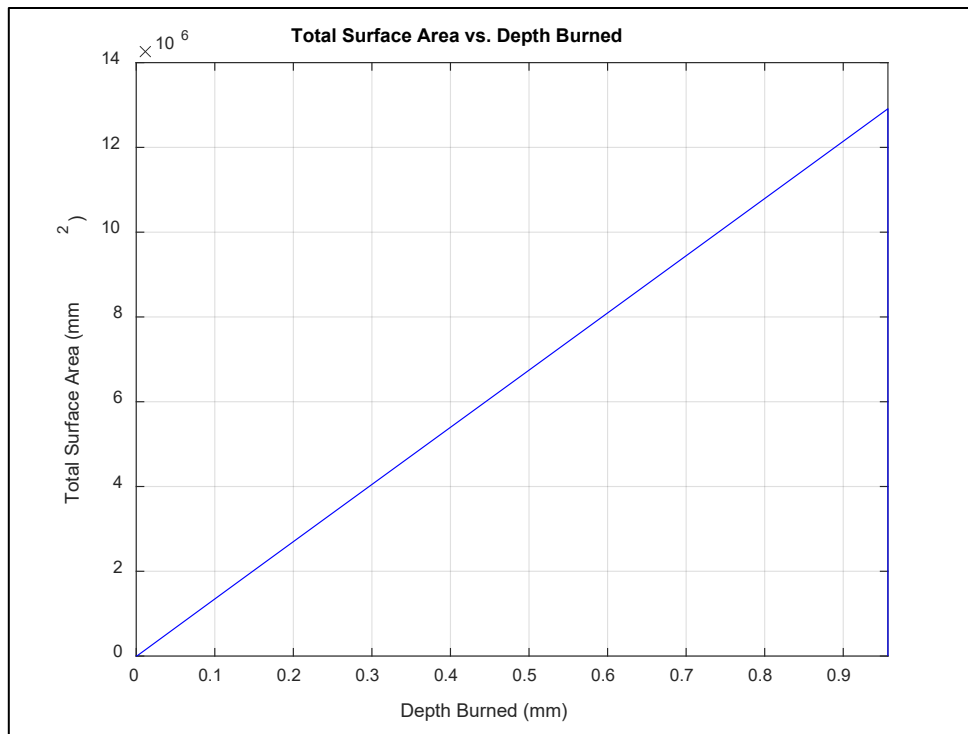


Figure 5

Surface area versus depth burned profile for constant pressure analysis of AGARD system

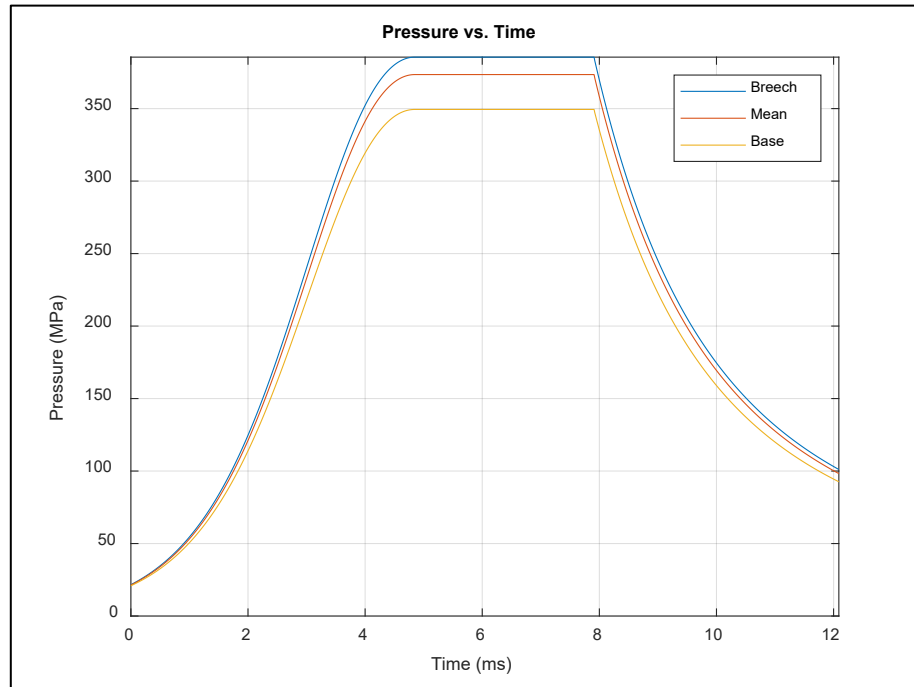
While a gun system operating continually at peak pressure is the upper echelon of interior ballistics performance, developing such a system in practice is unfeasible. Not only would an intensive hardware redesign be required to the gun itself, but the ignition system would need to have absolutely no variation on a shot-to-shot basis due to the extended time spent at peak pressure. Additionally, inspection of figure 5 demonstrates that at the initial time step of the analysis, the surface area of the solid propellant is 0 mm², which is unrealistic and is an inherent simplicity of the lumped-parameter approach. To elaborate, the constant pressure model pre-pressurizes the system to the specified operating pressure at the initial time step of the analysis via use of an aggressive ignition model. Since the burn rate of solid propellant is a function of the mean gas pressure, the surface area must be 0 mm² to preclude consumption of the solid propellant in the model and thus ensure that the system does not exceed the specified operating pressure.

Despite the limitations of the constant pressure model, the surface area versus depth burned curve in figure 5 provides some valuable insight to the charge designer. Per the aforementioned figure, as the solid propellant is consumed during the munition launch cycle, the surface area increases linearly until it is entirely expended—thus, experiencing a progressive-like profile. With this observation, the objective of the charge designer is to then develop an idealized topological profile that will allow the ignited propellant to quickly reach peak pressure (without expending too much mass) and then progressively burn in a controlled manner until all of the propellant is expended. With such a charge design, no hardware modifications are required of the gun system and thus, legacy performance of fielded weapons can be improved with use of forward fitted, optimized propellant grain geometries. The following subsection discusses this approach and provides the results for the AGARD system.

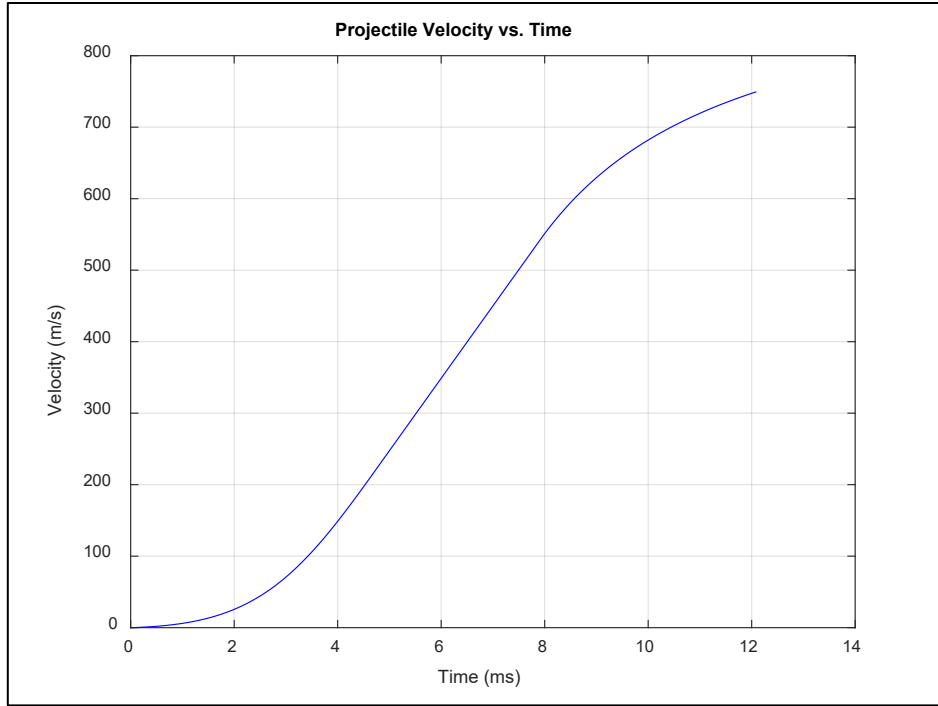
Progressive-Progressive Solid Propellant Surface Area Optimization for AGARD Gun

The hybrid interior ballistics model used in this paper to optimize the surface area of solid propellant sequentially couples a standard interior ballistics model with a constant pressure model. With this approach, a “seed” geometry is given to the model to pressurize the system to its operating pressure. Here, the surface area is known and the pressure of the system is determined at each time step. When the objective peak pressure is reached, the model switches to a constant pressure analysis, in which the pressure gradient is maintained constant, and the system of equations (defined in ref. 4) are manipulated such that the surface area of the charge is determined at each time step, until the total charge mass is consumed.

By optimization of the solid propellant grain geometry in such a manner defined previously, the muzzle velocity and piezometric efficiency of the AGARD system are 749 m/s and 60.7%, respectively. This results in a 9.7% increase in muzzle velocity and a 7.4% increase in piezometric efficiency with respect to the conventional AGARD system. Figures 6 through 8 show the resulting pressure versus time, velocity versus time, and solid propellant surface area versus depth burned profiles, respectively.



Figures 6
Pressure versus time profile of AGARD gun with optimized progressive-progressive solid propellant geometry



Figures 7
Velocity versus time profile of AGARD gun with optimized progressive-progressive solid propellant geometry

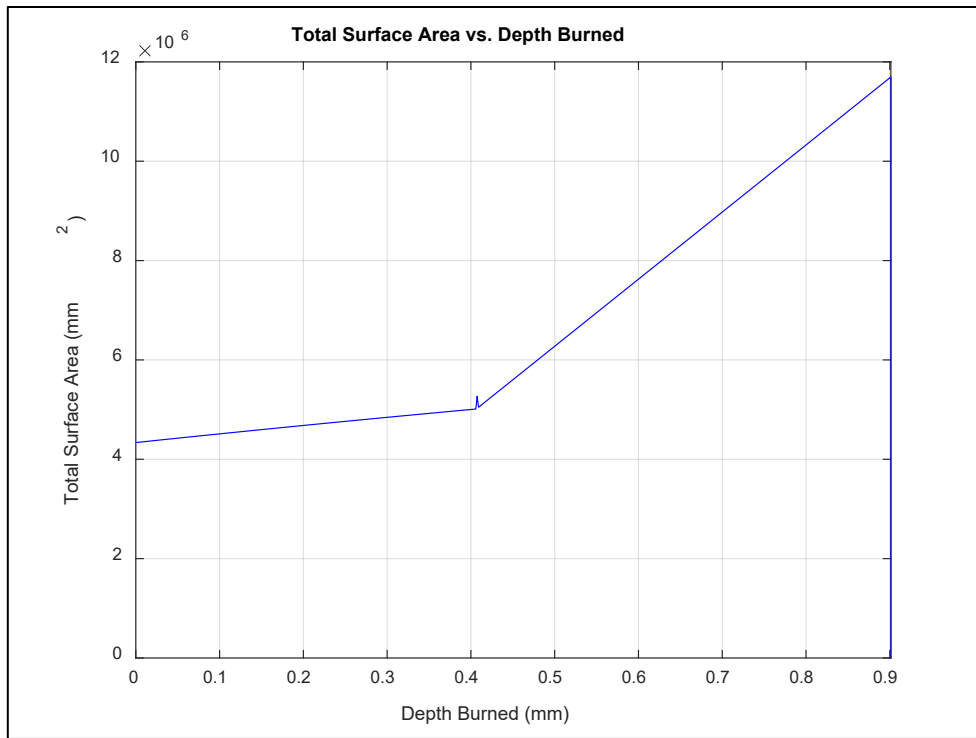


Figure 8
Surface area versus depth burned profile of AGARD gun with optimized progressive-progressive solid propellant geometry

Per these figures, it can be seen that the gun system operates at peak pressure for several milliseconds during the munition launch cycle, thus exhibiting the desired plateau-like pressure-time trace until all of the solid propellant is consumed. During the plateau region of the pressure-time trace, it can be seen that the velocity-time trace correspondingly experiences a steep linear profile (due to the constant acceleration of the projectile). Another interesting result worth mentioning is the profile of the surface area versus depth burned trace. As seen in figure 8, the profile is broken up into two distinct regions corresponding to the interior ballistics (IB) model used. For the first region, the surface area profile follows that of the 7-perf cylindrical grains dimensioned in table 1. When the AGARD system reaches peak pressure, the surface area versus depth burned curve then becomes piecewise linear with a more aggressive, progressive slope (neglecting the trivial noise shown in the plot). The solid propellant burns consistently in this manner until it is entirely consumed and, upon this instance, the surface area immediately plummets to 0 mm².

Regressive-Progressive Solid Propellant Surface Area Optimization for AGARD Gun

As discussed earlier, the interior ballistics performance of fielded gun systems can be improved if the gun system is quickly raised to its operating pressure and maintained at this pressure until all of the solid propellant is expended. Thus, further increases in the initial surface area of the bed of solid propellant should theoretically promote a more rapid increase in the initial pressurization of the gun chamber. With the constraints of a fixed charge weight and a piecewise linear surface area versus depth burned profile, use of a regressively burning geometry with a high initial surface area as the “seed” geometry will further improve the muzzle velocity and piezometric efficiency of the AGARD gun. Note that the latter constraint was used in this study since geometries with aggressively discontinuous changes in surface area are currently not feasible to manufacture.

In the earlier section, a bed of 7-perf cylinder grains was used to pressurize the system; however, in this section, a bed of cord grains was used. Cord grains were studied as the “seed” geometry since they are a regressively burning geometry with a high initial surface area. In this paper, the length of the individual cord grains were assumed equivalent to that of the 7-perf cylinders. However, the web was optimized to roughly 2.65 mm to ensure that the surface area versus depth burned profile maintained its piecewise linear nature. All other parameters identified in table 1 were used in the model.

With use of the parameters identified previously, the muzzle velocity and piezometric efficiency of the AGARD system were computed to be 751 m/s and 62.4%, respectively. This results in an astonishing 10.0% increase in muzzle velocity and a 9.1% increase in piezometric efficiency with respect to the conventional AGARD system. Additionally, note that these results verify that use of a regressively burning geometry with a high initial surface area as the “seed” geometry improves the overall interior ballistics performance. Figures 9 through 11 show the resulting pressure versus time, velocity versus time, and solid propellant surface area versus depth burned profiles, respectively.

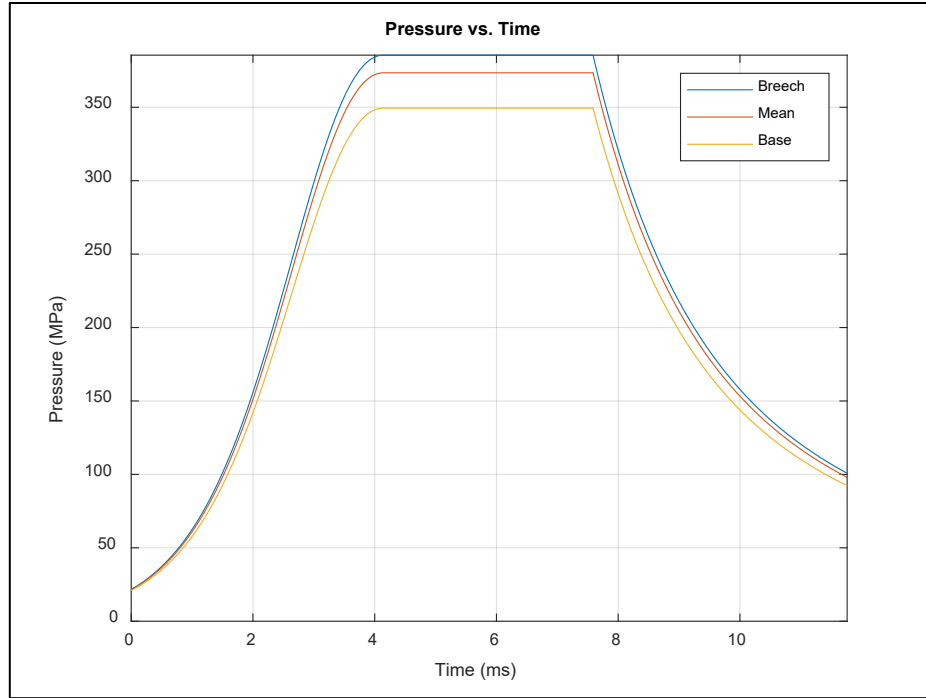


Figure 9
Pressure versus time profile of AGARD gun with optimized regressive-progressive solid propellant geometry

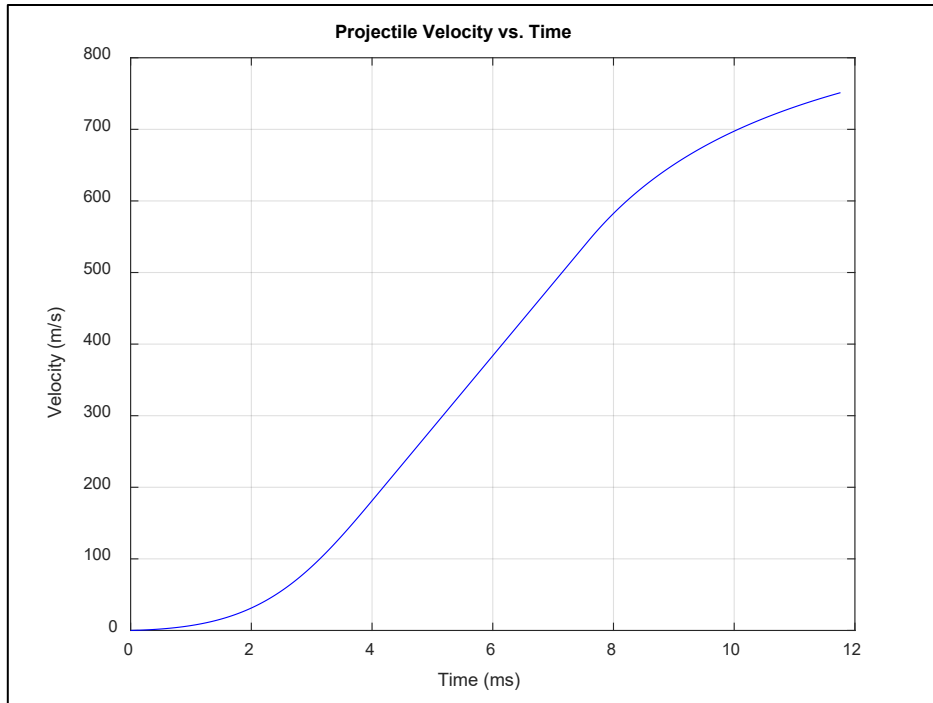


Figure 10
Velocity versus time profile of AGARD gun with optimized regressive-progressive solid propellant geometry

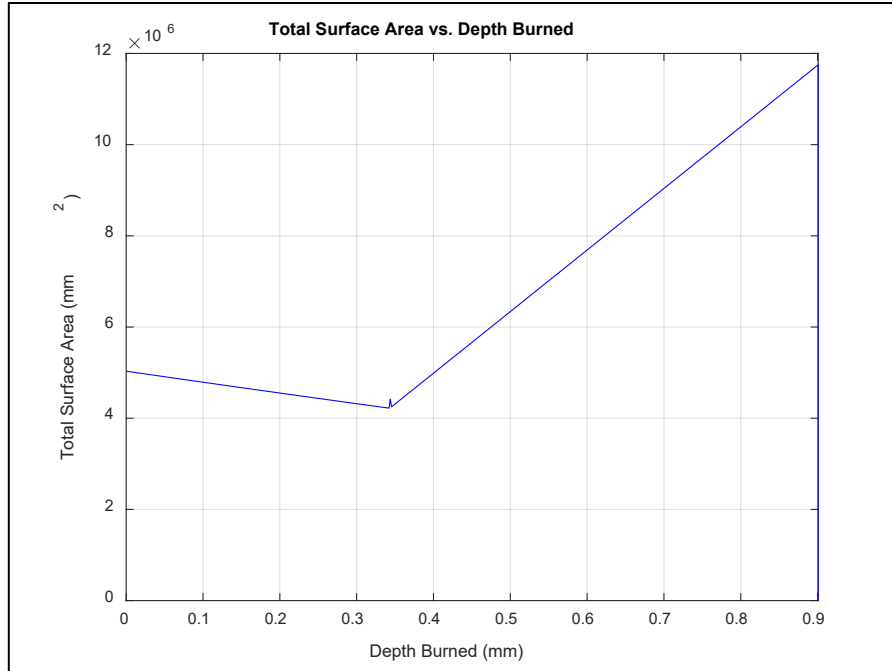


Figure 11

Surface area versus depth burned profile of AGARD gun with optimized regressive-progressive solid propellant geometry

As noted earlier, using an initial geometry with a high surface area allows the gun system to pressurize at a much quicker rate. It is therefore curious to see the performance increase if the initial surface area of the bed of cord grains was further increased (i.e., by reducing the web of the individual grains constituting the total charge weight). If the aforementioned web of 2.65 mm was reduced to 1.0 mm, the resulting muzzle velocity increase would be 4 m/s; however, this comes at the expense of a highly discontinuous surface area versus depth burned profile that would be unfeasible to manufacture in practice. The reason for the relatively small change in muzzle velocity is clearly illustrated when the breech pressure is plotted against the displacement of the projectile for each web size studied. As per figure 12, only a marginal amount of supplemental pressure-volume work is done on the projectile for the higher initial surface area cases. Thus, further increases in the initial surface area of the propelling charge will result in diminishing returns on the muzzle velocity.

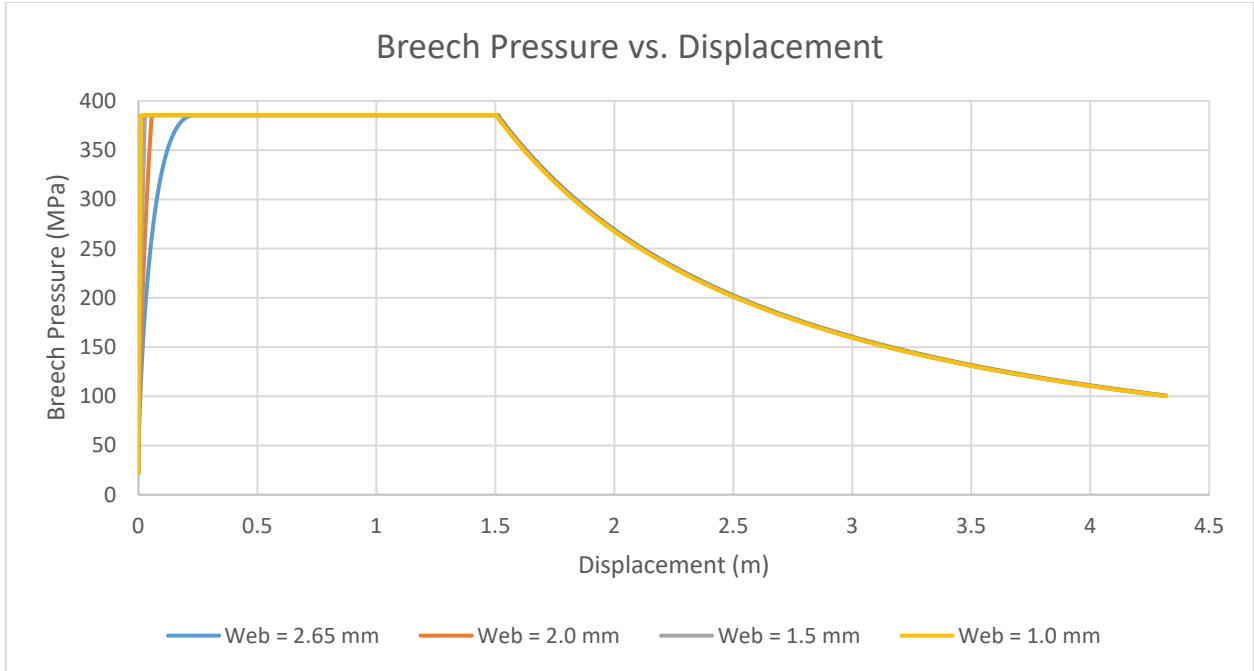


Figure 12

Breech pressure versus displacement profile of AGARD gun system with various initial webs

As alluded to previously, by perpetually pressurizing the system to peak pressure at the onset of ignition, a marginal amount of additional solid propellant mass is conserved to maintain the system at operating pressure during projectile transit. However, this comes at the expense of the total surface area of the charge, as the surface area must instantaneously decrease such that the system doesn't over-pressurize. The surface area then must exhibit a progressively burning profile to keep the rate of gas generation commensurate with the rate of volumetric expansion. As seen in figure 13, the discontinuity in the surface area profile becomes more severe as a function of the initial surface area; however, all curves illustrate a consistent surface area profile when the AGARD gun is maintained at operating pressure.

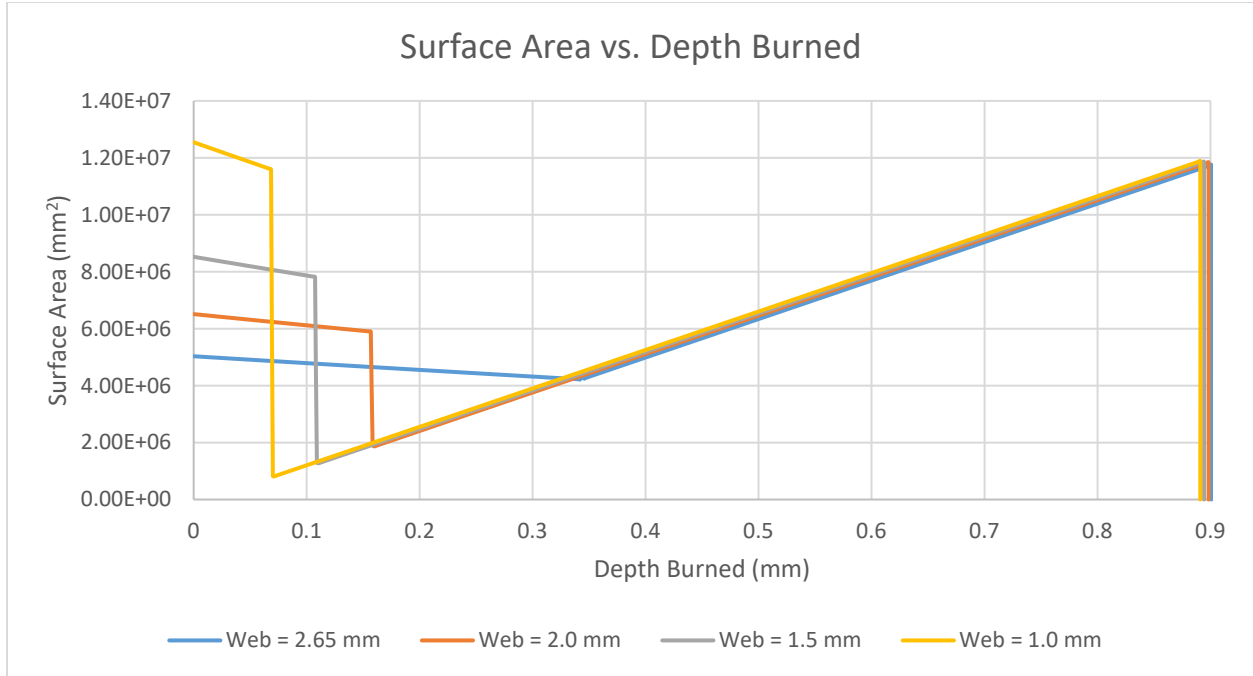


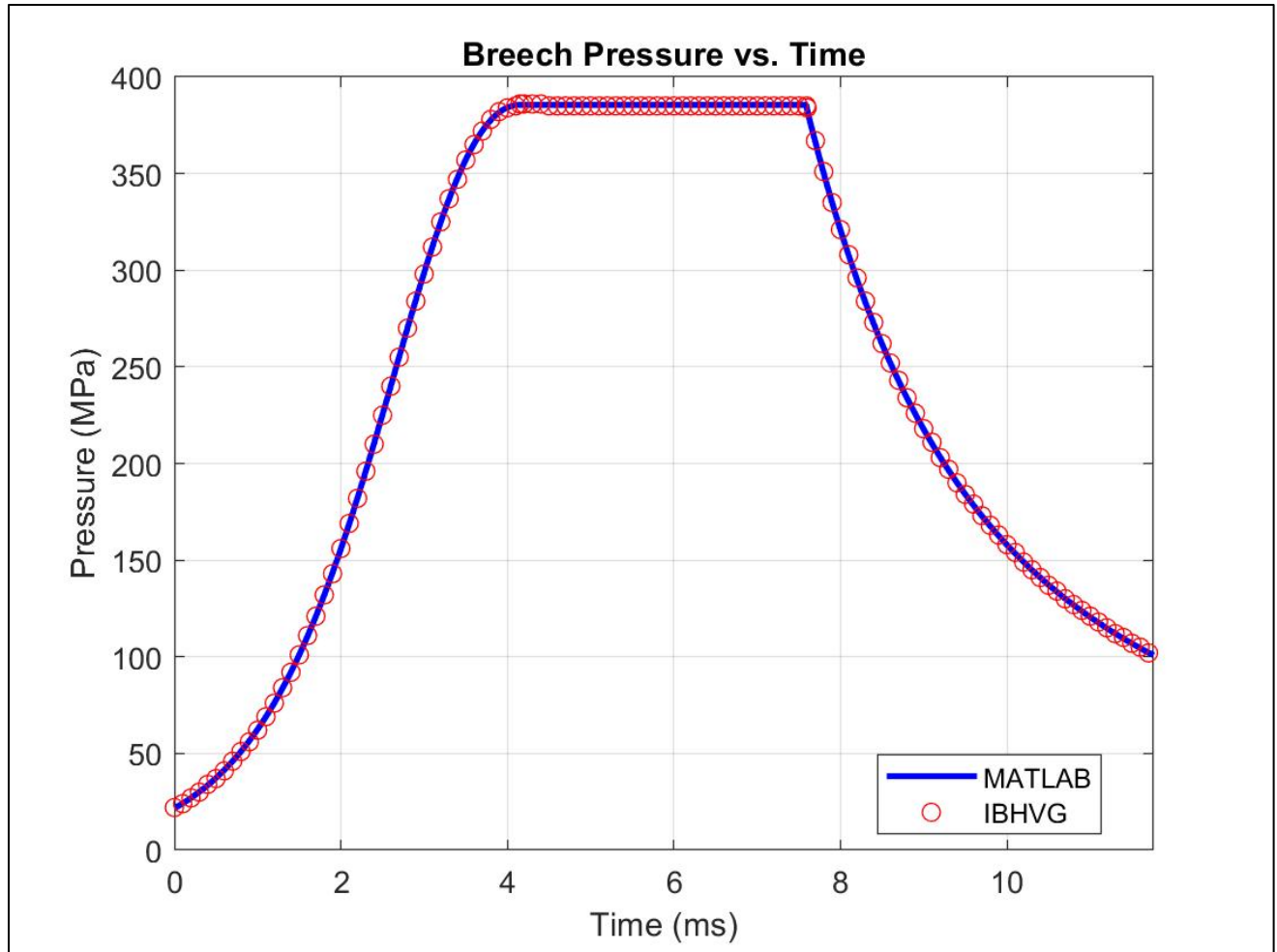
Figure 13

Surface area versus depth burned profile of AGARD gun system with various initial webs

With respect to both figures 12 and 13, it can be concluded that there is an optimal initial surface area for any given system. In this instance, the initial surface area equivalent to a bed of cord grains with a 2.65-mm web would be the optimal solution for a charge designer since the surface area profile is piecewise continuous and the resulting muzzle velocity is approaching its upper limit for the system.

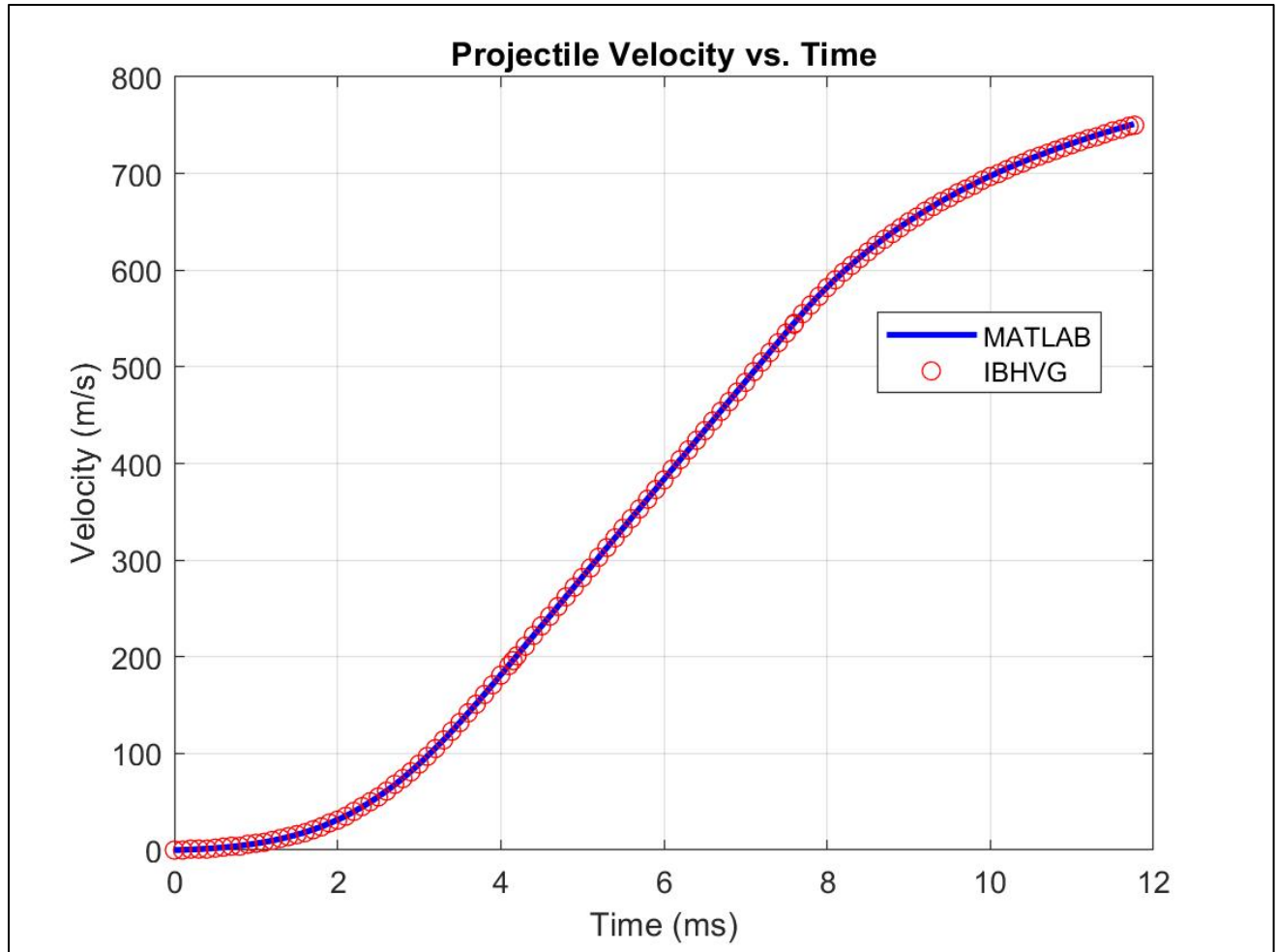
Validation of Optimized Surface Area Profile

In order to validate the optimized charge's surface area profile for the AGARD gun, IBHVG3's generic grain feature was used. This feature allows the user to specify the surface area and burn depth of a generic grain in a tabular format. The IBHVG3 then linearly interpolates the corresponding profile between intermediate data points. Discrete points from the optimized regressive-progressive profile obtained herein were entered into the IBHVG3 program to validate the model. The outputs from MATLAB were then compared with the outputs from IBHVG3 per figure 14. As shown in the previous, the models are in excellent agreement with one another. Variance between the models is mainly attributed to rounding errors associated with the surface area versus depth burned profile as well as differences in the numerical integration schemes used. Regardless, the results indicate that the user-developed, lumped-parameter model is in agreement with the legacy program.



(a)
Pressure versus time

Figure 14
Comparison of lumped-parameter, interior ballistics models for optimized solid propellant geometry



(b)
Velocity versus time

Figure 14
(continued)

CONCLUSIONS

This paper investigated the effect of optimizing the surface area of a propelling charge for the AGARD gun (a fictitious device, the acronym stands for the Advisory Group for Aerospace Research and Development). As demonstrated in this study, tailoring the surface area of the propelling charge improved the AGARD gun's muzzle velocity by upwards of 10.0%. This was achieved by using a geometry with a high initial surface area to quickly raise the system to peak pressure and then using a progressively burning surface area profile to maintain the system at peak pressure during projectile transit until solid propellant burn out. The results of all cases analyzed in this paper are summarized in the following table.

Summary of results for AGARD gun

AGARD gun model	Muzzle velocity (m/s)	Piezometric efficiency (%)
Baseline	683	53.3
Optimized charge design (progressive-progressive)	749	60.7
Optimized charge design (regressive-progressive)	751	62.4
Constant pressure analysis	788	80.1

In conclusion, the surface area of the solid propellant grains is a crucial parameter for gun propulsion. While the AGARD gun is a fictitious system, the conclusions and charge design methodology developed herein can be extended to legacy weapon systems. In doing so, the ballistic performance of various fielded weapon systems can be improved without the necessity of expensive system modifications/redesigns.

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6.2
Active Investigation of the Improvement of Interior Ballistic Performance Through the Control of Solid Rocket Motor Design

Title

Project

APEX

Chris Hawthorn
Author/Project Engineer

Report number/Date received (to be completed by LCSD)

4551
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382
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