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A Brief Journey Through the History of Gun Propulsion

by Albert W. Horst

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A Brief Journey Through the History of Gun Propulsion

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14. ABSTRACT
While the use of guns and gun-like devices extends back in history for more than a millennium, the past century has been marked by significant advances in the technology of guns, the projectiles they launch, and the propulsion systems employed to launch these projectiles to ever-increasing velocities. This report chronicles a sampling of theoretical and experimental advances in the science of gun propulsion and its application to a wide range of practical gun propulsion concepts.

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1. Background

In preparing for this report, the author had the privilege of reviewing hundreds of publications from numerous countries on both the seminal accomplishments and the technical details of theoretical and experimental efforts critical to the evolution of gun propulsion technology. The current work by no means attempts to catalog all of these efforts, but rather is intended to provide a sampling of interesting and important scientific accomplishments and practical developments leading to identifiable advances in gun propulsion. As this report was written primarily for oral presentation, the narrative performs the function of providing brief technical description and historical perspective associated with a clearly limited but hopefully interesting selection of topics pertinent to progress in the field of gun propulsion. (Much of this material was presented at the 20th International Symposium on Ballistics [*1*].) The reader is directed to the references for a more complete accounting of any of the reported accomplishments.

2. Interior Ballistics – The Underpinning Science of Gun Propulsion

The interior ballistics of guns is the science of converting some form of stored energy (classically, chemical energy of a solid propellant released upon burning) into significant kinetic energy of a launch package in a very short timeframe and employing a launch system that occupies limited space (as opposed to rocket propulsion, for which the propulsive cycle may be extensive in time and space, continuing well into the ballistic trajectory of the flight body). The very nature of this highly dynamic launch environment defines the fundamental problem for the gun interior ballistician – managing the competition between the production of gases from the burning propellant and the volume to put them in as the projectile moves down the bore, so as to maximize the conversion of stored chemical energy of the propellant to kinetic energy of the projectile at muzzle exit (figure 1).

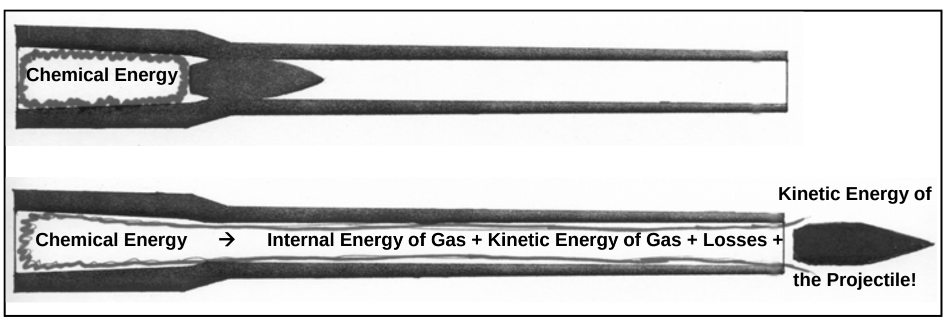


Figure 1. The overall problem: conversion of chemical energy stored in the propellant into kinetic energy in the projectile.

As depicted in figure 2, the challenge for more performance thus translates into one of increasing the area under the pressure vs. travel curve without exceeding the maximum pressure limits of the system, be they imposed by the gun tube, the recoil system, or the projectile itself. Produce the gases too rapidly and excessive pressurization occurs; too slowly, the propellant is not all burned and/or expansion of combustion gases is limited, reducing the extraction of energy to accelerate the projectile. Proper programming of energy release, however, broadens the curve and increases projectile kinetic energy at the muzzle. This interesting process thus defines the fundamental tasking to interior ballisticians throughout history: increasing interior ballistic performance by (1) increasing the total energy available to the propulsion system and, equally important, (2) tailoring the release of this energy, both temporarily and spatially, to maximize its transfer to the projectile. Numerous contributions, both experimental and theoretical, have addressed this grand challenge for centuries, but this report will limit itself to those of the past 150 years. Of necessity, only the briefest of descriptions are provided herein; the reader is encouraged to consult the references for additional information.

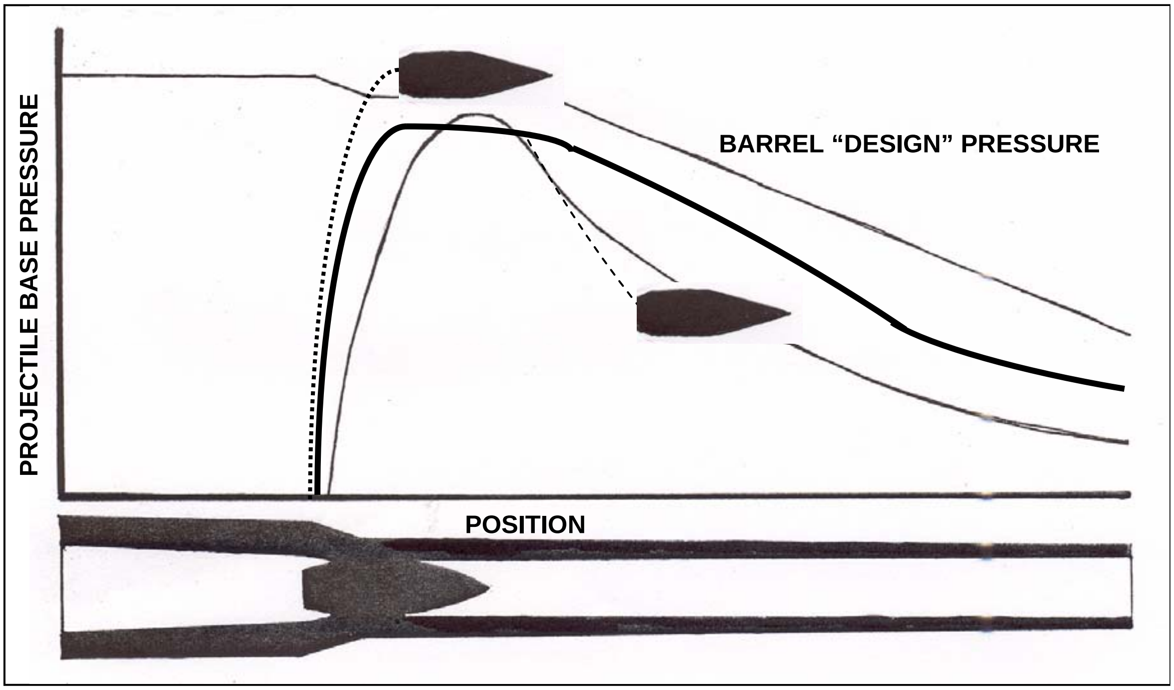
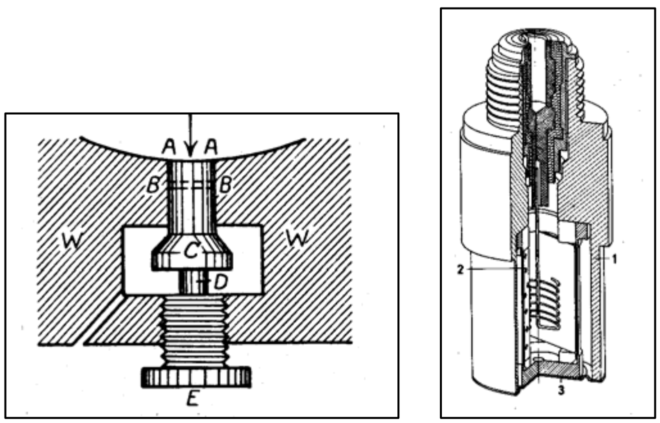


Figure 2. The challenge for more performance: increasing the area under the pressure vs. travel curve without exceeding system pressure limits.

3. Landmark Experimental Contributions

We begin our tour with a recognition of development critical tools, both experimental and theoretical, that have been essential to the progress of the interior ballistician and gun propulsion engineer. Experimental accomplishments are grouped here into three categories: practical charge design, propellant performance characterization, and research tools.

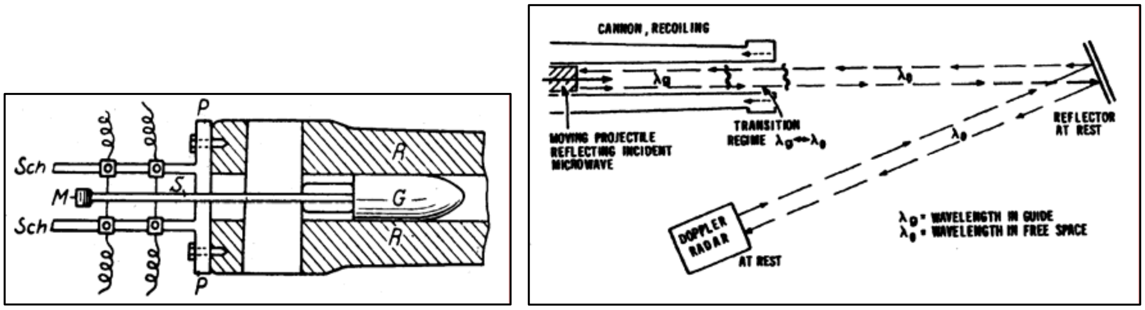
Clearly, a critical requirement of the early gun designer was measurement of pressure within the gun chamber. Early techniques were based on deformation of lead or copper plates, and later copper cylinders, such as the Noble gage (figure 3a), first introduced in England in 1860 and providing a monumental advance for experimental ballisticians (*1*). Revolutionary, however, was the development of piezoelectric crystal gages (figure 3b), introduced nearly a century later, but able to quantify not only the maximum pressure but also the entire temporal history of pressurization within the gun (*2*). The next step, of course, was to put a pressure gage on the projectile base, enabling quantification of the pressure gradient within the gun and hence establishing the actual pressure (and force) history acting on the projectile. Hardware techniques were introduced in the 1950s (*2*), though the wire seldom survived more than a few inches of travel. This technology was eclipsed, however, by the development and use of onboard recorders or telemetry systems (e.g., S-band FM/FM [*3*]) in the 1970s, which were then used routinely to provide in-bore data throughout the interior ballistic cycle.



(a) (b)

Figure 3. (a) Noble crusher gage (*4*); (b) piezoelectric crystal gage (*2*).

During this same period of time, a number of techniques were developed to enable characterization of the in-bore trajectory without instrumentation onboard the projectile. As far back as 1860, Krupp in Germany employed a projecting rod (figure 4a) to break successive electrical circuits to mark passage of the projectile down the bore. Similar methods were employed by Noble and Abel in England and Crehore and Squier in the United States in the following decades (*2*, *4*). Nearly a century later, investigators in many continents began using microwave interferometers (figure 4b) to make reliable in-bore trajectory measurements. A rotating drum camera capable of resolving interferometer frequencies up to 1200 kHz was developed at the U.S. Army Ballistic Research Laboratory (*5*). Again, onboard telemetry



(a) (b)

Figure 4. (a) Projecting rod technique (*4*); (b) microwave interferometry (*5*).

revolutionized such measurements in the 1970s and 1980s, as has miniaturization of electronics in the past decade, facilitating multi-axis, high-g measurements with minimal volumetric requirements.

Turning now to propellant characterization, the use of closed and vented chambers has long provided valuable assistance to both the propellant developer and the propelling charge designer. For many decades, closed bombs were used to establish relative performance characteristics, but with the development of piezoelectric pressure gages and computerized data reduction codes in the 1960s, they became the standard tool for not only quantifying relative force and quickness of the propellant, but also determining the all important burning rate of the propellant. Typically in sizes of several hundred cubic centimeters in volume, latest versions are as small as 25 cm^3 to facilitate evaluation of small samples of research formulations employing costly materials (*6*, *7*). Alternate chamber designs are fitted with blowout discs to allow convenient study of early phase interior ballistics or capture of partially burned propellant (*8*), or with nozzles to allow evaluation of the erosivity of various propellants (*9*).

Research interests dictated the development of more sophisticated approaches to address motion of the solid propellant, including the use of radioactive tracers (figure 5) by Yamakawa and others at the U.S. Ballistic Research Laboratory in the 1950s, who employed propellant grains seeded with gamma radiation sources such as Cobalt 60 (*2*). Most fruitful has been the development and use of a wide range of gun simulators employing optically and x-ray transparent chambers (figure 6) allowing direct monitoring of flamespread and early solid phase motion of developmental or pathogenic charge configurations. Now used throughout the world, first successful designs were provided by Soper (*10*) at the U.S. Naval Weapons Laboratory and Minor (*11*) at the U.S. Army Ballistic Research Laboratory. It should be noted that the previous paragraphs identify just a few of the innovative and highly significant advances made by the experimental community in the field of gun interior ballistics and propelling charge design.

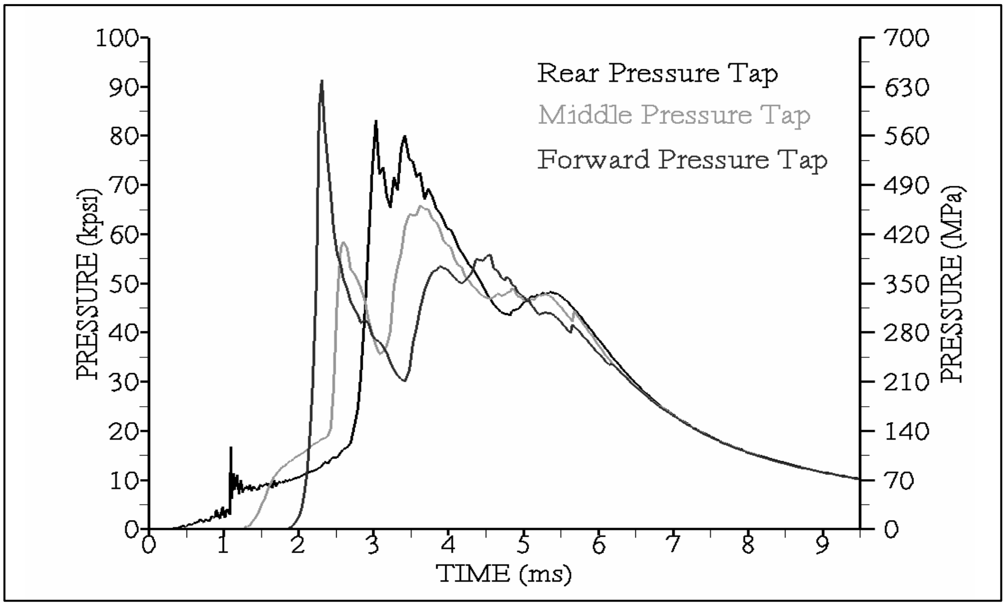


Figure 5. Predicted pressure vs. time profiles for nominal telescoped ammunition (*12*).

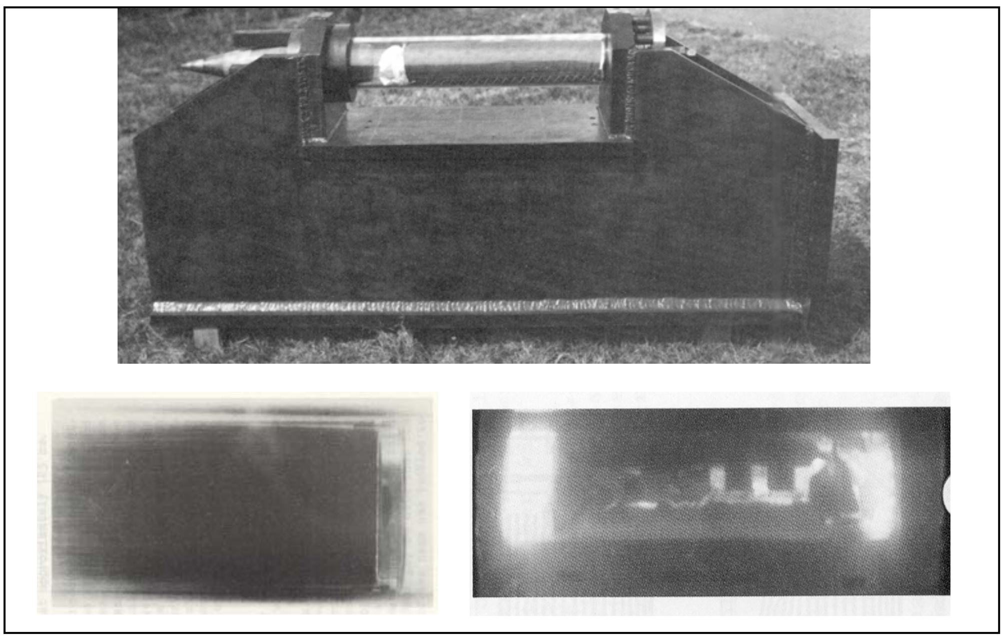


Figure 6. The 155-mm chamber simulator, flash radiograph, and cinematographic frame (*11*).

4. Theoretical Interior Ballistics

While "seeing is believing," underscoring the uncontested need for experimental data, the explanation for such observed behavior, as well as the description of behaviors not yet amenable to experimental elucidation, depend on the accomplishments of the theoretician. This is no less true in the field of interior ballistics than in any other field of applied science, with a rich history filled with the accomplishments of such famous names as Lagrange, Langweiler, Cranz, Coppock, Goldie, Resal, Liouville, Chabonnier, Kent, and Corner, to name but a few. In this section, we review a number of the key advances in interior ballistic theory, ranging from simplified closed form solutions to today's powerful multidimensional, multiphase flow codes.

In the beginning, the basic tools of the interior ballistics modeler were a few definitions, an equation of state, an isentropic expansion law, and a simple yet all-important energy equation, describing how chemical energy originally stored in the propellant is apportioned into internal energy remaining in the hot pressurized gas, kinetic energy of the projectile and propellant gas, and losses such as friction and heating of the barrel. The simplest of descriptions then follows by assuming the propellant is all burnt at time zero. One can employ the equation of state to define a hypothetical initial pressure, the expansion law to calculate it at muzzle exit, and then apply the energy equation to determine the kinetic energy and hence velocity of the projectile. Incidentally, while such a model is clearly not useful for predicting maximum chamber pressure, its application to the U.S. Army 120-mm tank gun yields a predicted muzzle velocity that exceeds experiment by only about 50 m/s.

A next step in the hierarchy of closed form interior ballistic representations was that of the constant pressure solution; this assumption is still used today by many for estimation of the performance of new propellants. It assumes combustion of the propellant and motion of the projectile at a constant pressure to yield conditions at burnout, followed by expansion of gases to the muzzle and application of the energy equation to yield muzzle velocity, typically about 5% high with respect to reality. And finally, the more elegant solution of Mayer-Hart (*13*), which includes recognition of the covolume of the propellant gases (effectively the volume per mass of the gas molecules – significant at high loading densities and pressures), and, importantly, the finite burning rate and burning surface of the propellant. With three basic equations – the energy equation, Newton's law, and the mass burning rate equation – and a not insignificant application of algebra, this technique provides results typically within 1% of reality at ordnance velocities.

Early WWII ballisticians, such as Roggla, Bennet, and Hirshfelder (*14*), developed expansive tables providing performance estimates based on grain dimensions, loading density, and expansion ratio. But it was the entrance of computers, starting with the introduction of the ENIAC in 1945 at the Ballistic Research Laboratory (with its 18,000 vacuum tubes and capable of multiplying two 10-digit numbers in 2.6 ms) and leading to today's massively parallel supercomputers, with capabilities at the teraflop level, that revolutionized the simulation and prediction of interior ballistics and gun propulsion phenomenology.

Perhaps the most prevalent of computerized interior ballistic codes are those based on lumped-parameter models, one of the earliest of which was developed by Baer and Frankle (*15*), which with a few more bells and whistles is used extensively today under the name of IBHVG2 (*16*). Five basic governing equations (energy equation, equation of state, mass burning rate equations, equations of motion, and pressure gradient equation) are solved numerically as algebraic and ordinary differential equations, facilitating parametric analyses and optimizations with minimal computer assets. Numerous equivalent codes exist and remain the workhorse tools of the gun propelling charge designer worldwide.

Acknowledgment also needs to be made to Love and Pidduck's 1922 introduction to the gas dynamics occurring in the gun tube (*17*). The "Lagrange gun," as it became known, was a hypothetical gun initially pressurized with a frictionless projectile that was released at time zero. Love and Pidduck provided an analytical solution to the problem of the transit of this projectile and the transit of the resulting rarefaction wave. Not only did this work provide a transition from the world of lumped parameter codes to modern multiphase flow codes, but it was the likely inspiration for a current interior ballistic concepts, such as the wave gun for high velocities (*18*) and the rarefaction wave gun for mitigation of recoil forces (*19*).

Today's focus, however, is on the use of multiphase (and often multidimensional) interior ballistic codes to treat the problems of ignition and flamespreading, and the development of pressure waves and potentially damaging overpressures – all beyond the scopes of both lumped-parameter and single-phase flow models. Figure 7 provides a block diagram of a state-of-the-art multiphase flow interior ballistic code, known as NGEN3, developed by Paul Gough Associates (*20*, *21*), incorporating three-dimensional continuum equations and supporting auxiliary relations in a modularized code structure. A coupled Eulerian Lagrangian approach is utilized to provide accurate modeling of the continuous gas phase and discrete solid (particulate) phase, employing the balance equations for conservation of mass, momentum, and energy on a sufficiently small scale of resolution for treating this multicomponent reacting mixture problem. A macroscopic representation of the flow is adopted by employing a formal averaging technique to render a solution appropriate to the scale of the phenomena of interest but large with respect to the scale of heterogeneity of the problem. Closure is provided through a number of constitutive laws including state equations, intergranular stresses, and interphase transfers of mass, momentum, and energy. The numerical representation of these equations is based on a finite-volume discretization and high-order accurate, conservative numerical solution schemes.

One example of application of NGEN3 to a problem of current interest is provided by Nusca and Horst (*12*) and addresses a notional, telescoped ammunition configuration (figure 8). Flamespread is complicated in such a configuration, and the potential for severe longitudinal pressure waves is a concern. Results from simulations from NGEN3 (run in the two-dimensional axisymmetric mode) are shown, with figure 5 depicting a strong predicted pressure spike at the front of the chamber, and figure 9 providing a elucidation via snapshots at various times of gas velocity vectors and pressure fields. Subsequent calculations in this study identified a solution based on providing a high-permeability longitudinal path in the annular region exterior to the projectile, perhaps through the use of stick or scroll propellant. Numerous pathogenic charge configurations have been studied over the past several years with this code, providing suggested solutions, first validated in companion simulator firings and subsequently adopted in actual charge designs.

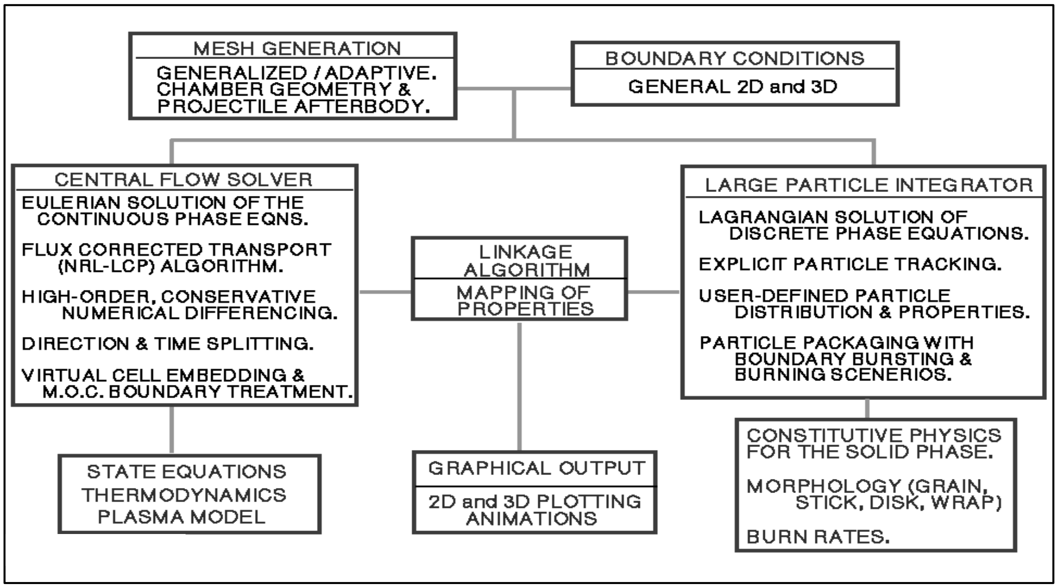


Figure 7. Schematic of NGEN3 multidimensional multiphase flow interior ballistics code (*21*).

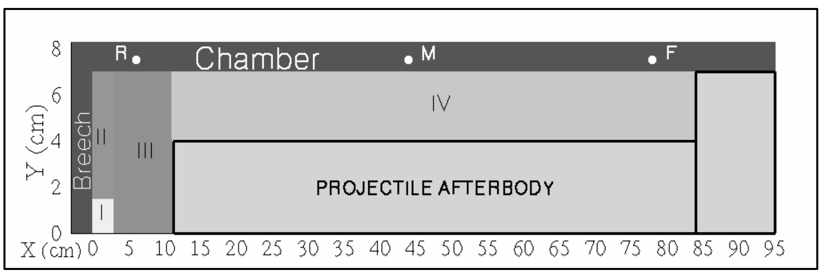


Figure 8. Schematic (axisymmetric half figure) of nominal telescoped ammunition (*12*).

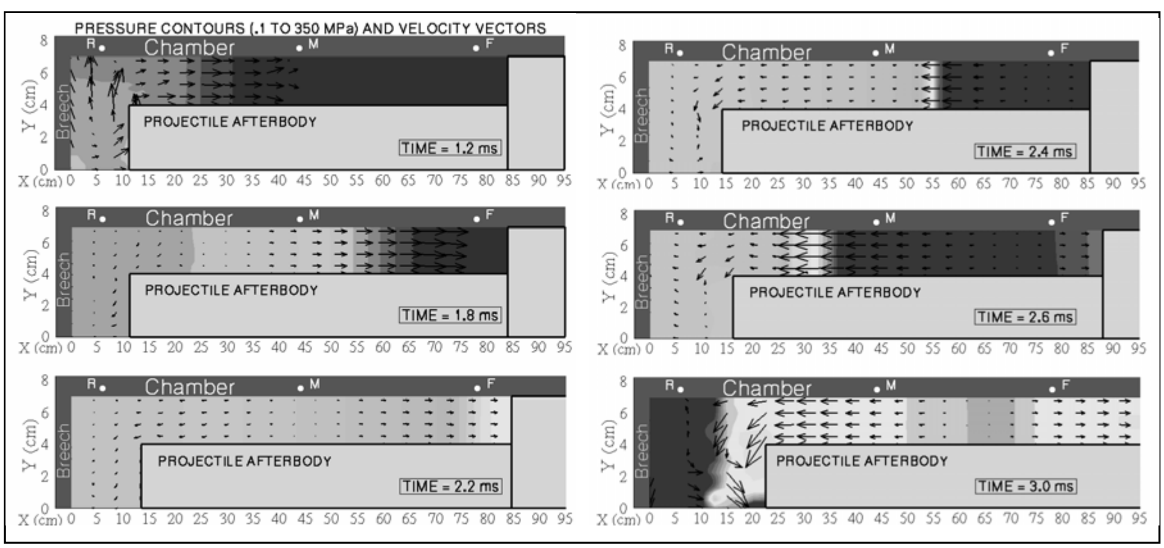


Figure 9. Predicted gas velocity and pressure fields for nominal telescoped ammunition (*12*).

5. Gun Propulsion – Ordnance Applications

Over the course of history, propelling charge designers have faced a formidable range in gun parameters – some three decades in bore diameter and six decades in muzzle energy – with a common goal of maximizing performance, at least in part, by increasing the energy in the propellant charge and tailoring its release spatially and temporally to maximize transfer to the projectile.

In terms of intrinsic energy of gun propellant formulations, history has seen a transition from conventional solvent processed single and double base propellants to nitramine-based composite propellants (originally in pursuit of low vulnerability as much as increased energy), the use of NENA-based plasticizers, and most recently the incorporation of high energy crystalline oxidizers like RDX and CL20 into energetic thermoplastic elastomeric (ETPE) binders like BAMO-AMMO and BAMO-GAP (*22*). Current efforts also address the use of novel high energy molecules and nanostructured energetics to provide increased energies.

Any such increases in energy provided by these efforts, however, require concomitant improvements in the ability to program their release during the interior ballistic cycle to provide usable increases in gun performance. Toward this end, propellant engineers have provided alternatives to conventional perforated cylinders for more aggressive approaches to providing a programmed increase in the mass generation rate after peak pressure (figure 10). Techniques include the use of concepts such as programmed splitting propellant (*23*) to, at prescribed time in the interior ballistic cycle, discontinuously increase surface area, and layered materials (*24*) to similarly increase burning rates and energies, a technique made possible by the use of ETPE propellants which offer the chemical stability between adjacent layers required for such applications.

It is important to point out that the competition between gas production and volume production, key to optimization of the interior ballistic cycle, is not simply a global concern, but as extremely important on the local level, as either a nonuniform initial distribution of propellant in the gun chamber or a localized ignition of the propellant bed can lead to significant longitudinal pressure waves with attendant safety problems. The process is then further influenced by grain configuration and loading density, which determine the overall charge permeability to gas flow, and propellant mechanical properties, which determine the potential for grain fracture.

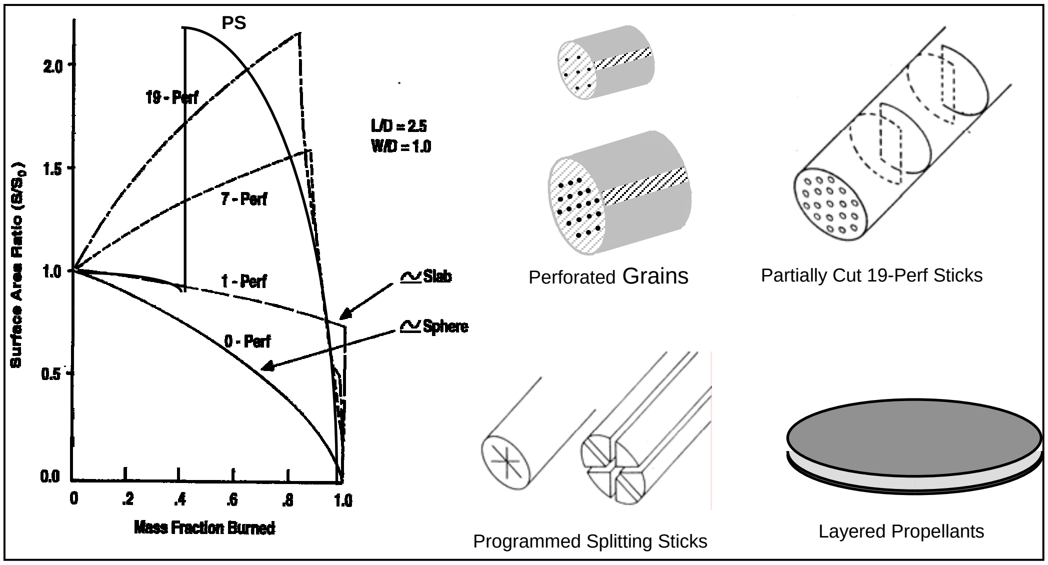


Figure 10. Progressivity and geometry of various propellant configurations (*1*).

The traditional role of artillery fire has been to provide large volume fire at a variety of ranges with the gun always pointed at a high firing angle for terminal performance reasons; the solution to this challenge has been the use of multiple zone charges to provide a range of muzzle velocities to allow this high angle firing under all conditions. Accompanying problems, however, have included difficulty in smooth and reproducible ignition of all increments, a susceptibility to damage to the bagged or combustible cased increments during handling, and, of course, an added logistics burden associated with use of the various types of increments required to meet ballistic requirements. Recent efforts both within the United States and abroad have focused on the development of single, universal increment concepts, fast enough to burn out at low (one or two) zones, and slow enough not to overpressure the gun at top (maximum number of increments) zones.

Tank guns, on the other hand, have benefited from the use of rigid case assemblies. Performance has been the paramount issue, and the quest for maximizing propellant energy, loading density, and progressivity of gas production are major considerations for the charge designer. Today's high performance tank gun cartridges boast extremely high energy loads of propellant in novel progressive geometries or chemically coated or layered formulations providing muzzle velocities in the 1700 m/s range. Moreover, the closely coordinated optimization of gun, projectile, and propelling charge as a system has yielded substantial benefit.

Alternate approaches to gun propulsion for ordnance applications have included the use of liquid propellants employed in various combustion schemes. The potential benefits of a liquid propellant are both obvious and subtle, with the logistics advantage of "one size fits all" near the top of the list, but including many other items such as propellant cost and even certain aspects of performance. Specific approaches have included bulk-loaded liquid propellant guns (*25*) and various injected concepts (*26*), where the potential benefit of simplicity of mechanical design is traded for increased control over the physical process. In bulk loaded concepts, the initial burning surface is defined by the ignition process, with subsequent burning surface determined by complex hydrodynamic processes (figure 11), both subject to a lack of reproducibility which all too often led to overpressures and even catastrophic failures – and ultimately the termination of development efforts. Regeneratively injected liquid propellant gun approaches (figure 12) enjoyed a considerably longer period of interest from the development community, but finally succumbed to problems of system size, weight, and complexity; propellant/gun steel incompatibility; and a chronic history of high frequency pressure oscillations of debatable concern. It is worth pointing out, however, that revised propellant formulations and oscillation mitigation techniques pursued in recent years have provided solutions to some of these concerns.

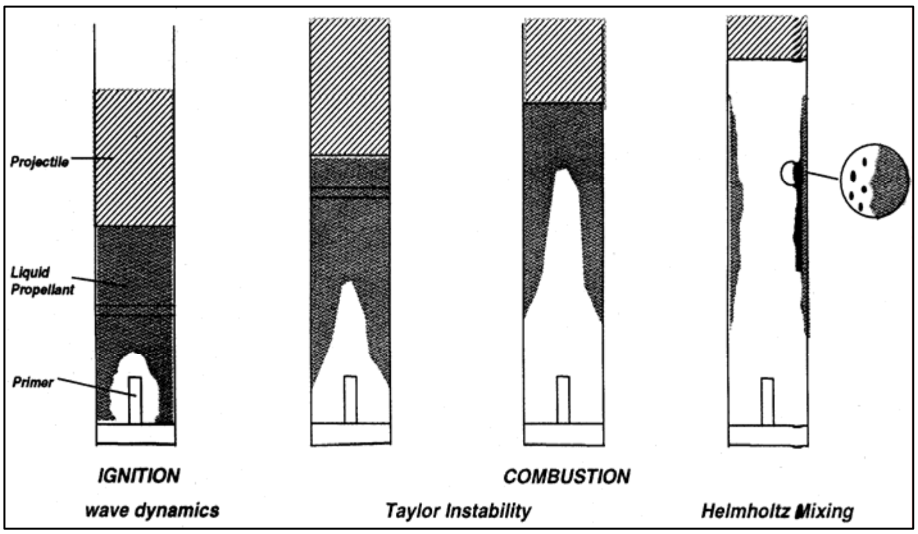


Figure 11. Conceptual interior ballistic process for bulk-loaded liquid propellant gun.

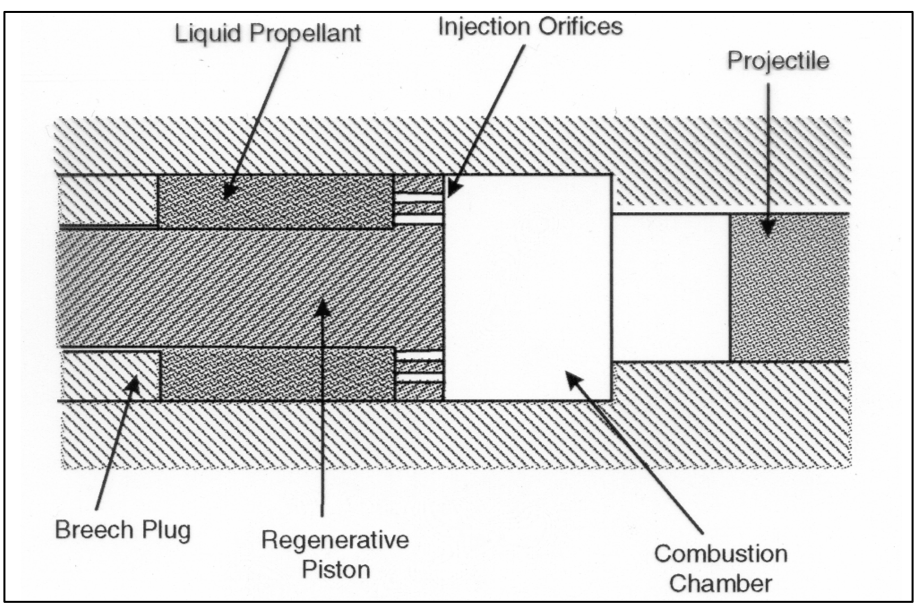


Figure 12. Simplified schematic of regeneratively injected liquid propellant gun.

Considerably more success has been achieved with another family of concepts most commonly known as electrothermal-chemical (or ETC) propulsion. First conceived simply as an electrothermal gun, electrical energy in the form of a plasma was injected into a working fluid such as water, which was then vaporized to pressurize the gun chamber and accelerate the projectile down the bore. Further, proper electrical pulse shaping could, in theory, be used to tailor the process to provide the required progressivity of gas production to optimize performance of the launcher. Owing to the high cost, in terms of volume and mass, of electrical energy, the concept was quickly hybridized to use energetic working fluids that would release additional energy from combustion. Plagued by the same problems of process stability as bulk-loaded liquid propellant guns, the concept then migrated to the use of solid propellants (though some variations such as metal-water guns are still being considered). With the resulting system (figure 13), a minimal amount of plasma energy can be used to control or at least influence the rate of energy release from the propellant. High-temperature, low-mass plasmas provide an excellent medium providing very rapid and extremely reproducible ignition for propellants of all types, including very high density charges, with the side benefit of being able to provide temperature compensation by altering the amount of electrical energy to compensate for the temperature-dependent burning rate of the propellant (*27*).

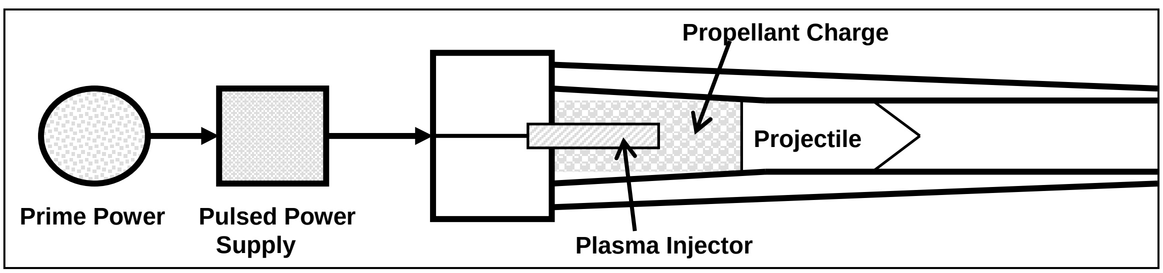


Figure 13. Simplified schematic of ETC propulsion gun.

As of today, electrical energy alone cannot compete with chemical propellants as a primary source of energy for ordnance velocity guns. However, as an enabler of very high loading density layered propellants, performance increases in excess of 25% in muzzle kinetic energy have been demonstrated in a range of U.S. guns (*28*). Also, the UK has pursued a concept whereby adjustments in electrical energy are used to provide closed loop corrections for extreme precision in muzzle velocity (*29*). Of current interest is the potential to exploit a chromophoric coupling between the plasma spectral output and the response of the propellant to achieve a tuned match for a specific ignition response, perhaps enabling the use of very high energy propellants that are responsive only to the intended stimulus both otherwise relatively insensitive.

6. Gun Propulsion – Hypervelocity Applications

Time now for a brief visit to the world of hypervelocities achieved from gun launch. A chart very similar to that shown in figure 14 was first presented to the Seventh International Symposium on Ballistics by Heiser in 1980 (*30*). Muzzle velocities from various classes of guns are shown as a function of their propellant charge to projectile mass ratio (C/M), with this ration for artillery typically around 0.25 g/cm^3, tank guns at about 0.95, and research launchers at 3 or above. Also presented in the figure are theoretical limits computed using various assumptions. If one were to use the simple global energy equation used in the closed form interior ballistic models mentioned earlier, and assume an arbitrarily high C/M, an infinite expansion, and no losses (such as heat loss or friction), the result falls in the range of 5-6 km/s range.

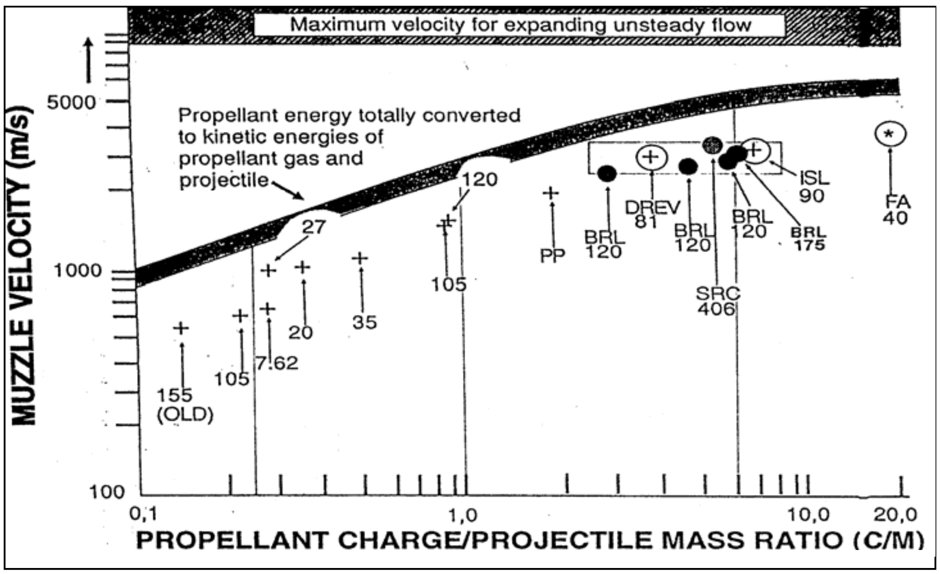


Figure 14. Experimental and predicted muzzle velocities as a function of propellant charge to projectile mass (C/M) (based on reference [*30*] and updated by Horst).

Actual experimental results, though somewhat more conservative, are still quite impressive. While small payloads (31.5 g) are reported to have been launched to velocities in excess of 3.5 km/s from a 40-mm barrel and a C/M of 25 (*31*), substantial masses too have been launched to hypervelocities using truly conventional propulsion. Over 30 years ago, in a follow-on program to the joint US/Canadian High Altitude Research Program (HARP) program, a 60-kg projectile was launched to a velocity of over 3 km/s from what was essentially a triple travel 16-in Naval gun (*32*). More recently, this author and others conducted hypervelocity firings at more modest C/M levels, still achieving velocities in the 2.5–3km/s range, but with detailed interior ballistic measurements that showed excellent agreement with multiphase flow calculations for downbore pressures throughout the firing cycle (*33*, *34*).

Digressing for a moment to consider a broader view of history of ballistics, including hyperenergy as well as hypervelocity, we note use of a number of techniques, including “brute force,” alterations to the tube and chamber geometries, and various downbore gas generation techniques. History provides many examples of big guns. The Wilhelmgeschutze (or Paris Gun), shown in figure 15, dates back to WWI and launched 106-kg projectiles to 126 km, but with muzzle velocities of under 1700 m/s (*34*). Some half a century later, the 16.4-in HARP gun (figure 16) launched a variety of high velocity projectiles, including 160-kg research vehicles at muzzle velocities of nearly 2200 m/s and achieving an apogee of 180 km (*32*). These latter firings were conducted at a C/M of about 2.4 and employed a unique distributed ignition system to achieve satisfactory flamespreading and prevent the formation of pressure waves. A number of investigators, primarily in Germany, but also in the UK and the United States, have looked at ways to modify the geometry of the gun to prevent downbore pressures from dropping off rapidly after peak pressure. Concepts have included tapered bore guns and multichambered guns, such as the mighty German Hochdruckpumpe (figure 17), which included not only the standard gun chamber at the rear of the barrel, but also ten additional chambers down the length of the bore (*35*).

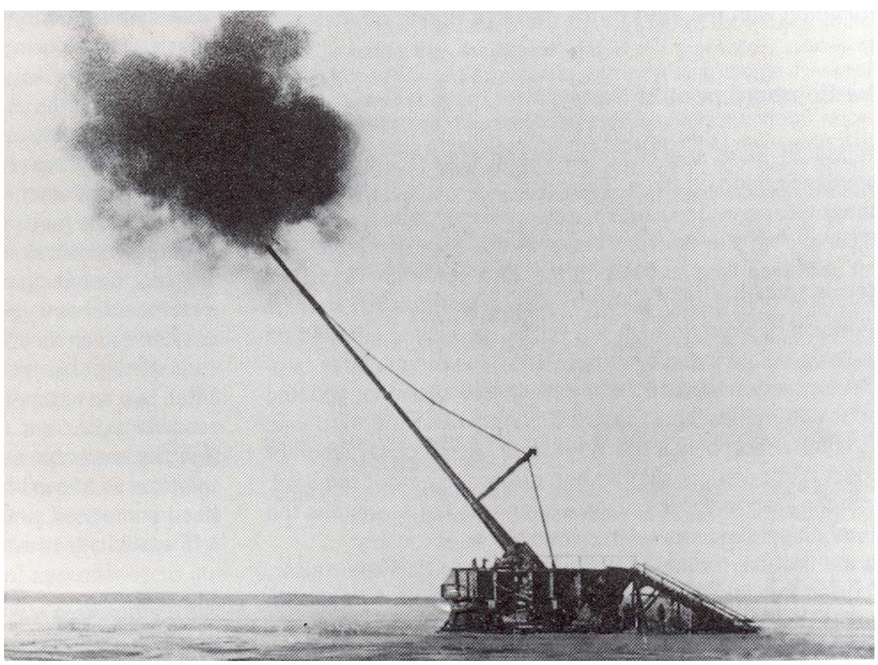


Figure 15. The 210-mm, 140-cal Wilhelmgeshutze (Paris Gun) – 1917 (*32*).

The quest for gun propulsion concepts which provide high downbore pressures has continued to modern times. More recent efforts of limited success have included the use of propellant-lined tubes by the U.S. Navy, whereby a very high burning rate propellant progressively ignites as the projectile moves down the bore (*36*), and more aggressive extensions to this concept by Kryukov in the USSR (*37*), employing explosive liners providing a focused detonation wave on the base of the pressure to achieve hypervelocities, as shown in figure 18. U.S. investigators have also studied this concept (*38*). The traveling charge gun first discussed extensively by Langweiler in 1947 (*39*) has been pursued experimentally at numerous sites including the U.S. Army Ballistic Research Laboratory in the 1980s (figure 19), where very high burning rate propellants were employed to provide the high gasification rates necessary for a simple end burning grain geometry (*40*). Success was limited, however, by propellant problems, including the lack of mechanical properties required to support resulting stresses in the charge fixed to the accelerating projectile base.

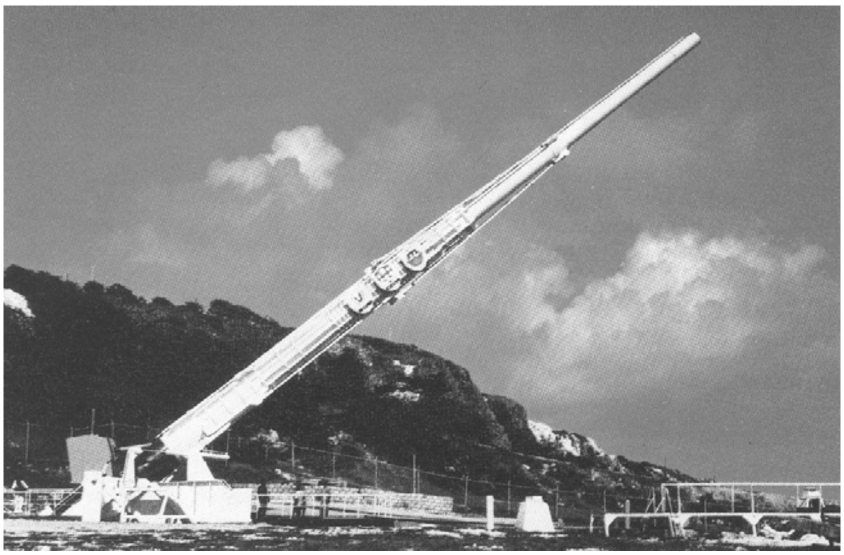


Figure 16. The 16-in, 86-cal HARP Gun – 1965 (*32*).

Figure 17. The 150-mm, 100-cal German Hochdruckpumpe – 1944 (*35*).

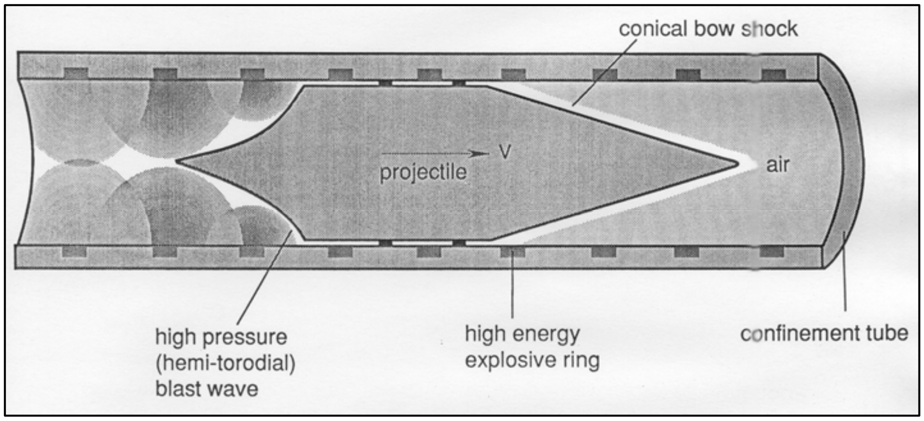


Figure 18. Detonation wave acceleration from explosive lined tube (*38*).

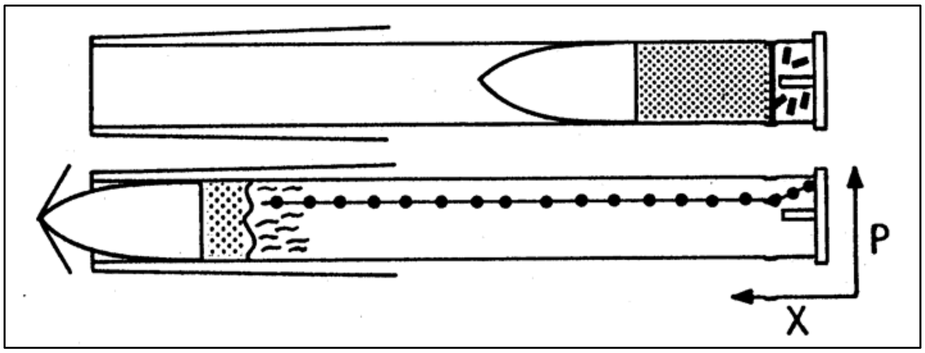


Figure 19. Schematic of traveling charge propulsion concept (*40*).

Extensive research was conducted at several sites throughout the world in the 1990s on the inbore ram accelerator, a concept based on injecting a moving projectile shaped like the centerbody of a ramjet into an accelerator tube precharged with a combustible or detonable mixture (*41–43*). Heating and ignition of these gases, by a variety of mechanisms, at the base of the projectile resulted in a local pressurization that traveled with the projectile as it moved down the tube. Successes to about 2.5 km/s were achieved in various gun sizes up to 120 mm, but both fundamental and practical problems limited success beyond that point.

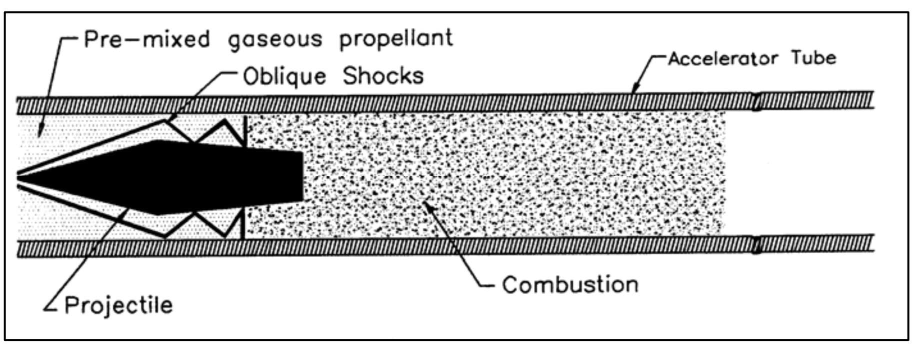


Figure 20. Schematic of inbore ram accelerator concept (thermally choked mode) (*43*).

Two topics are largely excluded from this report: light gas guns (LGG), a single stage version depicted in figure 21, and electromagnetic guns (EMG), shown in two forms in figures 22 and 23. Only a brief comment will be made on each. Regarding LGG, the reader is reminded once again of the simple energy equation introduced early in this report. The usual losses associated with accelerating the propellant gases, which grow prohibitively large at hypervelocities, are substantially reduced with the use of low molecular weight gases like hydrogen and helium, leading to an entire field of accelerators whereby a light gas is first pressurized by conventional propellants, explosives, chemical reactions, or electrical heating, prior to a highly efficient expansion cycle (*44*). LGGs perform well as laboratory devices but are difficult to weaponize, though hybridized concepts have been proposed for weapon applications. EMGs, on the other hand, have seen extensive investment for both strategic and tactical weapon application. Again, one principal advantage is the avoidance of losses to KE of an accelerating gas, though numerous other challenges are present, not the least of which is the low relative energy density of electrical devices (~5J/g) versus that of propellants (~5000 J/g). Both the U.S. Army and Navy are currently pursuing electromagnetic propulsion for future gun systems (*45*), as are various agencies in numerous other countries.

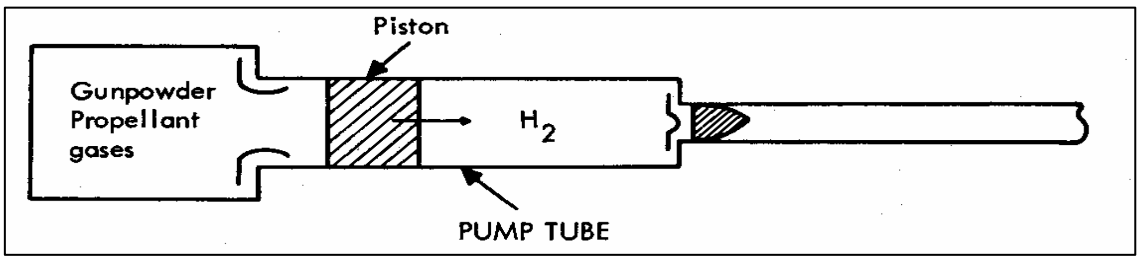


Figure 21. Simplified schematic of single-stage light gas gun (*44*).

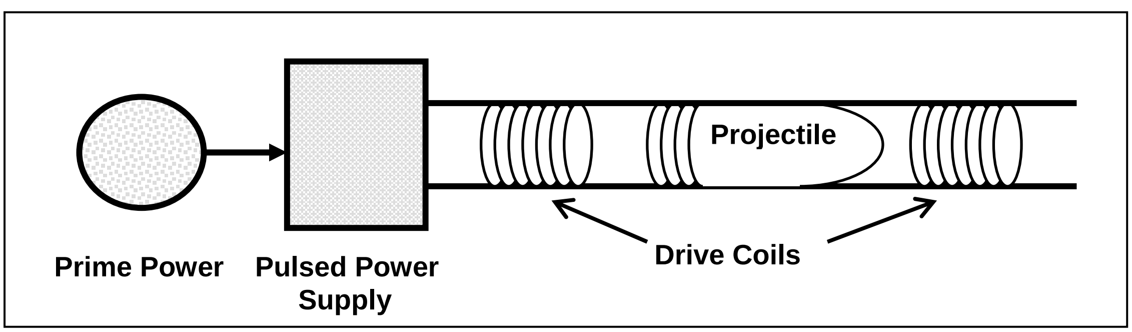


Figure 22. Simplified schematic of electromagnetic gun – coilgun concept.

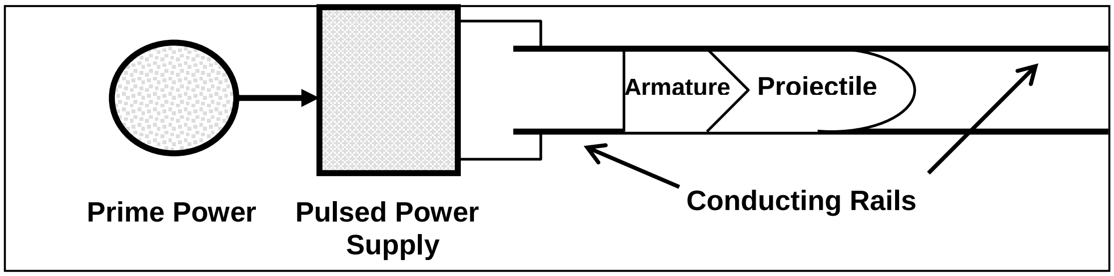


Figure 23. Simplified schematic of electromagnetic gun – railgun concept.

7. Current Drivers for Research and Prognosis for the Future

Future requirements for gun propulsion focus not only on increases in performance but also on reductions in size and mass to support the trend for lightweight yet highly lethal weapons systems. Compact systems require compact weapons and ammunition, motivating concepts such as telescope ammunition, posing substantial challenges to projectile and charge designers alike. High performance from small gun systems necessitates recoil impulse management, such as fire-out-of-battery or novel approaches like Benet Laboratory's rarefaction wave gun (*19*). Reduced weight systems limit the amount and type of armor protection employed, posing a need for reduced vulnerability of ammunition. Add to all of the above the requirement to deliver smart munitions, posing additional constraints on the launch environment. As many of the above may offer conflicting requirements on gun propulsion, future interior ballisticians and charge designer will have to appeal to two major approaches to achieve success.

The first is the application of ever-improving design and analysis tools. Modeling capabilities exist or are emerging that address atomistic level energetic materials modeling, detailed component combustion modeling, ignition and flamespread modeling, multiphase-flow interior ballistic modeling, and transient projectile and tube response modeling. Each of these areas of research has shown great progress in the past decade, but linkages between the efforts remains a challenge. Nano- to micro- to meso- to macroscale modeling transitions may allow not only identification of new materials and processes, but also true across-scale optimization of the overall system to push gun propulsion to its physical limits.

The second depends on the identification of breakthrough technologies, in part a result of the previously mentioned modeling efforts. However, new technology does not just happen – priority and focus are required to mobilize and coordinate national intellectual and financial assets on key challenges. In the area of advanced energetics, those elements have been recently addressed in the Office of the Secretary of Defense (OSD)-sponsored National Advanced Energetics Program, leading to coordination of activities in this area among the Department of Defense, the Department of Energy, the Defense Threat Reduction Agency, and affiliated universities and contractors (*46*).   Novel molecules, nanostructured energetics, and thermobaric material research are among the topics receiving national interest under this program. Yet even with incremental improvements, gun propulsion, perhaps at times hybridized with rocket propulsion, is expected to continue to play a major role on the battlefield for the foreseeable future. Beyond this, however, innovators throughout the community continue to provide numerous concepts and approaches to advance propulsion, promising as much as decadal improvements in performance. While such promises remain as yet unfulfilled, limitations on the future are not posed by this author. Indeed, special purpose gun applications, such as gun-launch of insensitive materials to space or at least low orbit, may relieve the launch system of many of the constraints that render most innovative concepts impractical for tactical systems.

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