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THE DISTRIBUTED-INJECTION BALLISTIC LAUNCHER

Should future demands for cheap access to space or for sustainable Fleet defense lead to the development of large hypervelocity guns? If the answer is yes, distributed injection may offer a way to reduce launch loads or increase muzzle velocity, not only for those applications but also for a number of others. It may be a 125-year-old idea whose time has come.

INTRODUCTION

When the U.S. space shuttle lifts off the ground, its total mass is more than 1.8×10^6 kg, almost 1.6×10^6 kg of which are the fuel and oxidizer needed to power the engines. Only about 1% of the lift-off mass is payload. Depending on whose figures one uses, the cost of delivering that small payload to low earth orbit is somewhere between \$4000 and \$13,000 per kilogram. These numbers are high but not particularly surprising, since rocketry has always been an expensive business. Adding up the hundreds of millions of kilograms the U.S. may need to carry into space in the next several decades, many are beginning to worry that the tried and true technology may soon become unaffordable.

The dimensions of the space transportation problem led Robert M. Fristrom to hark back to the giant cannon described by Jules Verne in 1865 in *De la terre à la lune* (*From the Earth to the Moon*) [see the boxed insert]. As a modern elaboration of Verne's approach, Fristrom proposed launching delicate payloads into orbit using a very long low-pressure gas gun (perhaps as long as 8 km) built at high altitude along the slopes of the Rockies or maybe webbed to the side of a Hawaiian volcano.[1] The basic idea was to maintain a moderate pressure force on the projectile over a very great distance by adding mass and energy behind it as it moved along an evacuated launch tube, as opposed to starting the launch at the extremely high but rapidly falling level of pressure associated with conventional guns. Hydrogen and oxygen were proposed to be injected and burned in the projectile's wake at a number of discrete stations along the tube axis. Once the subject was opened, we began to think of many applications for hypervelocity launchers of various shapes and sizes, and our interest grew. What we are going to describe in this article is a general concept that emerged from the original space transportation proposal, which we have come to call the distributed-injection ballistic launcher. The concept is elementary, and certainly not new; but, as far as we can tell, it has not been reconsidered lately with either modern technology or new applications in mind.[2]

Before going further, we should define the term "ballistic launcher." The meaning we have in mind implies simply that the projectile carries no primary propulsion system; all of the launch impulse is supplied by some external means. To people of few words, a ballistic launcher may be nothing more than a gun; but the definition does not rule out using sophisticated projectiles with second-stage engines or attitude-control systems, which might be used to alter the trajectory after launch.

The principal advantages of a ballistic launcher are simplicity and propulsion efficiency, gained by *not* having to accelerate things that are not part of the payload (such as engines, fuel, and associated supporting structure). The major disadvantages are bulkiness and high launch loads and heat-transfer rates. As a practical matter, the latter disadvantages almost certainly rule out the use of ballistic launchers for human transport, and perhaps for applications demanding peak launch accelerations below several thousand g. Yet a variety of interesting payloads, including complex electronic packages, can easily tolerate accelerations of tens of thousands g.[3]

Ballistic launchers have turned out to be widely useful devices. Over the centuries, applications have ranged from simple mechanisms for toys to massive weapons of war. One day the uses may even include the generation of unlimited amounts of power by impact fusion, provided someone discovers a way of accelerating about 0.5 g of matter to a speed of several hundred kilometers per second.[4] To add some perspective to judgments about the future, we will review a little of the history of ballistic-launcher technology in the next section.

The fundamental problem of interior ballistics is to achieve a high muzzle velocity without fragmenting the projectile or bursting the gun barrel. We will show the basic connection between pressure and velocity in a launch tube and then explain the distributed-injection technique by devising and analyzing several "thought experiments." We will also briefly consider the major technical uncertainties, as well as some possible applications.

HISTORICAL PERSPECTIVE

One way of summarizing ballistic-launcher technology is by plotting projectile mass versus muzzle velocity (Fig. 1). The very first ballistic launchers—slingshots, spears, bows and arrows, catapults, and the like—are not shown in Fig. 1. Although the matter of the invention of the gun is in dispute, a bamboo/blackpowder device built in China in 1132 A.D. during the Song Dynasty was probably the first high-speed launcher, and was also the first launcher finally to be free from the requirement of human muscle for energy storage. Some

To the Moon by Gun

Almost everyone remembers that the first moonship left the earth from Florida and that it carried three men; but many forget that the trip occurred not in 1969 with the flight of Apollo 11, but in 1865 in the imagination of Jules Verne.

Verne's three imaginary passengers were members of the Baltimore Gun Club, and they traveled to the moon aboard a 9-t capsule 3 m in diameter, made of "exotic" aluminum (Fig. A). The spacecraft was fired from a 275-m barrel-lined well using 180 t of guncotton (nitrocellulose). Because one of the Club members guessed that the muzzle velocity would have to be about 50% greater than escape velocity to overcome the resistance of the atmosphere, the capsule left the ground at a speed of 80 km/s (Mach 50)!

Sixty years ago, and a little more than 60 years after Verne published his extraordinary book, members of the Verein für Raumshiffahrt (German Society for Space Travel) examined his ideas in technical detail, more or less for the fun of it. Instead of 386,000 km, they estimated the range of the moonship to be a mere 30 m, but then found the shortfall irrelevant because the passengers "would have been spread into a thin film by the enormous acceleration."[18]

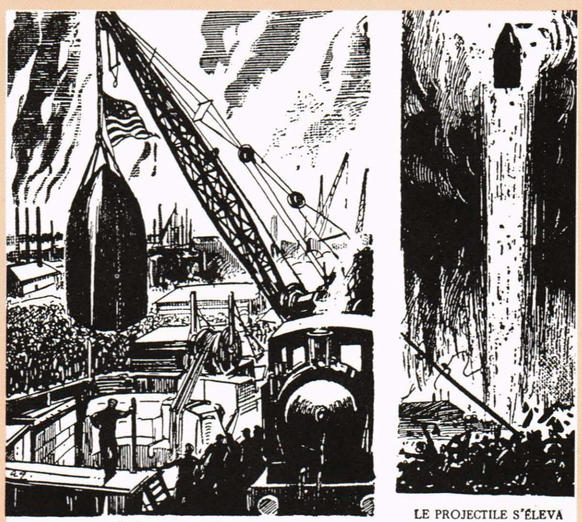
One of the Society members, Baron von Pirquet, later considered the problem of modifying the cannon so that at least something might survive a gun-launched trip to the moon. First, he increased the barrel length to 900 m and moved the launch site to a 5-km mountain peak near the equator. He decreased the projectile caliber to 1.2 m, increased its length-to-diameter ratio to 6, and finally added additional firing chambers along the length of the barrel, leading into the barrel from the side. By virtue of this last innovation, we credit the Baron with the concept of the distributed-injection launcher.

Despite these modifications, the German Society for Space Travel remained unsure about the feasibility of a moon gun. Nevertheless, the Baron's multi-chambered gun was to reappear in 1943 as the V-3, Germany's third Vengeance Weapon—a 120-m-long, eight-stage gun designed to lob 14 t of shells an hour on London from Mimoyecques, France, 150 km away (Fig. B).[19]

Some of the criticisms written in the 1920s, which ridicule Jules Verne's story, often seem laughable themselves when read in modern light. But one of them may stand the test of time. Humans, even if not spread thin, cannot tolerate accelerations above 4 *g* for more than a few minutes. Above 6 *g*, serious physiological problems can occur; above 12 *g*, voluntary muscle movements become very difficult, if not impossible. Test pilot Scott Crossfield lived through a 50-*g* acceleration when the X-15 experimental aircraft exploded during a ground engine test, but that was a miraculous outcome that can occur only when the force is distributed over a large part of the body's surface area. Without very well designed support, the human spine fails structurally at around 25 *g*.

We are told that Jules Verne's passengers were protected from the shock of launch by water buffers, but notwithstanding Verne's recognition of the problem, they would have had to deal with an average acceleration of 50,000 *g*! Yet we have no intention of making fun of Jules Verne. Through the literary device of a giant cannon, he first popularized the notion, as true now as then, that escaping the earth is simply a matter of velocity.

As for the V-3, despite problems with shell instability and barrel rupture, sub-scale testing was promising enough for Hitler to approve construction of a 25-gun underground battery late in the war. Fortunately, these guns, encased in hundreds of thousands of tons of concrete, were never fired at London, and in May 1945 the ground-level entrances were destroyed by British demolition teams. Quoting David Irving, "The sealed subterranean workings of Adolf Hitler's extraordinary high-pressure pump project [the V-3], complete with steelwork, railways, and high-speed ammunition lifts, remain to this day, and will endure, no doubt, to perplex the archaeologists of some future age."[19]



L'OBUS FUT EXPÉDIÉ PAR RAILWAY A STONE'S HILL.

LE PROJECTILE S'ÉLEVA DANS UNE GERBE DE FEU.

Figure A—Jules Verne's moonship is loaded and fired. In an actual launch, the crew would have had to bear a load equivalent to the weight of a large hotel building.

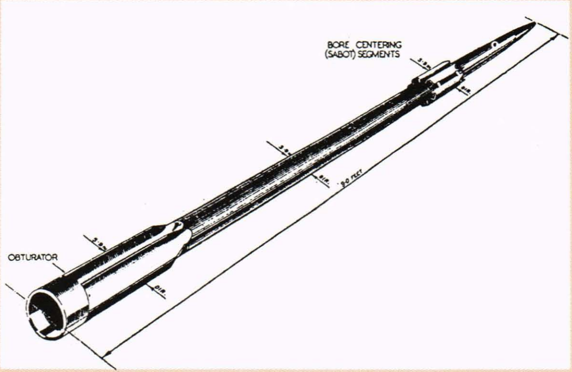


Figure B—The V-3 projectile, launched by a distributed-injection gun, had a tendency to be unstable and was never fired toward London.

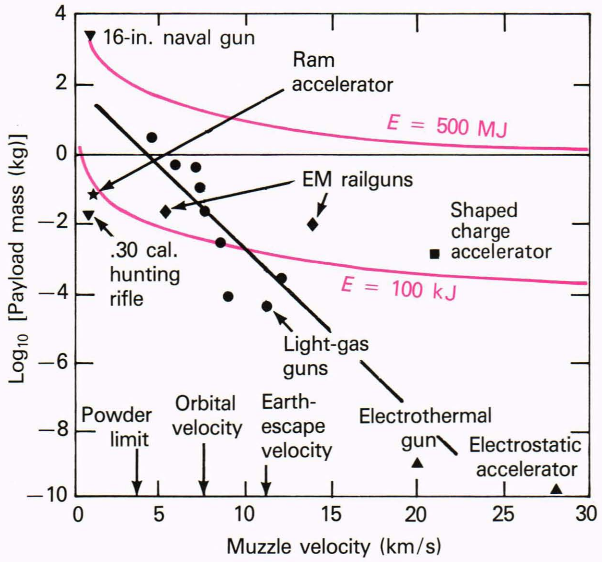


Figure 1—The limits of ballistic launcher technology can be gauged by this plot of projectile mass versus muzzle velocity, which shows a strong, nearly exponential fall-off with increasing speed. Isopleths of kinetic energy are indicated by the colored lines.

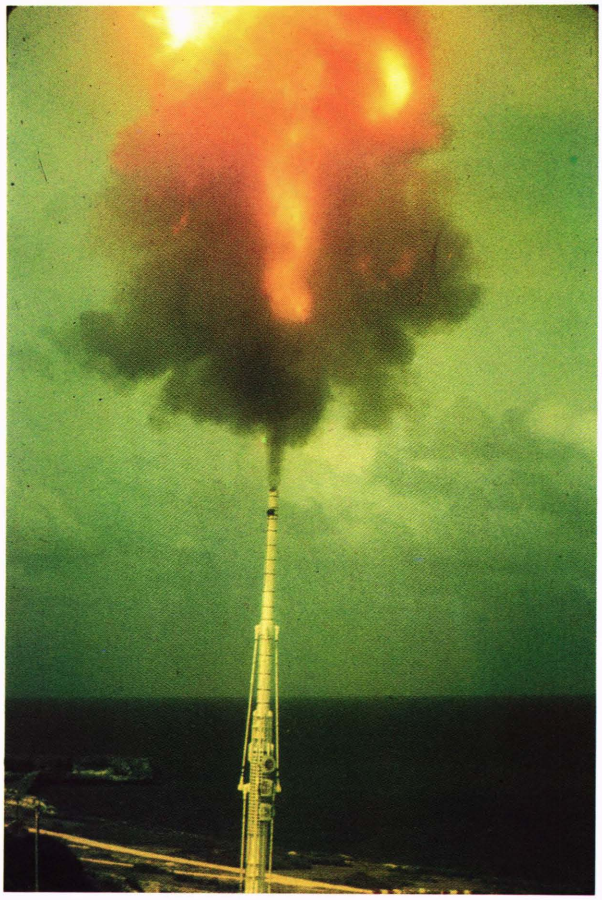


Figure 2—Firing of the extended 16-in. gun in Barbados. This gun was operated in the 1960s under the auspices of the High-Altitude Research Project of McGill University and the Space Research Corporation. The gun set many records and attained significant milestones by launching upper-atmospheric diagnostic probes to altitudes of the order of 100 km. In the late 1960s and early 1970s, the gun was used to launch rockets as well as scramjets at muzzle velocities up to 1.6 km/s.

insist that both gunpowder and the gun were invented simultaneously by Berthold the Black, a German alchemist and monk, who, according to one story, blew himself to Kingdom Come while demonstrating his discovery around 1300 A.D.[5] One can speculate about how he came by his name.

Although much of the early effort was spent trying to make the gun more dangerous to the enemy than to the gunner, it is clear that a substantial portion of the next 600-plus years of development (particularly during wartime) was devoted to moving up the vertical axis of Fig. 1 (projectile mass), culminating in the fielding of the 16-in. naval gun. That gun could launch a shell with the mass of an automobile (1230 kg) and a muzzle velocity of 850 m/s to a range of about 40 km.

Powder guns, whether they be hand weapons or huge naval cannons, are limited to muzzle velocities of less than about 4 km/s. The movement farther to the right in Fig. 1 (that is, to much higher muzzle velocities), didn't begin in earnest until after World War II, when the interest in supersonic flight, ICBMs, and artificial earth satellites produced a need for high-speed-research facilities. (As a reference, the speed required for a low-altitude circular orbit around earth is a little less than 8 km/s.) The mainstay of hypervelocity research during the 1950s was the light-gas gun invented in 1946 at the New Mexico School of Mines. Velocities up to 12 km/s and phenomenal accelerations of more than a million *g* were eventually achieved with this device.[6]

Between the late 1950s and late 1960s, research on hypervelocity techniques was given a boost by Project Defender, a Defense Advanced Research Projects Agency project to develop anti-ICBM weapons. Both chemical and electromagnetic launchers were studied. It was also during this period that a group of scientists at the U.S. Army Ballistic Research Laboratory and at McGill University in Montreal began the development of gun-launched probes for upper-atmosphere studies under a program called the High-Altitude Research Project (HARP). During testing on the island of Barbados, payloads weighing about 180 kg were shot on suborbital trajectories to altitudes greater than 100 km using a modified 16-in. naval gun (Fig. 2). (Although not a very meaningful gauge for space transportation applications, the launch costs were only a few dollars per kg.) Project scientists went on to launch supersonic-combustion-ramjet vehicles with the gun (Fig. 3); even though the particular designs being tested failed at launch, those vehicles were theoretically capable of traveling more than 3700 km with apogees of almost 1000 km.[7]

A combination of technical and political developments, building throughout the 1960s, caused hypervelocity research budgets to be cut by large amounts near the end of the decade. As a consequence, the field remained dormant for a number of years.[8] Interest was kept alive by people working in planetary science and

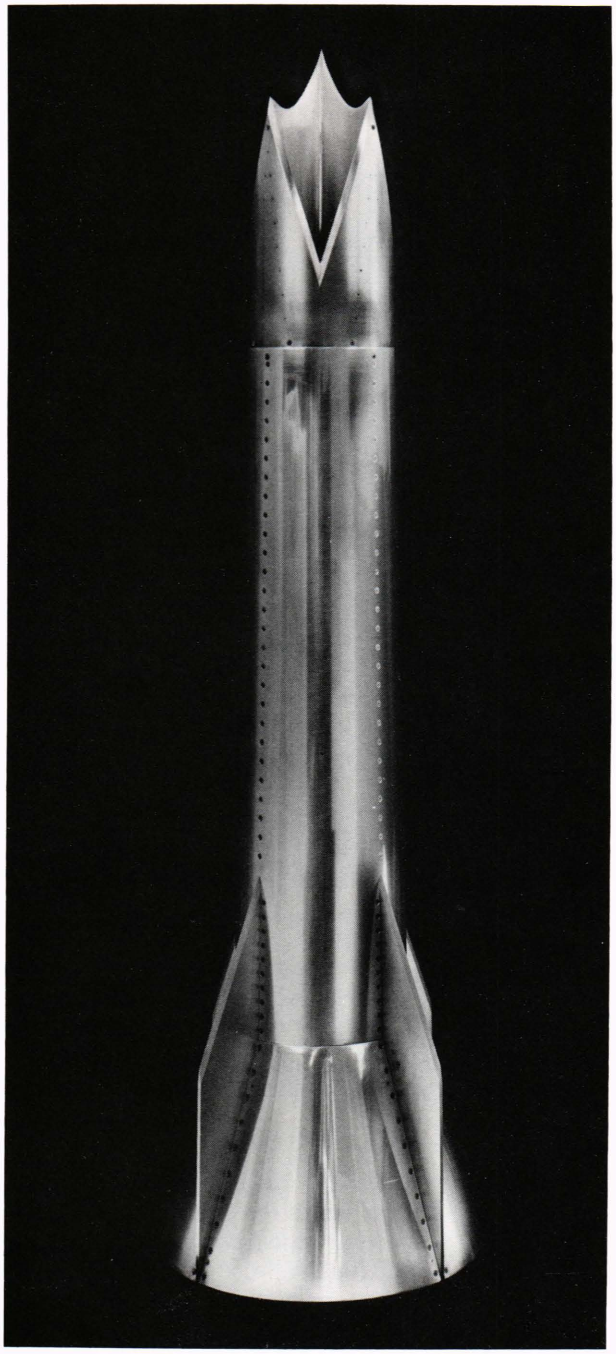


Figure 3—This supersonic combustion ramjet vehicle was designed by Prof. S. Molder for launching from the Barbados 16-in. gun. The intake design is based on streamline tracing of conical axisymmetric flow. The freestream flow is split into four equal segments that are compressed in the intake and passed into four annular dump-type combustion chambers. Three kg of triethylaluminum fuel was burned and the exhaust products were ejected through a 35-cm-diameter exhaust nozzle. The vehicle had a mass of 100 kg and was designed to withstand acceleration loads up to 10,000 *g*. At launch the vehicle became aerodynamically unstable because of structural damage suffered by the skin and stabilizing fins.

fusion research until, in 1983, the start of the Strategic Defense Initiative brought renewed and wide-based interest in hypervelocity research.

In the category of kinetic-energy weapons, much of the early emphasis in the Strategic Defense Initiative, and more recently in conventional defense programs, has been on electromagnetic railguns. A few points corresponding to railgun performances reported in the press are plotted in Fig. 1. At the highest levels of launch mass and muzzle velocity, both chemical and electromagnetic guns apparently destroy themselves when fired, an occurrence Berthold the Black would surely have understood.

The use of ballistic launchers for space transportation has been pursued seriously on several occasions in the past, including a detailed consideration (by Gerald O'Neill and his colleagues) of electromagnetic mass-drivers to support space colonization.[9] O'Neill foresees a need to deliver 680 t of lunar ore daily to low earth orbit. With talk of a U.S. lunar base becoming more serious, it is reasonable to suppose that ballistic launchers will soon be examined anew for moon-to-space missions, for which they may be particularly well suited.

We should mention in passing that several novel chemical-launcher concepts are also currently receiving attention, the ram accelerator[10] being a notable example. A ram accelerator can be thought of as a ramjet in a tube, where the launch tube wall is, in effect, the engine cowl. Other examples are the traveling-charge gun (akin to a solid-propellant rocket in a tube), and the regenerative liquid-propellant gun. Each concept has its own particular set of strong points and shortcomings, but for now we will not compare them.

The wide range of potential uses for ballistic-launcher technology should be kept in mind. In Fig. 4, various "regimes of application" are shown overlaying the same axes and scales as in Fig. 1. In the most general terms, the regimes cover an enormous area, with very large guns at one extreme and particle accelerators at the other. The distributed-injection launcher might occupy any of the territory to the left of (that is, velocities less than) 15 km/s.

TECHNICAL BACKGROUND

A Few Basic Principles

The mechanism of a gun is simple: a projectile is placed in a tube, gas at high pressure is introduced behind it, and the projectile is driven down the tube by the expanding flow. When the driver is a gas of low molecular weight (usually hydrogen or helium), the device is called a light-gas gun.[11] All other factors being the same, light-gas guns produce higher projectile velocities than powder guns because less energy is expended in accelerating the gas itself. Most existing ballistic ranges use a two-stage gun similar to a toy pop gun, wherein the gas at the breech of the launch tube is compressed by a piston in the drive tube.

For present purposes, we can get by without much detail. Some basic characteristics of the launch process are illustrated in Fig. 5 for a simple single-stage constant-diameter gun. The trajectory of the projectile can best be displayed as a plot in the *x–t* (displacement-time) plane, as shown in the upper part of Fig. 5. The inverse

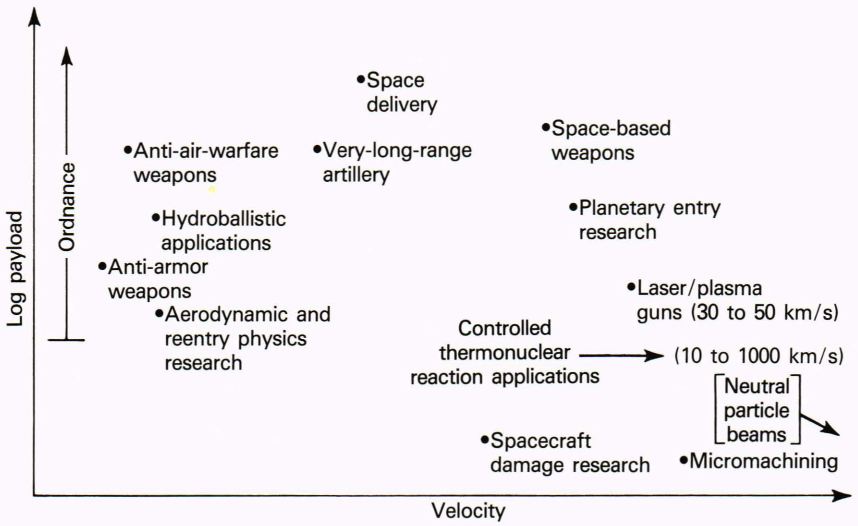


Figure 4—The range of applications of ballistic launcher technologies is very large, spanning an interval in mass from 10^{-27} to 10^3 kg, and in velocity from a few meters per second to 70×10^6 m/s, if neutral particle beam technology is included. Most endoatmospheric military applications cluster in the speed regime below 5 km/s.

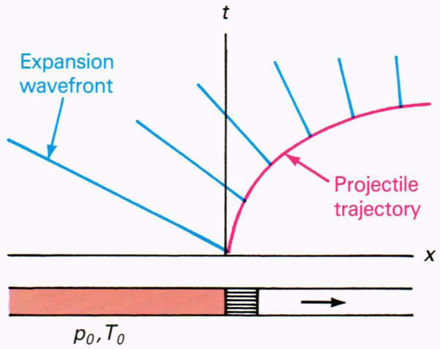


Figure 5—The trajectory of a projectile can be portrayed by plotting its displacement down the gun barrel as a function of time. In a conventional gun, the speed of sound controls the rate at which the gas behind the projectile adjusts to the increase in volume. The propagation paths of a few expansion wavefronts are indicated by the lines inclined from right to left along the projectile's trajectory. Expansion causes the pressure to drop and, as a result, the acceleration continually declines.

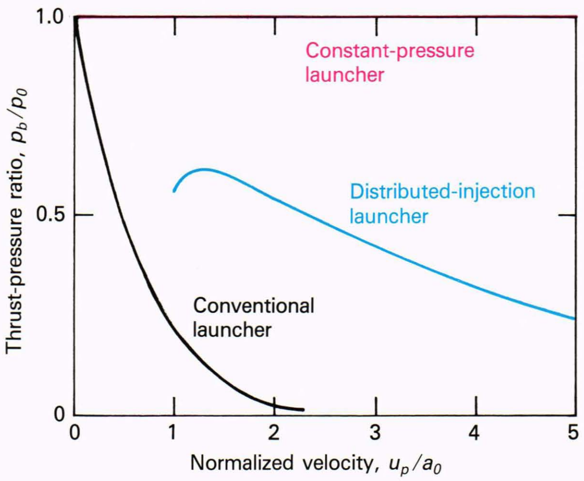


Figure 6—The pressure at the base of a projectile decreases with increasing speed, except in the limiting case of a constant-pressure launcher. For a conventional launcher, the rate of decrease is nearly exponential, but for an ideal distributed-injection launcher, the falloff is much more gradual, with the rate depending on the speed of the projectile and the angle of the boat-tail.

of the trajectory's slope is the projectile velocity, which is seen to increase with distance but at an ever-decreasing rate. Also shown in Fig. 5 are the trajectories of several of the infinite number of expansion waves that emanate from the rear of the projectile as the gas volume increases.

Since the force acting on the projectile is equal to the product of the base pressure and cross-sectional area, the falloff in acceleration is tied to the rapid decrease in pressure accompanying the gas expansion. For isentropic (lossless) flow, the base pressure depends solely on the projectile speed, as shown by the curve marked "conventional launcher" in Fig. 6. In this plot, p_0 and a_0 are the initial values of pressure and sound speed, respectively, in the drive tube. The maximum possible projectile speed corresponds to an expansion to zero base pressure. In the absence of losses, this speed is given by

$$\left[\frac{u_p}{a_0}\right]_{\max} = \frac{2}{\gamma - 1} , \tag{1}$$

where γ is the ratio of specific heats. Putting aside the possibility of real gas effects (which would make γ a variable), Eq. 2 implies that projectile speed can be increased by increasing the initial speed of sound,

$$a_0 = \left[\frac{\gamma \hat{R} T_0}{M}\right]^{1/2} , \tag{2}$$

where $\hat{R}$ is the universal gas constant, M is the molecular weight, and T_0 is the initial temperature of the driver gas (the stagnation temperature). The appearance of the molecular weight in the denominator of Eq. 2 explains the importance of working with light gases.

In practice, the maximum projectile speed can never be reached. The highest speeds achieved in experiments are generally only 30 to 40% of the theoretical maximum. Practical limits on the length of the launch tube cause much of this shortfall. As illustrated in Fig. 7, achieving a given increment of speed requires more and more tube length as the projectile displacement increases. The variable evaluated along the abscissa in Fig. 7 is a nondimensional distance, $p_0 Ax/ma_0^2$, where A is the projectile's cross-sectional area and m is its mass. The decrease in base pressure with distance produces the pronounced flattening of the curve.

The Constant-Pressure Launcher

A given projectile can withstand only a certain level of base pressure before it fails mechanically. The limit depends on the average density of the projectile and the ultimate strength-to-weight ratio of the material from which it is made. In some applications, it is the strength of the launch tube that limits the maximum pressure, but for now we will skirt the details of this complicated subject and concentrate on kinematics.

Forgetting the basis of the limit, if the maximum allowable pressure could be applied and then held constant during the entire launch interval, the projectile would reach the highest possible muzzle velocity attainable in a given launch tube of fixed length. Conversely, a chosen velocity would be imparted to the projectile in the shortest possible distance. In the sense of these performance measures, a constant-pressure launch tube is an ideal device and represents the perfect ballistic launcher.

The acceleration produced by an ideal constant-pressure launcher is also constant, so the kinematic problem is very simple if real-gas and dissipative effects are ignored. Under these circumstances, the theoretical speed limit can be reached in a nondimensional distance, pAx/ma^2, of 12.5, assuming the drive gas is diatomic ($\gamma = 1.4$). A plot of speed versus distance is shown in Fig. 7, where the results for the constant-pressure case can be compared with those for a conventional launcher. The very large difference between the two is apparent.

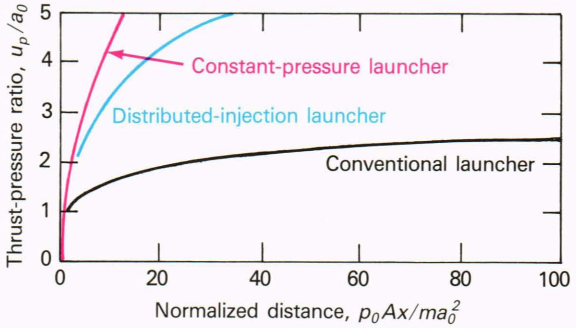


Figure 7—The increase in projectile velocity with distance would be very rapid if the base pressure could be held fixed. In a conventional launcher, the expansion of the driver gas produces a pronounced flattening of the trajectory. A distributed-injection launcher might recover much of the difference in performance.

A number of attempts have been made to build launchers that approach constant-pressure performance. In general, such devices operate by increasing the supply pressure continuously during the acceleration of the projectile, so that the gas flow into the breech increases as the projectile moves down the launch tube. Material properties again impose a limit, since the required supply pressure will, sooner or later, exceed the ultimate strength of the drive tube. For some cases of interest, the use of breech injection requires that the breech pressure build to a value more than an order of magnitude greater than the pressure at the base of the projectile.[12] Choosing to ignore pressure limits (for example, by using a shaped-charge driver to maintain the base pressure) can lead to high muzzle velocities, but at the expense of destroying the launcher.[13]

As a matter of interest, the barrel length required to launch an object at orbital speed, assuming the acceleration to be fixed at its maximum value (α), is simply

$$L = \frac{(V_{\text{orb}})^2}{2\alpha} \ . \tag{3}$$

Suppose we decide that a useful standard payload container would carry a total of 2000 kg in a package 2 m in diameter. Figure 8 shows that, if the maximum launch acceleration were held to 10^4 *g*, reaching orbital speed would require a constant-pressure launcher only 300 m

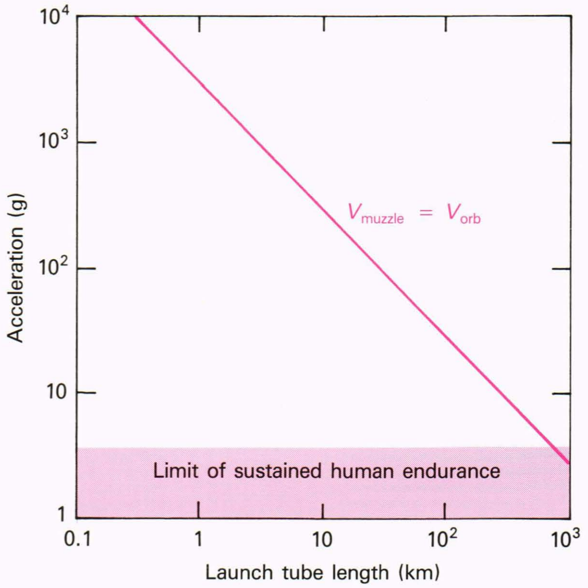


Figure 8—Launch-tube length is inversely proportional to the acceleration in a constant-pressure launcher. In the example shown, the muzzle velocity is taken to be equal to the velocity required to orbit the earth. In principle, a distributed-injection launcher can be made arbitrarily long and thereby can avoid high acceleration loads, but space transportation using a single-stage projectile seems implausible because the heating rates encountered in the lower atmosphere would be very large.

in length. The net drive pressure would have to be about 600 atm. If we restrict the maximum launch load to no more than 4 *g*, so that humans could be transported to orbit, Jules Verne's 3-m-diameter, 9-t vehicle would require a constant-pressure launcher more than 700 km long, but the net drive pressure would be only 0.7 atm.

Those are interesting examples that aid intuition, but they ignore a major limitation—aerodynamic heating. Launching projectiles at orbital speed in the troposphere means having to deal with heat-transfer rates as high as 1 MW/m^2. Although it is true that the total time spent crossing the atmosphere is short at such high speeds, the weight penalty associated with meeting the ablative or active-cooling requirements (assuming they could be met at all) would be very great. For this reason, it is likely that ballistic launchers used to deliver payloads into space from the earth's surface would have to be first-stage devices, operated at muzzle velocities less than orbital speed. The same constraint does not apply to space or lunar applications, of course.

ANALYSIS OF THE DISTRIBUTED-INJECTION LAUNCHER

In considering distributed-injection techniques, we are interested primarily in the upper end of the speed regime, since all of the limits are encountered there. We will, from here on, confine our attention to the portion of the launch for which the projectile speed is greater than the speed of sound in the supply gas.

Staged Injection

We start by first looking at staged injection, an elementary version of the distributed-injection concept designed to approximate the performance of a constant-pressure gun by adding mass at various discrete points along the launch tube, boosting the base pressure intermittently. This is essentially the method proposed by Baron von Pirquet in 1928 (see the boxed insert). If the injection stations are widely spaced, the base pressure will, of course, still drop in the sections between them. The question is, how close to constant-pressure performance can one come for given injector-supply conditions and spacing?

One approach to finding a rough answer is to carry out a "thought experiment" that sidesteps the complexity of the real mass-addition process. An experiment of this kind is illustrated in Fig. 9. The projectile is seen moving from left to right in an infinitely long launch tube, a forward section of which is assumed to be removable. Directly beneath this segment is another section of tube, identical in length, that contains a cartridge of fluid at high temperature and pressure. The instant the base of the projectile reaches the end of the removable segment, the section containing the gas slug is fired into position in an arbitrarily short time, in the manner of a cartridge in a Gatling gun.

At this point, the added mass (characterized by length L, pressure p_0, and temperature T_0) is in contact with the base of the projectile, which is traveling at speed u_p. What happens next is sketched in Fig. 10, which makes use of the x–t system of coordinates introduced previously. This picture approximates the early evolution of the flow as a combination of two classical flows in interior ballistics: on the right, the flow associated with an impulsively started piston; and on the left, the flow

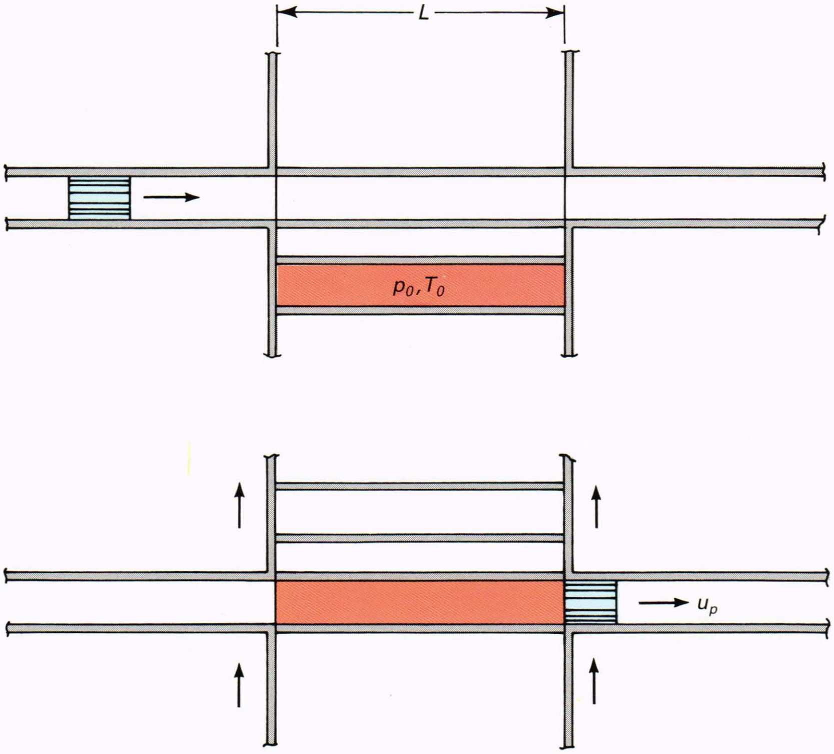


Figure 9—Thought experiment number 1: mass and energy are imagined to be added instantaneously at the rear of the moving projectile.

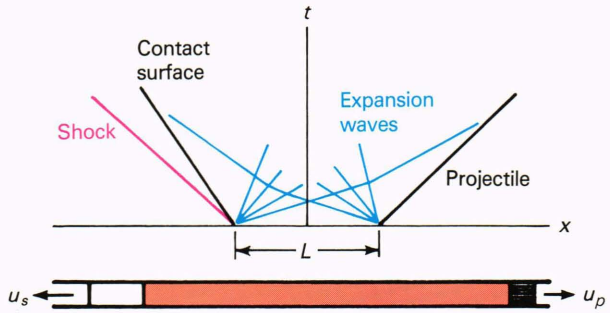


Figure 10—A simplified picture of the evolution of the flow (following the isolated injection event illustrated in Fig. 9) shows a shock wave traveling to the left leading the contact surface between the old and new fluid, with the projectile continuing its movement to the right. The rate of expansion in the gas behind the projectile increases with projectile speed, so discrete injection at high speed is not a very effective means for adding impulse.

in a shock tube. At later times, the two wavefields begin to interact, and the picture becomes very complicated, in spite of all of our idealizations.

The key points concerning the results of this "experiment" can be made without need of much elaboration. The occurrence of a centered expansion emanating from the projectile's base at $t = 0$ (although not strictly an exact result) implies that the base pressure drops precipitously to a lower value, estimated reasonably well by

$$p_b = p_0 \exp(-\gamma u_p / a_0) , \tag{4}$$

where p_0 and a_0 refer to the values in the fluid slug before injection (the supply conditions). When the projectile speed is high, a large fraction of the driving force is lost almost immediately—more than 90%, for example, when $u_p / a_0 = 2$. The base pressure begins to drop even further at some later time, as expansion waves from the "shock-tube flow" catch up to the projectile (the exact arrival time depending on the length of the slug). Increasing p_0 or T_0 to make up for expansion losses will soon result in structural problems, akin to the breech-injection case.

These basic results are quite discouraging, especially when we consider that the performance of a real system is likely to be worse. What we have learned from this first experiment is that adding mass or energy just once in a while along on the launch tube probably won't work very well. In fact, the little that can be garnered from existing literature suggests that this approach (that is, injection at widely spaced stations) may have been taken before without much success.[4]

Continuously Distributed Injection

In concept, one could prevent a large sudden expansion by continually firing one slug of fluid immediately after another as the projectile moves down the tube. Because the tube volume swept by the projectile in a unit time increases with speed, the number of fluid slugs injected behind it per unit time must also increase, and therefore the required injection rate must grow with distance. An arrangement of that sort would constitute, in the limit, a continuously distributed injection system.

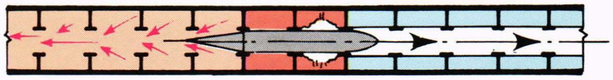


Figure 11—Thought experiment number 2: the precisely timed rupture of the diaphragms between the compartmented inner and outer tubes causes slugs of high-energy fluid to be introduced continually as the projectile moves down the barrel. The presence of a boat-tail decreases the rate of expansion of the entering gas. The diaphragms are conceptual devices; in many applications of interest, they would not be used.

To estimate the supply conditions and mass-flow requirements for the case of continuously distributed injection, we imagine carrying out another ideal experiment (Fig. 11). This time, the projectile is moving from left to right through a double-walled tube whose inner wall is ported. The space between the walls is divided into compartments that contain the driver gas. For the convenience of thought, the wall ports are assumed to be sealed initially by a thin diaphragm.

Just as the cylindrical section of the projectile reaches a position directly above a particular compartment, energy is added to the gas (say, through the discharge of an electric arc heater or the detonation of a combustible mixture). The temperature and pressure rise to high values, rupturing the diaphragm covering the ports. As the projectile moves past the compartment, the gas is now free to flow into the launch tube. The sequence of events repeats at each compartment along the tube.

Note that in this "experiment" the aft end of the projectile is tapered. That feature, known as a boat-tail, is crucial to a practical distributed-injection device. In the case of a bluff-base projectile, the injected gas must assume an axial velocity equal to the projectile speed; but with the addition of a boat-tail, the velocity need only be $u_p \tan \theta_b$, where θ_b is the boat-tail half-angle. Without the boat-tail, our imaginary "Gatling gun" injector would have to fire nearly infinitesimal slugs at a nearly infinite rate before much of a performance advantage could be achieved.

We can analyze the upper bounds of performance of a distributed-injection device by looking at the flow in a coordinate system fixed with respect to the projectile, while assuming (for simplicity) that the processes take place at low acceleration far from end boundaries and with unlimited compartment volume. From this viewpoint, an observer sitting on the projectile would see the compartmented fluid approaching with the speed u_p. He would also see the inner wall and its ports moving rearward at the same speed, so it is apparent that the flow into the tube would still be highly unsteady in the new frame of reference. In a realistic situation, one would expect to find a complex pattern of shock waves, turbulence, and separated flow, and the associated losses could be substantial.

If we consider a limiting case in which the separation distance between compartments approaches zero, so that the ratio of port area to inner surface area approaches unity, the wall "disappears" and the injection occurs as an unemcumbered, lossless flow. The pattern (Fig. 12) now resembles a steady corner flow, which is a much studied subject amenable to easy analysis.

Sparing the reader the analytical details, a plot of the ratio of base pressure to supply pressure as a function of the projectile Mach number, u_p/a_0, is shown in Fig. 6 for a boat-tail of half-angle 10°. The effect of changing the boat-tail angle is shown in Fig. 13. Notice that at high values of u_p/a_0, the drive pressure in a distributed-injection device can be much larger than the pressure in a conventional gun.

We can see from these results that—at least in principle—we may be able to produce a high thrust-pressure ratio (that is, the ratio of drive pressure to maximum pressure) in launch tubes of arbitrary length. By making a simple extrapolation of the thrust-pressure ratio curve into the regime for which $u_p < a_0$, using the form $p_b = p_0 \exp(-ku_p/a_0)$, we can integrate the equations of motion, starting at $x = t = 0$, to predict the projectile's trajectory. The outcome is superimposed on the previous results for conventional and constant-pressure launchers in Fig. 7. The nearly constant-pressure performance apparent in this plot makes the results much more encouraging than those implied by our earlier analysis of discrete staging.

The nondimensional form of the plot in Fig. 7 conveys a lot of scaling information (but not all of it, we must add). Within an envelope defined by material limits and operational constraints, a wide range of trade-offs are possible among muzzle velocity, launch-tube length, projectile size, and propellant characteristics. By rising steeply, the curve for distributed-injection promises added flexibility.

There is one more question to consider. The stored propellant represents a certain capacity to do work; how much of that capacity ultimately appears as projectile kinetic energy? In our case, a measure of the available work is the total enthalpy of the supply gas, and a convenient yardstick for its conversion to kinetic energy is the ballistic efficiency (the ratio between the rate at which projectile kinetic energy appears and the rate at which total enthalpy is supplied).[10] We can show that the ballistic efficiency η_b of an ideal distributed-injection launcher is given by

$$\eta_b = \left[\frac{\gamma - 1}{\gamma}\,\frac{p_b}{p_0}\right]^{(\gamma-1)/\gamma} \quad . \tag{5}$$

For the perfect diatomic gas that we have been considering, η_b lies between 27% and 40%, which is a little better than has been achieved so far with railguns, and about equal to the limiting performance of ram accelerators.

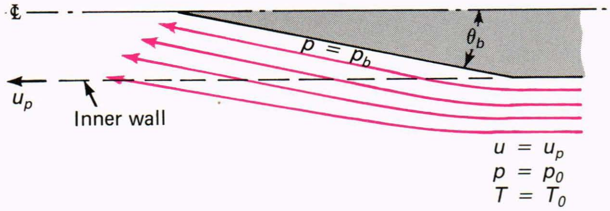


Figure 12—A quasi-steady flow around a corner would be seen by an observer of thought experiment number 2, if he were moving with the projectile and if the gap between compartments were negligible.

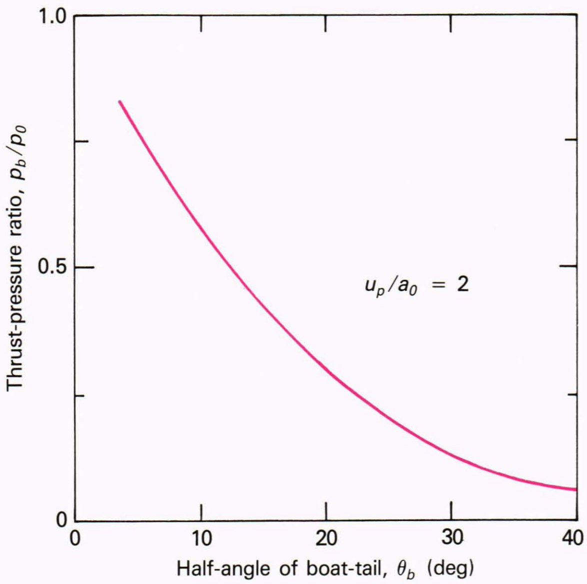


Figure 13—The pressure at the base of the projectile approaches the supply pressure as the boat-tail angle goes to zero, but the projectile length increases without bound. On the other hand, using a bluff-based projectile in a distributed-injection launcher offers very little advantage, as compared with conventional methods.

ISSUES AND APPLICATIONS

In modern technical parlance, we have "bounded the problem"—at one end, isolated-injection methods are seen to be decidedly poor, especially at high projectile speeds, while, at the other, continuous-injection methods seem to promise performance approaching the ideal. Bounds so wide are instructive, but hardly decisive. Also balancing the good news is the recognition that our examination of continuous injection has been idealized, and perhaps over-idealized. The analysis, being lossless, can't distinguish between the possible and the impossible.

The principal uncertainty, at the head of a long list of engineering design questions, is whether or not the injection and interstage expansion losses will be severe enough to drive the required supply temperature and pressure beyond structural limits, or otherwise to make the overall efficiency unacceptably poor. Other significant issues involve (1) friction, heat transfer, and erosion in long, ported launch tubes; (2) process control (for example, fluid and energy management during launch); and (3) structural fatigue and other problems related to materials. None of these areas of uncertainty can be addressed by theoretical methods alone. A distributed-injection launcher, suitably scaled, must be built and tested.

Presuming that high-performance systems could be built, and staying with the broad viewpoint adopted at the beginning of this article, we think that distributed-injection launchers might find a wide range of practical applications. It is the freedom to trade drive pressure for launch-tube length (and vice versa) that is the major reason for such a diversity of potential uses. If an application calls for a relatively large and slow launch system, the required pressure may be low enough, and the characteristic time scale (as measured, say, by the time required for the projectile to move its own length) may be large enough, to consider using conventional fuels and mechanically actuated injectors. Such a system can be pictured as a "linear" form of an automobile engine, in which the cylinder is the launch tube and the piston is the projectile (other engine components, such as valves, fuel injectors, spark plugs, and ignition timing devices, also have direct analogs).

If the emphasis is on reaching ultrahigh speeds in a short distance, the drive pressure and supply sound-speed must be very high, and the time scale will be exceedingly small. Applications in this regime require the precise triggering of a sequence of strong implosions as the projectile moves along the segmented launch tube, suggestive of nuclear weapons technology. In effect, the timed sequence of blasts would amount to a computer-controlled oblique detonation wave. A time-phased, cylindrical version of the hemispherical implosion device developed by I. I. Glass and his colleagues at the University of Toronto may offer some interesting possibilities as a distributed-injection driver.[14]

Once a particular application is in mind, a natural question occurs: How would a distributed-injection launcher fare in a match against a railgun, or a ram accelerator? The three central areas of comparison are material limits, energy storage density, and energy conversion efficiency. The first depends strongly on the required acceleration; if the value is fixed by the application, all approaches are subject to structural problems of comparable difficulty. The relative ease of application of modern materials technology, with the possibilities for using composites, plastics, or ceramics, might swing the balance here.

The differences in the other two areas also appear to be a close call. Railgun developers expect to achieve an energy-storage density of about 10 GJ/m^3 by the mid-1990s, which is essentially the same as the value associated with liquid hydrogen and liquid oxygen when they are stored in proportions so as to react completely. The conversion efficiencies of the various devices can be argued to be comparable, as we noted in the last section. Of course, if one opens to consideration the use of a plasma as the working medium, with the option of applying both electromagnetic and fluid-dynamic forces, the possibilities become very interesting. The MAID launcher (Mass Accelerator using Imploded Discharges) is designed to apply a strong magnetic pinch to a plasma created at the rear of a small projectile, with the ultimate goal of reaching the speeds needed for impact fusion.[15]

All factors considered, distributed-injection launchers appear to be most suitable in applications that can couple moderate drive pressures with long launch tubes. Such a combination makes them especially interesting in naval systems, since the platforms are large and sustained rapid fire is often essential. Improving the range and accuracy of its large guns is already a requirement[16] and, in the future, the Navy must worry about defending against low-flying, high-speed, nearly invisible missiles where a short time-to-target, high firepower per unit volume, and low dispersion are critical considerations.

Dispersion (the average difference in impact locations among a number of identical shots) is small in gun systems, but usually not small enough. When the range is large, a typical dispersion of 1% can mean literally missing by a mile. For this reason, long-range guns will probably need to fire what amounts to rugged, intelligent guided missiles, powered perhaps by supersonic combustion ramjets.

In its early years, the Applied Physics Laboratory played a prominent role in the interregnum between guns and missiles. During World War II, when the U.S. was far behind in rocket technology, one of the strong motivations for catching up quickly was the need to provide a (low-acceleration) rocket launcher for proximity-fused shells, which depended in those days on vacuum-tube technology. By developing a five-tube fuse that could nevertheless withstand the 20,000 *g* acceleration of a gun, APL supplied to the country a critically needed capability, as well as buying time during the war.[17] Later work showed how guided missiles could overcome the limitations of conventional guns, when the basic survivability of warships against air attack came into serious question after the war. Now, anticipating future threats, the time may be right to consider guns again—or perhaps gun-launched guided missiles.

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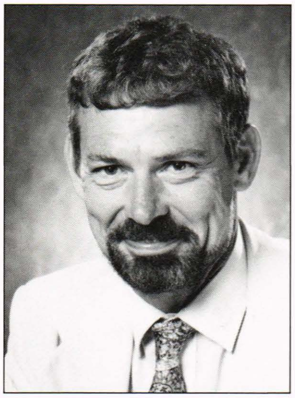

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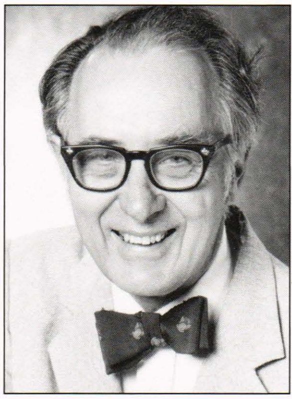

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