Gun Launch to Space - A Discussion of Technology Options

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ABSTRACT

After nearly half a century of space flight, the cost of putting payloads in orbit hovers around $4000 per pound for commercial launchers and about $10,000 per pound for the Space Shuttle. Such high costs are the single most important limiting factor to expanded business and exploitation of space.[1] Because of the history of difficulties in reducing the cost of rocket launch, researchers have been investigating alternative methods using hypervelocity gun launch systems. The idea goes all the way back to Isaac Newton in his Principia, and was later popularized in a fictional account by Jules Verne in 1865 in his novel "From the Earth to the Moon." While Verne took some literary license in launching people with his gun, technology has now progressed to the point where launch of more robust payloads to orbit is technically feasible. Gun launches of fuel, water, food, solar panels, building materials and other supplies, and even constellations of small robust satellites, could be accomplished, saving not only billions of dollars, but enabling near term industrialization of space by reducing launch costs of such payloads by one to perhaps two orders of magnitude. A brief review of the major gun launch systems under consideration is presented with primary attention to two likely candidates, distributed hydrogen side injection and ram accelerators. Gun Launch to Space (GLTS) has great promise for reducing launch costs, but some technical issues still need to be resolved, and demonstrations of the technologies at a scale size beyond the laboratory is required before significant private investment seems likely.

INTRODUCTION

The basic GLTS concept is illustrated schematically in Figures 1 and 2. A relatively long, high velocity gun barrel is mounted on the side of a hill or mountain at an angle of about 20 degrees. The direction of the gun is chosen for a particular range of orbits, and once chosen, is basically fixed in place, due to the size of the gun. Two separate launchers would thus be needed, for instance, to place payloads into both polar and into equatorial orbits. In order for gun launch to be economically useful, muzzle velocities in the range of 4-10 km/s appear to be required, with the 6-8 km/s range generally receiving the most attention. For a low earth orbit velocity of about 7.6 km/s , a gun fired projectile will typically need a total delta V of approximately 9 km/s to reach that orbit, since some velocity is lost to atmospheric drag. The difference between the total

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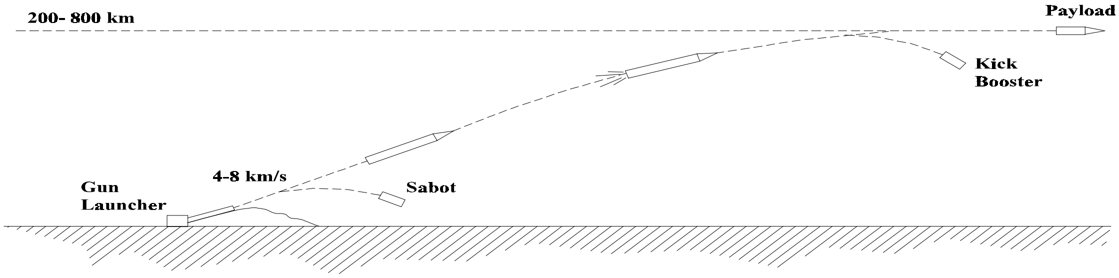

Figure 1 *Basic concept of Gun Launch to Space utilizing a long launcher barrel tilted up the side of a small mountain. An on-board booster provides the final boost into orbit and orbit circularization.*

required delta V and the muzzle velocity is made up by an on-board booster, fired at or near apogee to achieve the final orbit height and/or to circularize the orbit.

The muzzle velocity has an enormous impact on the overall size, design and cost of the launcher. The mass ratio (i.e. initial mass divided by final mass) of the launched projectile is determined by the rocket equation:[2]

$$\Delta V = g\, I_{sp} \ln\left(\frac{M_i}{M_f}\right) \qquad \textbf{(1)}$$

where Isp is the specific impulse, $M_i = M_{structure} + M_{payload} + M_{fuel}$, and $M_f = M_{structure} + M_{payload}$. If we assume Isp=300 sec, then the mass ratios for a range of ΔV's are shown in Table 1. The launch package can thus range over an order of magnitude in mass for the same payload, depending on launch velocity.

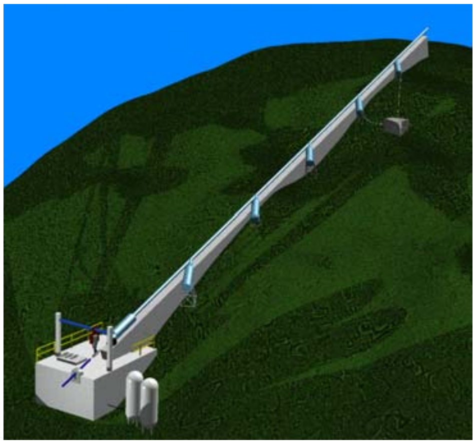

Figure 2 *Artist's concept for side injected launcher.*

In general, the higher the muzzle velocity, the less delta V is needed and the smaller the on-board booster required to reach orbit. In principle, this leads to lower cost per pound to orbit, but only when amortized over sufficiently many launches, since the capital costs of the higher launch velocity gun scale roughly as the square of the launch velocity.

Table 1 *Mass ratios vs deltaV for an Isp=300 sec.*

ΔV	M_i/M_f
7000	10.80
4000	3.90
2000	1.97
1000	1.40

This scaling comes about from the basic physics of constant acceleration launch. Assuming constant acceleration, the length of the barrel is given by the well know equation $v^2=2ax$, where v is the muzzle velocity, a is the acceleration, and x is the barrel length. This equation provides an obvious but still interesting insight into a launcher of this type. For a given launch velocity and acceleration, the barrel length is fixed. It doesn't matter how large or small the payload is, a given acceleration requires a certain distance to achieve a specified velocity. The bore size simply expands or contracts to accommodate the mass of the launch package, which in turn depends on the launch velocity. Figure 3 shows the launcher length vs. velocity for accelerations from 500 gees through 5000 gees. It is clear from these plots that these guns are going to be unrealistically long, unless payload packages can be cheaply fabricated to withstand a few thousand gees. Fortunately, this appears to be possible, certainly for bulk payloads, and probably also for small robust satellites.

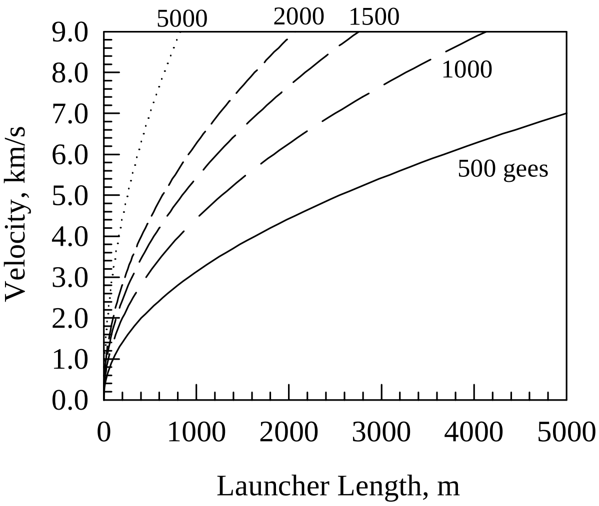

Figure 3 *Launcher length as a function of velocity and acceleration.*

The design of a GLTS system is, like most engineering systems, a compromise between many competing and often mutually exclusive requirements. On the one hand, the shortest possible barrel is desired, but this drives up the acceleration, increases the operating pressure, the stresses on the projectile/payload package and the barrel, and thus drives up cost. On the other hand, low barrel pressure and acceleration is desirable in order to limit material stresses and increase the range of possible payloads that can be launched. But this tends to increase the barrel length, which drives up costs. Obviously, it is an iterative process to arrive at an optimal design, where optimal could mean lowest system cost, lowest operating cost, highest profit margin, or whatever is most important to the customer.

The basic idea, of course, is that there exist a number of sets of operating parameters which in fact lead to lower total costs than existing rocket systems, and potentially by a large margin. The ground based gun becomes in essence the ultimate reusable first stage, imparting most (or at least a large fraction) of the energy required to reach orbit. By leaving the large expensive systems on the ground, and reusing them over and over again, gun launched projectiles can reach orbit with a relatively small, low cost booster. If, in addition, the projectiles can be mass produced, then additional economies of scale can help reduce overall cost further.

BACKGROUND

Gun Launch to Space has been a recurring topic since at least the 1800's. A serious effort was made in the 1960's with the High Altitude Research Project (HARP)[3,4]. In this project, instrumented projectiles were gun launched to altitudes of over 180 km. Plans were made to gun launch a payload into orbit (with rocket assist) but were scrapped because traditional rockets appeared to be a more attractive option at the time. In the late 1980's and early 1990's, there were extensive studies aimed at gun launching missile defense hardware.[5-7] In addition, there was a controversial launcher which was partially completed in Iraq just prior to the gulf war. This device, had it been completed, may have been capable of intercontinental artillery or launching LEO satellites.[4,8]

There have historically been three major drawbacks with gun launch to space efforts:

1) Launching the necessary mass at the required velocity (muzzle energy) is fundamentally not easy. For many years powder guns were the only available option. Although capable of launching large masses, fundamental physics issues limit solid propellant launchers to moderate velocities, typically less than 2-3 km/s. Nevertheless, muzzle energies in excess of 200 MJ have been achieved with 1000 kg projectiles using solid propellants, and the only serious attempts at GLTS in the past were made using solid propellant gun technology.

2) The second drawback concerns acceleration loads. Past efforts at GLTS using breech fed only systems (solid propellants) necessitated high acceleration loads. Acceleration loads in the thousands to tens of thousands of gee's obviously limited the types of cargo which could be launched without damage. Electronics were one area of particular concern. Although useful electronics packages were and still are gun launched, additional care must be taken with design and packaging. New advances in electronics and micro-electromechanical systems (MEMS) currently allow virtually any electronics package to withstand loads up to 100 kgee's. In addition, gun systems with distributed energy addition, or constant acceleration guns, like the Ram Accelerator, now allow much lower and better tailored acceleration profiles relieving these concerns somewhat.

3) Traversing the lower atmosphere at near orbital speeds entails an additional set of problems associated with severe thermal loads, ablation, and gas ionization (control systems). Payloads must be designed with heat shields or transpiration cooling in order to withstand heat fluxes as high as 1 MW/m^2.

Some excellent historical reviews and general discussion of Gun Launch to Space can be found in References 4,8-12. We refer the reader to those references for more extensive details, and limit ourselves to a general discussion of the few main gun launcher technologies of interest. Additional extensive technical information can also be found in final reports of the Brilliant Pebbles studies.[5,6,7]

Single Stage Breech Fed Guns

The basic physics of breech fed guns (such as solid propellant and single stage light gas guns) is straightforward. By Newton's Laws the acceleration of a projectile in a gun is given by;

$$a_p = F_p/m_a \tag{2}$$

where a_p = projectile acceleration, F_p = force on the projectile and m_p = projectile mass.

An idealized gun can be approximated by the isentropic expansion of a propellant gas given initial pressure (P_o) and sound velocity (a_o). Since F_p is a product of the pressure on the projectile base and its base area (A_b) and a_p is the derivative of the velocity, Equation 2 above may be rewritten as [13]:

$$\begin{aligned} m_p \frac{du_p}{dt} &= p_{base} A_{base}, \\ \textit{where} \quad p_{base} &= p_0 \left(1 - \frac{u_p}{u_{esc}}\right)^{\frac{2\gamma}{\gamma-1}} \\ \textit{and} \quad u_{esc} &= \frac{2a_0}{\gamma-1} \end{aligned} \tag{3}$$

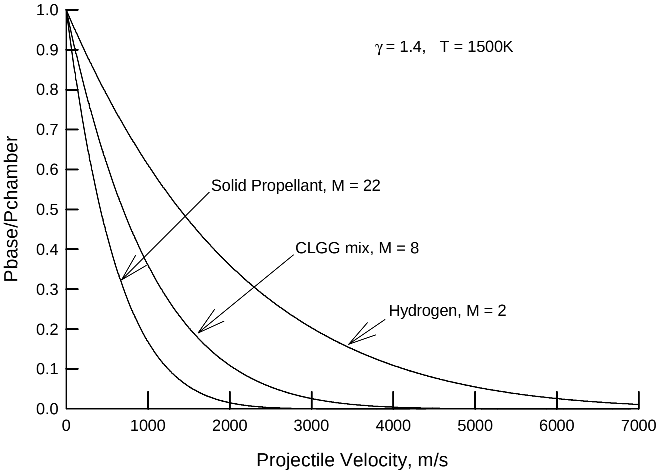

Figure 4 *Light gases with low molecular weight, M, extend effective gun operation to higher velocities than solid propellants can attain.*

where u_p is the projectile velocity, u_{esc} is the "escape velocity", i.e. the maximum velocity for the propellant gas, and **(** is the ratio of specific heats for the propellant. Due to non-ideal effects, such as projectile friction and gas viscous drag and heat loss to the wall, the performance of an idealized gun suggested by Equation (3) is not generally achieved. However, the parameters which control the performance of any gun are similar. As can be seen, the pressure transmitted from the combustion chamber to the projectile base is largely controlled by the combustion gas sound speed and ratio of specific heats. Single stage light gas guns, by using propellants with low molecular weight, M, achieve much higher sound speed for a given temperature, and are able to achieve considerably higher performance. In physical terms, the pressures produced in the "combustion" chamber of the light gas gun are transmitted much more efficiently to the projectile base as the projectile accelerates downbore. This is illustrated in Figure 4 where the ratio of projectile base pressure to initial chamber pressure is plotted as a function of projectile velocity for three cases: 1) a solid propellant gas with M=22, 2) a Combustion Light Gas Gun (CLGG)[14] gaseous propellant consisting of a mix of hydrogen, oxygen, and helium yielding an average molecular weight of 8, and 3) a pure hydrogen gas electrothermally heated in the Electric Light Gas Gun (ELGG).[15] The two light gas guns show markedly higher pressure ratios at the higher velocities, and this is confirmed by experiments in which the CLGG achieved 4.2 km/s and the ELGG achieved 7.0 km/s in single stage breech fed tests at the 16mm bore size.

In its simplest configuration, as first described by Lord[16] in 1960 and later by Tidman et al[17], CLGG consists of a chamber (Figure 5) sealed with a diaphragm and filled with a combustible mix of light gaseous propellants such as methane, hydrogen, oxygen, and helium, in various combinations. Prefill pressures can range from a few thousand psi up to 20 kpsi or more. The helium (and hydrogen) acts as a diluent to lower the average molecular weight of the gas. The mixture is ignited using a specially designed ignition system. As the combustion pressure rises, the diaphragm bursts or shears, allowing the projectile to accelerate down bore propelled by the high pressure, *light* combustion gases. Note that at 20 kpsi these gases are very nearly at cryogenic liquid density, even though still at room temperature, an important factor in generating high pressure at moderate temperature so that barrel lifetime is long.

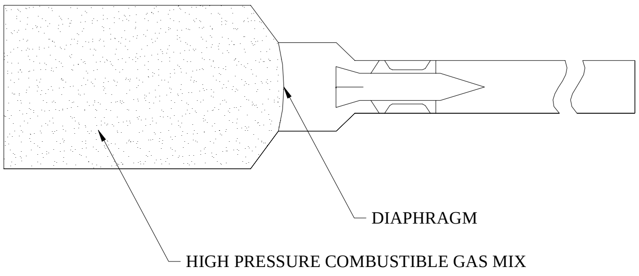

Figure 5 *The basic CLGG concept. Controlled combustion of light gases in a low molecular weight diluent provides high sound speed at moderate temperature, yielding projectile velocities above 4 km/s.*

The ELGG consists of a chamber similar to that shown in Figure 5, but with an insulating liner and with electrodes added at each end for arc attachment. It is prefilled with hydrogen gas to 20 kpsi , and then arc heated to about 90 kpsi using a high voltage capacitor bank. It launched 2 gram projectiles to extreme velocities of 7.0 km/s in a purely breech fed mode at about 11% efficiency.

Because of the high initial pressures and chamber sizes required, single stage breech fed guns are not likely candidates for GLTS launchers.

Two Stage Light Gas Guns

Two stage light gas guns have achieved the highest demonstrated performance to date and have been the standard workhorse for high velocity experiments for decades. A heavy piston is accelerated in the first stage pump tube by a conventional powder charge or combustion of light gases. This piston then adiabatically compresses a light gas, usually hydrogen restrained by a diaphragm at the beginning of the second stage, which also contains the projectile and barrel. When the compressed hydrogen reaches a threshold value, the diaphragm bursts and the hot high pressure hydrogen accelerates the projectile down the barrel. At 7 km/s and above, such a system is only a few per cent efficient, and imparts very high initial acceleration to the projectile.

SHARP (Super High Altitude Research Project)[6,12,18,19], located at LLNL, was the largest 2SLGG ever built. It was a precursor to Hunter's proposed Jules Verne launcher concept[9,20] which uses distributed injection of hydrogen, to be described below. SHARP was unusual not only for its gargantuan size, which had a compression pump tube 270 feet long and 14 inches in diameter, and a launch tube 4 inches diameter by 155 feet long, but also for the 90 degree angle between the two. The gun never quite achieved all of its design goals, which included launching a 5 kg projectile at 4 km/s, but performed many useful experiments and paved the way for the Jules Verne concept. This launcher received a lot of press because of its size, but will never be a serious contender for GLTS, mainly due to material and acceleration limitations, and other technical factors.

Railguns and Coilguns

Railguns attempt to overcome the sound speed limitation of gas guns and attain a constant acceleration by utilizing magnetic forces created in the interaction of a large arc current behind a projectile with its own self magnetic field. In principle, this can achieve the desired propulsion parameters, but in practice has been limited by a number of practical problems that appear unsurmountable.

There have been a lot of promises and much high quality, innovative research, but unfortunately little performance payoff to show so far for all the work, due primarily to some intractable fundamental technical problems. Reliable operation above about 3 or 4 km/s has not yet been demonstrated. The main issues here are control of the plasma armature to prevent bifurcation and generation of secondary trailing arcs, elimination of rail arc damage, development of smaller, lower cost pulsed power supplies, and development of reusable high current high voltage opening switches. The barrels themselves are very complex, very expensive, and short-lived even at velocities below 4 km/s. Development of long-life barrels does not seem likely in the foreseeable future.

Coilguns also use magnetic forces but applied inductively and impulsively in a series of distributed coils along the length of the barrel. There was a lot of initial promise, but technical issues again seem insurmountable for the foreseeable future for velocities above 2-3 km/s for large masses. Large coilguns theoretically require very high voltage operation and very fast switching.

The biggest disadvantage of railguns and coilguns, even if they worked at the required velocities, is the cost of the pulsed power supplies. All GLTS approaches that depend on pulsed power for most or all of the projectile kinetic energy suffer the same problem - the enormous size of the power supply. As an example, to launch a 100 kg payload at 7 km/s requires a total package mass of perhaps 700 kg to get to LEO. The total kinetic energy required is given by ½mv^2 = 0.5 x (700kg) x $(7000\text{m/s})^2$ = 17.2 GJ. If the launcher is even 10% efficient, which is unlikely at that velocity, the total pulsed energy required is 172 GJ. Very quickly the cost of the power supply becomes completely unacceptable.

Blast Wave Accelerator

The Blast Wave Accelerator[21] is an interesting concept which could theoretically provide extremely high velocity with short barrels. It utilizes a series of imploding discrete or continuous charges along the length of the barrel. The radially imploding high pressure gases act on the tapered trailing end of a projectile producing a net component of force in the direction of projectile travel. Very high accelerations can be achieved in this manner.

The primary advantage of this approach, namely, the short acceleration lengths, is also perhaps its primary disadvantage, namely extremely high acceleration. This may be acceptable for some defense applications, but probably not for commercial operations. Even if it is operated in a lower acceleration mode, some very real additional problems will still need to be addressed such as barrel lifetime and complexity, fast propellant reloading procedures, and safe handling of bulk solid explosives in enormous quantities (which also is not that environmentally friendly). This approach will probably work technically - but it is difficult to see how it would be converted to true commercial operations any time soon.

THE DISTRIBUTED INJECTION LIGHT GAS GUN

Single stage breech fed hydrogen gas guns, and 2SLGG’s can both achieve the desired launch velocities (i.e. 6-7 km/s), but only if using lightweight projectiles. Such projectiles would be too lightweight for useful payloads, and in any case, it is desirable to launch projectiles with as high a ballistic coefficient, **$**, as possible, in order to reduce atmospheric drag effects. High **$** means projectiles with high mass per unit cross sectional area. As seen earlier, however, the exponential dropoff in pressure as the projectile accelerates, means that the initial peak acceleration has to be very high. In order to achieve the initial high acceleration, the chamber pressure must necessarily go beyond practical material strengths for large projectiles. Distributed injection launchers provide a way around this problem. The fresh injection of light combustion gases constantly replenishes the driving gases, and each succeeding injection module can be tailored (within limits) to provide a roughly

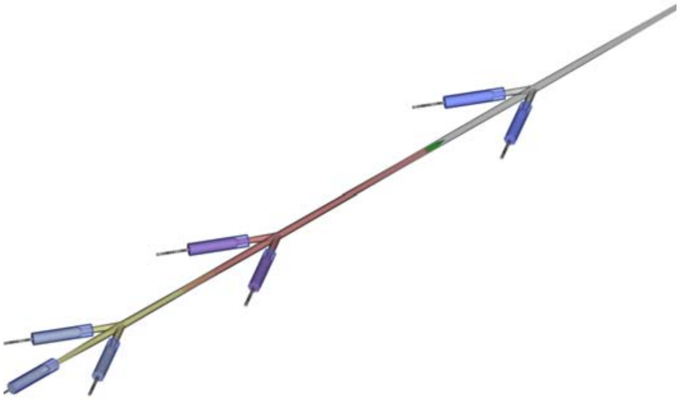

Figure 6 *Distributed injection launcher showing initial injector and first three side injector modules.*

constant acceleration, a practical impossibility with a breech fed gun. Figure 6 illustrates a generic side injector system, showing the first, or injector module, followed by the first three of many following side injector modules.

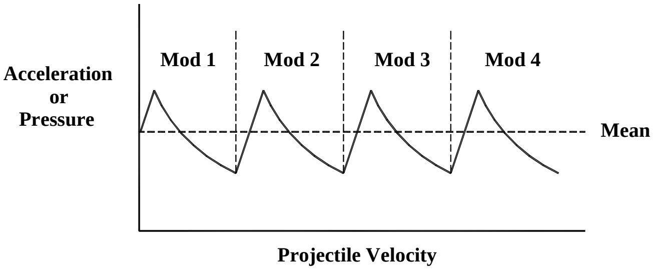

Figure 7 *Projectile base pressure (and acceleration) oscillates in a roughly sawtooth-like pattern when plotted vs projectile velocity.*

Distributed injection of propellant gases behind the projectile along the length of the barrel was first described by Baron von Pirquet[22] in the 1930's as a way of reducing the peak acceleration of Jules Verne's fictional gun. The German's actually built and test fired an experimental gun 120 m long with eight side injectors during WWII using solid propellants, but it was never used operationally due to technical difficulties.[22]

The distributed injection approach has been analyzed in some detail by Gilreath, Fristrom, and Molder[22], and by Higgins[23]. Their analyses led to the conclusion that distributed injection provided no advantage over breech fed guns for achieving higher velocities. This is correct, however, only in the sense that a distributed injection gun cannot achieve any higher ultimate velocity than a breech fed gun, since the side injected gas must still expand to the projectile velocity before it can do any work, and thus suffers the same pressure dropoff described earlier in Equation 3. However, distributed injection provides a means of accelerating heavy projectiles under controlled acceleration to above 7 km/s

The effective pressure on the base of the projectile, and hence the projectile acceleration, will be an oscillating value about a mean, looking something like that shown in Figure 7. Each time the projectile passes an injection port, the pressure will suddenly rise to a value P_{upper} and then exponentially drop off as the projectile accelerates (given by Equation 3) until it reaches P_{lower} at the next injection port, where the process starts all over again.

The location, spacing, and peak operating pressures and temperatures of each side injector will be determined ideally by Equation 3 and by the allowed excursion in the acceleration about the mean value. Note that the pressure in each successive module must increase to compensate for the local velocity of the projectile, in order to maintain a roughly constant acceleration. Eventually, as velocity increases, the required pressures in the side chambers become too large for practical materials and designs, and the acceleration must be relaxed. This was analyzed by Witherspoon et al.[24] for the case of a side injected CLGG launcher.

Electrothermal Side Injection

The ELGG, described earlier, not only has achieved the highest single stage gun launch velocity, but also provided the test bed for the most dramatic demonstration to date of the distributed injection concept at high velocity. In those experiments, performed at GT-Devices, Inc., a 2 gm projectile accelerated to 6.56 km/s by an ELGG breech chamber was then "kicked" to 7.2 km/s by a single ELGG side injector, a velocity increase of 640 m/s in one “kick”. The configuration provides an ideal method for launching high DR projectiles to high velocity with both modest and controllable acceleration. These experiments proved the concept, and showed that substantial velocity “kicks” were possible even at very high velocity.

An even earlier distributed injection system using pulsed plasma jet technology was also developed at GT-Devices in the mid-1980's. The mechanism relied more on a momentum collision than on pressure drive, but the final effect is the same. In that device, called the “Ten Mod”, a breech plus ten kicker modules accelerated 10mm diameter, 0.5 gm projectiles to 5.1 km/s, thus successfully demonstrating operation of multi-kicker systems.[25] This system utilized “sense and fire” circuitry to control the firing times of the side injectors.

Unfortunately, electrothermal side injection also suffers from the high capital cost associated with the pulsed power supply, and thus does not appear to be economically feasible at this time.

The Combustion Light Gas Gun (CLGG)

The case of a purely chemical driven side injector launcher using the Combustion Light Gas Gun was analyzed by Witherspoon et al.[24] The basic thesis was that developing a modest velocity side injection launcher (about 4 km/s) would be much quicker and less expensive than developing a 7 km/s hydrogen launcher, and thus more likely to lead to a near term implementation. The trade-off was that larger on-board boosters would be required, leading to higher operating costs. This approach would indeed be cheaper for a modest number of launches, but would presumably eventually lose out to higher velocity launchers as the number of launches increased, but where that breakover occurs remains to be determined. Although technically feasible, a side injected CLGG system does not appear to be a viable candidate at this time unless the cost of the launch package (mainly the on-board booster) can be reduced significantly.

Jules Verne Launcher

Based in part on their experience with the SHARP 2SLGG experiments, Hunter and Cartland went on to design a family of launchers called the Jules Verne Launchers.[9,20] The proposed Jules Verne Launcher utilizes distributed injection of hydrogen. DARPA sponsored an analysis of the proposed launcher for a specific reference mission. An excellent detailed report of this effort is given in Reference 20.

The proposed launcher was designed to place a 113 kg payload (a small satellite) into a 700 km polar orbit. The total projectile launch mass was 682 kg. This included the on-board booster, the heat shield, the projectile structure and the satellite. Muzzle launch velocity was assumed to be 7 km/s, well within the capability demonstrated by the ELGG. Peak acceleration was arbitrarily limited to 2500 g, with an average acceleration of only 1640 g. For the given booster and payload size, the barrel diameter turned out to be 63.5 cm, and the barrel length 1.52 km. Not an unreasonable length given the launch velocity. Acceleration was controlled by using 15 hydrogen side injectors equally spaced 150 bore diameters apart (about 95 m).

The highest technical risk of the whole concept is the engineering of the side injectors. Each injector consisted of a high pressure hydrogen reservoir, a heat exchanger, and a fast acting valve opening into a slot in the barrel. The high pressure hydrogen (typically about 70 MPa) must pass quickly through the heat exchanger where it is heated to 1500K and expanded at high speed into the barrel through a 20 degree angled coupler. Requirements on the timing of valve opening and transporting the hydrogen gas into the barrel are very challenging. Their calculations showed the need for opening times of about 1 ms. Burst diaphragms, such as those used in the subscale 16mm ELGG tests, are not feasible for the throat openings of a few tens of centimeters needed here, and thus alternative very fast valves will need to be developed to satisfy this opening time. The valves must also be capable of precision timing and be reliable and repeatable.

The technical and economic analysis reported in the reference [20] indicates that the proposed Jules Verne launcher will probably work, but there are some challenging technical obstacles to overcome, and the end result in terms of projected cost per pound to orbit is a little disappointing, with only a factor of roughly two reduction. On the positive side, the cost per launch was estimated at $2.5M, which would be competitive with small rockets.

Discussion

Side injection has been successfully demonstrated at small scale and at high velocity, but not on the massive scale required for gun launching useful sized payloads into orbit. Unfortunately, scaling side injection up to large size involves more than just increasing the size of components. New technology needs to be developed, such as the very fast valves and durable, high temperature heat exchangers mentioned in the last section.

Part of the problem here is trying to force a technical solution where the laws of nature don’t exactly forbid a solution, but certainly discourage it, due primarily to the exponential pressure drop off of expanding gases. A solution can indeed be brute forced, but it may not be the best way to solve the problem, and in fact appears to have diminishing returns or much growth potential beyond 7 or 8 km/s, or apparent potential for much simplification.

To gain a feel for the scale of the problem, consider the following simple calculation for the proposed Jules Verne Launcher described above. For a 682 kg projectile (113 kg payload), launched at a constant average acceleration of 1640 g to 7 km/s, the kinetic energy of the launch package as a function of position is given by

$$E = \frac{1}{2}mv^2 = \frac{1}{2}m(2ax) = m \cdot a \cdot x$$

where m is mass, a is the constant acceleration, and x is position along the barrel. The energy input per unit length is given by the first derivative:

$$\frac{dE}{dx} = m \cdot a = (682\,kg)(1640 \cdot 9.8\,m/s^2) = 11.2\ MJ/m$$

To put this number into perspective, this is roughly equivalent to the muzzle energy of a 120mm Abrams tank gun being fired into the launch barrel every meter along the entire length of a 1520 m long barrel. In fact, though, the efficiency of the process has not been included, which would make the energy input per meter larger by a factor of about three at the breech end of the launch tube, and increasing to over 10 near the muzzle end.

Despite the difficulties of scaleup, side injection could still potentially make a sensible system if the technical challenges mentioned above can be solved, and if a very large number of launches could be supported. Of course, the same arguments have been made for rockets. However, modest scale side injection demonstrations could at least pave the way for more efficient, simpler, and less expensive GLTS systems, such as the Ram Accelerator to be discussed next.

THE RAM ACCELERATOR - A CONSTANT ACCELERATION LAUNCHER

The Ram Accelerator provides an elegant technique for achieving high velocity constant acceleration launch. If ever there was an ideal “gun” launcher for GLTS, it is the Ram Accelerator. It has been under development since 1983 at the University of Washington, where it was conceived by Hertzberg, Bruckner, and Bogdanoff [26] as a way around the problems of exponential pressure dropoff in breech fed guns, specifically for GLTS.[27-29]

The Ram Accelerator is not a gun in the normal sense. The basic operation of the Ram Accelerator is more analogous to an inverse ram jet, as illustrated in Figure 8. Instead of confining the combustion gases to a combustion chamber which then expand to push on the projectile with an ever decreasing base pressure, as described earlier by Equation (3), they are instead distributed throughout the entire volume of the launch tube. The projectile does not fly ahead of the propelling gases, but instead flies through them, basically “surfing” on a wave of high pressure combustion which immediately follows the projectile down the bore[30]. Combustion energy is released dynamically as the projectile flies through the gas, creating a localized region of high pressure immediately behind the projectile which travels along with the projectile as illustrated in Figure 9. The gas expends no energy accelerating itself, thus increasing efficiency dramatically, and locating the high pressure exactly where it is needed, i.e. right behind the projectile, instead of far back in a combustion chamber. The limitations of Equation (3) no longer apply, and velocities in excess of 10 km/s are theoretically possible.

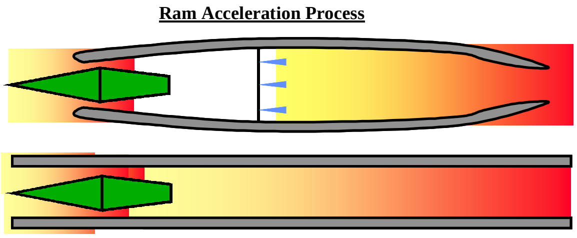

Figure 8 *The Ram Accelerator (lower) is analogous to an inverse ram jet (upper) in operation. The ram cowling becomes the launch tube, while the stationary ram centerbody becomes a moving projectile.*

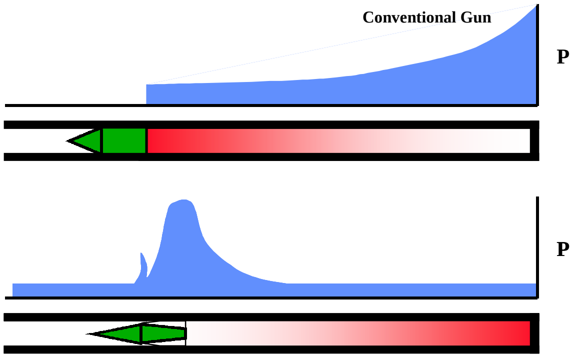

Figure 9 *The pressure profile of a ram accelerator (lower) travels along with the projectile, providing a nearly ideal constant acceleration, as opposed to the exponentially decaying pressure in a conventional gun (upper).*

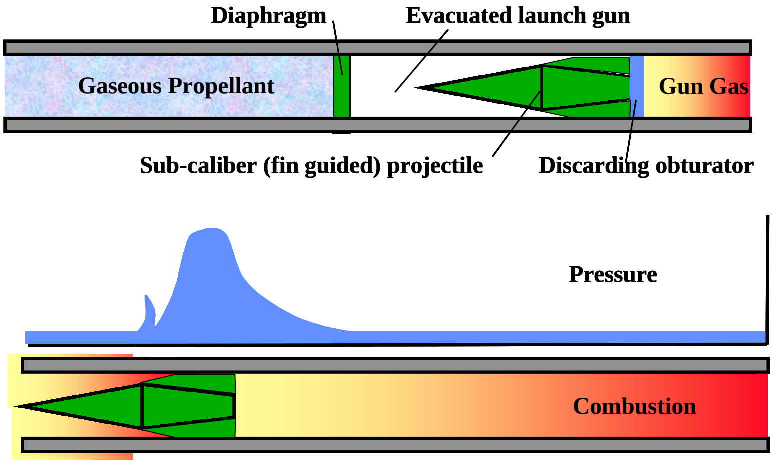

Figure 10 *In upper view, the injected projectile enters the ram acceleration section through a thin membrane, followed by establishment of ram action in the lower view.*

In order to initiate the ram process, the projectile must be pre-injected into the barrel at a supersonic velocity, typically about Mach 3 (which can be as low as 700 m/s). This is accomplished by using either a conventional powder gun, or even better, a light gas gun. The ram barrel contains a mix of combustible gases, typically containing various mixtures of oxygen, methane, hydrogen, and sometimes diluent gases, at a few to several tens of atmospheres. Thin diaphragms at each end contain the pressure. When the projectile is injected, it pierces the entrance diaphragm, discards the obdurator it needed for launch from the injector, and immediately establishes the flow patterns around the projectile necessary for propulsion. The shape of the projectile forces the premixed combustible gas out and through the small annular gap between the projectile body and the wall, where it is ignited by passage through a shock. Combustion energy is rapidly released, producing high pressure on the base of the projectile. This process is illustrated in Figure 10.

Operating Modes

There are a number of propulsive modes, depending primarily on the speed of the projectile relative to the Chapman-Jouguet (CJ) detonation speed of the combustible gas mix. The thermally choked mode operates at projectile velocities (typically Mach 2.5 to 4) below the CJ speed, the transdetonative mode at Mach 4 to 6 operates in a mixed mode from below to above the CJ speed, and the superdetonative mode at higher Mach numbers, above the CJ speed.[27,28]

The thermally choked mode has been the most tested and is shown in Figure 11. The thermally choked mode provides good thrust for Mach numbers between 2.5 and 4. In this mode the thrust decreases as the projectile velocity increases, so that to maintain good acceleration, it is necessary to tailor the composition of the premixed gas along the barrel to gradually transition to higher and higher gas sound speeds. This trick maintains the projectile Mach number in the

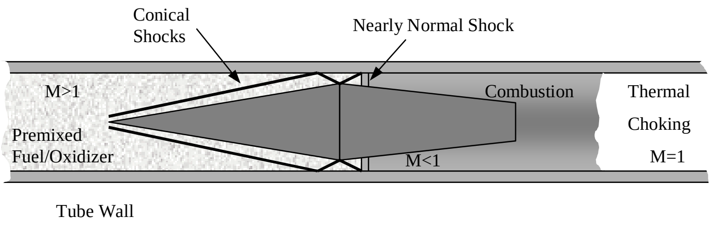

Figure 11 *The ram accelerator thermally choked propulsive mode. This mode works for Mach 3-5.*

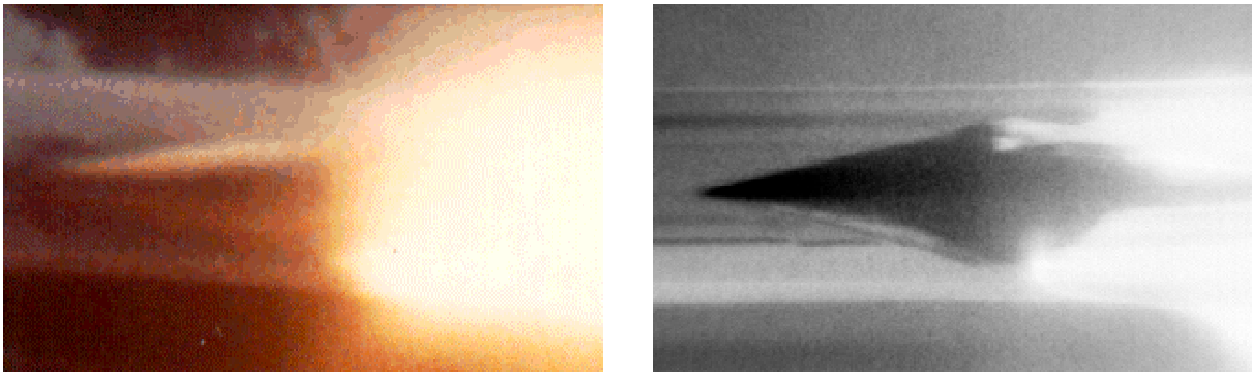

Figure 12 *Two views of a 120mm ram projectile in mid-flight through a clear plastic tube for visualization.*[34] *The hot high pressure region is clearly visible immediately behind the projectile as it travels to the left.*

desired 3 to 5 range. This is called staging and can be accomplished by simply separating the "stages" with thin sheets of mylar. This has the added advantage of reducing projectile aerodynamic heating, which is Mach number dependent.

The highest velocity results to date and the widest range of experimental conditions have been attained on the 38mm ram accelerator at the University of Washington[30], while the highest energy tests have been performed on the 120mm ram accelerator, the largest ram accelerator in the world, located at Aberdeen Proving Ground, and operated by UTRON, Inc. for the Navy.[31-33]

UW has successfully performed experimental investigations in all three propulsive modes, demonstrating the basic physics of the launcher. In particular, the thermally choked mode has received extensive testing using 60-90 gm projectiles in the range of Mach 2.5 to 4 at velocities of 0.7 to 2.7 km/s in tubes 16 m long. Tests of the other modes have been performed at velocities less than 2.7 km/s by adjusting the composition of the propellant mixtures to achieve up to Mach 8.5 conditions.

Scaling the ram accelerator to larger bore sizes such as the 120-mm accelerator shown in Figures 13-15

Figure 13 *120mm Ram Accelerator at Range 18, Aberdeen Proving Ground, MD. Ram barrel is 14.1 m long. The projectile is injected from the left using a standard 120mm powder gun.*

Figure 14 *Closeup of the 120mm cannon injector to ram accelerator barrel.*

Figure 15 *5 kg ram projectiles utilized in 120mm test shots.*

has been straightforward. In fact, issues associated with boundary layer build up choking flow channels and projectile integrity (strength) become more manageable at larger bore sizes. In the 120-mm accelerator shown below, velocities of just under 2 km/s were obtained launching 4 kg projectiles. Further progress in the 120-mm facility has been limited by funding, not technical issues.

Development Issues for GLTS

Velocity

The number one issue for now is demonstration of velocities in the 4-8 km/s range suitable for GLTS. To date, ram velocities have been limited by two factors - 1) projectile structural failure due to overheating, and 2) limited barrel lengths. The latter is straightforward to solve, but the first requires some development.

Projectile heating

Most experiments to date have utilized lightweight aluminum or magnesium projectiles in order to achieve the very high accelerations demanded by defense missions which funded the research. This has led to projectile structural failures as the projectiles heated during launch. Using higher temperature materials such as titanium and nickel alloys would solve most of this problem, and some recent steps in this direction have been taken at UW. Transpiration cooling and composition staging should solve the rest.

Potential for Pre-ignition

At the high velocities required for GLTS, bow shocks from the nosetip of the projectile, or even a very hot nosetip, could conceivably induce ignition of the combustible gas ahead of the projectile. If this were to occur, the ram acceleration would cease, and the projectile could even be damaged or destroyed by trying to fly through a long tube full of hot combusted gas. This potential problem can be reduced or eliminated by staging so that the projectile Mach number always remains relatively low, or by stratifying the gas in the radial direction, so that the molecularly heavy oxidizer is located in a thick boundary layer near the wall, while the core along the axis consists of pure low molecular weight hydrogen.[29] This also reduces projectile aerodynamic heating.

Staging - Controlling the Mach number

Maintaining the proper Mach number by adjusting the combustible gas mix along the tube length is relatively straightforward using thin replaceable mylar sheets. In the long run, it may be cheaper and operationally easier to use fast gate valves, but such devices would need to be developed.

Attractive Features for Application to GLTS

Assuming that higher velocity operation will indeed be achieved when better projectile materials are substituted, there are a number of compelling features of the Ram Accelerator which make a strong case for its application to GLTS:

A truly simple barrel.

In comparison to virtually all other GLTS systems, the barrel for ram accelerator is very simple. It is basically a steel barrel with ports to admit gas, and if needed, a few mylar diaphragms between barrel sections. No complex side injection systems, or high voltage copper rails, or coils are needed. Low peak pressures eliminate need the need for exotic high strength steels. All this translates to a low capital cost launcher.

Constant acceleration

Ram Accelerator is an inherently constant acceleration propulsion device through the entire length of the barrel. This leads to very low peak pressures in comparison to typical light gas guns, including the distributed side injection version.

Scaling

Scaling to large size is straightforward and, in fact, is of the key advantages of ram accelerator. As the projectile increases in size, the barrel size scales correspondingly, automatically storing more combustion energy in the premixed gas.

No hydrogen muzzle blast.

If operated with hydrogen/oxygen mixes, the only product is water, and large muzzle combustion plumes are eliminated entirely, making this environmentally benign. If methane is used, the main products are water and CO_2, again eliminating combustion plumes.

No timing issues

If passive mylar separator sheets are used between stages, then there are essentially no timing issues, and the entire launch sequence does not require any active control other than the initial start signal.

Low residual barrel pressure and temperature

This is a crucial issue for all light gas guns, since the barrel temperature must be kept well below its melting temperature. This limits the gas temperature in the distributed light gas gun, and thus its performance efficiency. For a given barrel location in the ram, peak temperature occurs for only a very short pulse as the projectile goes flying by. Only the projectile sees high temperatures for the whole sequence.

Minimal Recoil

The ram accelerator can be operated with essentially no recoil to absorb.

No expensive pulsed power supplies

No electrical pulsed power is required, and no heating system of any kind is required. Only requires simple pumps to prefill the barrel to a few hundred psi.

DISCUSSION

Reducing launch costs has proven to be a very difficult problem. Reusable rockets may ultimately be able to reduce costs a factor of 10 or more, but this isn't assured, and it may take decades. In the interim, Gun Launch to Space holds great promise for major reductions in the cost of orbiting acceleration insensitive payloads.

As things stand now, it is difficult to see why a commercial entity would invest in R&D for a GLTS system in order to launch a few dozen or even perhaps a few hundred satellites, until the technical risk has been reduced a lot further. It's less near term business risk to go with traditional launch systems. It is much easier to support development of a GLTS system to launch thousands or tens of thousands of bulk delivery payloads to orbit. GLTS makes most sense for delivering bulk materials such as fuel, water, building raw materials, or prepackaged components of large structures such as SSP. It then becomes essentially a pipeline to orbit of basically commodity type materials. Most such payloads are inherently gee tolerant and thus no significant penalty is paid to harden against high gees such as would be required for sophisticated satellites. There may indeed be a market for such sophisticated satellites but, developing a GLTS system to make a profit on only such payloads seems difficult. Some might disagree with this statement, but we feel that GLTS will make its mark mainly by delivering bulk payloads to orbit, perhaps with a few satellites along the way for good measure.

Before substantial private investment is likely, GLTS needs some technology development followed by a series of substantive system demonstrations to validate the technology and reduce the perceived technical and business risk. We have only discussed the launchers in this paper, but all system components need development work, the projectile and payloads, and on-orbit infrastructure, i.e. systems for handling and using all these payloads once they are in orbit.

The federal government can play a crucial role supporting technology development and ultimately supporting a major demonstration. The federal government, and DOD in particular, have a vested interest in maintaining a lead in GLTS technologies for its own needs, and can play a unique and critical role in supporting the technology development and demonstration experiments which reduce the risk to the point where private investment is attractive.

At the moment, side injection has the perceived edge because light gas guns have demonstrated the required velocity, but successful development of the required sub-components is by no means certain. By successful, we here mean specifically economically feasible for commercial operations. If the Ram Accelerator can demonstrate the same velocity, however, (assuming that the issue of pre-ignition and projectile structural failure are resolved satisfactorily), then we feel that it will immediately become the launcher of choice. because of its inherent simplicity and lower capital cost.

Does it make sense to invest substantial funds to develop the component technologies needed for doing side injection? Or does it make more sense to invest a modest amount quickly in a ram accelerator and find out definitively whether pre-ignition is indeed a problem or not. If it is not, then ram is the superior choice for development. Ram holds even greater promise, but is progressing more slowly due to very limited funding to date. Partly this has been due to the perceived difficulties in weaponizing the technology.

Despite the fact that ram accelerator has not yet produced velocities over 2.7 km/s, we maintain that ram accelerator is still the superior choice for GLTS. We base this on the elegant simplicity of the approach, the potential very low cost of the system, and the belief that the velocities attained to date are limited only by the choice of projectile materials used and the funding constrained short barrel lengths. We believe these difficulties are solvable, thus leading to a very attractive GLTS system readily scalable to virtually any size.

Although not “guns” in the traditional sense, it is worth noting that there are other non-traditional launch technologies that could play a role further in the future. Two in particular are the Slingatron[35], which is a mechanical analog to a cyclotron accelerator, which has been successfully demonstrated in the lab at tabletop size, and the other is the general class of beamed power launchers, primarily lasers[36] The beamed energy approach has the potential for low g launch, in principle including people. Slingatron would be a high g launcher subject to similar payload limitations as guns. Both of these technologies are in their early development phase, but bear watching for the future.

While millions of dollars continue to flow into railgun and ETC research with little or no hope for breakthrough performance gains after all these years, virtually none is directed toward a technology that could literally revolutionize low cost access to space and other defense applications. On the other hand, development of ram technology is accelerating in other countries, with programs underway in Europe, Japan, Brazil, China, and Korea. In the U.S., only two small experimental efforts are funded, the 38mm launcher at the University of Washington and the 120mm launcher operated by UTRON, Inc. in Manassas, VA. Both of these programs are currently funded by the Navy.

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