Launch to Space With an Electromagnetic Railgun

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***Abstract*—Many advances in electromagnetic (EM) railgun and power supply technology have been made in recent years. Laboratory experiments with railguns have demonstrated muzzle velocities of 2–3 km/s and muzzle energies $>$ 8 MJ. The extension of this technology to the muzzle velocities ($\geq$7500 m/s) and energies ($\geq$10 GJ) needed for the direct launch of payloads into orbit is very challenging, but may not be impossible. For launch to orbit, even long launchers ($>$1000 m) would need to operate at accelerations $>$ 1000 gees to reach the required velocities, so that it would only be possible to launch rugged payloads, such as fuel, water, and material. A railgun system concept is described here and technology development issues are identified. Estimated launch costs could be attractively low ($<$\$600/kg) compared with the Space Shuttle ($>$\$20 000/kg), provided that acceptable launch rates can be achieved. Further evaluations are needed to establish the technical and economic feasibility with confidence.**

***Index Terms*—Launch, railgun, space, system.**

I. Introduction

In the past 40 years, mankind has ventured into space using well-established rocket technology involving liquid fuels and/or solid propellants. This approach has the advantage for astronauts and fragile payloads that the rocket starts slowly from the surface of the Earth with its full fuel load, and, as the fuel is burned off, the altitude and speed increase. In addition to minimizing the aerodynamic and aerothermal loads, this provides relatively modest accelerations—maximum values of a few "gees" are used for human passengers. Because only a small fraction of the initial mass reaches orbit, rockets of substantial size are required to place tens of tons into near-Earth orbit.[1] Offsetting these remarkable successes is the very high cost of burning chemical fuel with a modest efficiency in a rocket engine to get out of the Earth's gravitational well. Present estimates are that it costs $>$\$20 000 to get one kilogram of material into orbit. Unless alternatives can be found, it seems likely that mankind's ventures into space will be limited to a few adventures that can only be undertaken by wealthy nations—the science-fiction writer's dream of colonizing the planets and stars may be unaffordable.

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[1]Saturn V was $>$3000 tons.

Proposed solutions fall into four general categories: better rocket propellants; the space elevator; gun launch from the Earth's surface; and laser launch. Although these options will not be discussed in detail, a few comments are appropriate. First, there appear to be no acceptable alternative rocket propellants that can offer substantial improvements compared with present choices. Second, although the space elevator seems to have great promise as a concept for the future, its practical realization awaits the development of a material that is strong enough to be able to carry its own weight (and that of the payloads it will lift) from the Earth's surface to geosynchronous orbit.[2] Third, estimates indicate that to launch payloads of less than a ton with a laser would require multigigawatt lasers far larger than any presently in existence.

Gun launch techniques date back to at least the time of Jules Verne. These techniques have the advantage that the launch mechanism remains on the Earth and does not have to be lifted into space, as with a rocket. If the launcher is sufficiently long, the acceleration can be reduced to a level that is compatible with present component technology, although the acceleration forces will not allow people or fragile payloads to be launched with feasible launcher lengths. Guns may therefore be limited to launching robust packages such as food, water, fuel, and replaceable components. This may be an important support function for the International Space Station (ISS) or other missions.

A disadvantage of gun launch is that the launch package has to leave the gun barrel at a very high velocity ($\sim$7500 m/s) through the Earth's atmosphere, leading to a very high aerothermal load on the projectile. The reentry vehicle community has successfully developed techniques to overcome this situation (when traveling in the reverse direction), and it seems possible that similar techniques can resolve this problem, either through the use of refractory or ablative nose materials or by evaporative cooling techniques. The mass of coolant required for this appears to be acceptable, as discussed below. The second concern for a gun is the size of the package that can be launched. Unless a very large gun can be built, the payload launched into orbit per launch will be a few hundred kilograms, which will require a large number of launches per year. For example, to provide 500 tons/year to orbit would require $\sim$2000 launches/year—a little over five per day on average. An infrastructure in space for handling this traffic and distributing the payloads will have to be created. Issues to be addressed will include decisions on handling or recycling the nonpayload components that reach orbit.

The parameters for a railgun system suitable for launch to space are discussed here. Parameters are given for a notional system that includes the projectile/launch package, railgun, and

[2]With further development, nanocarbon fiber technology could be this material.

pulsed power components. The nominal mission was to launch 1000 kg to 7.5 km/s.[3]

II. Gun Options

Several gun options are possible, as discussed below. Four criteria can be used to assess whether these concepts could be feasible for this mission: 1) a proven capability to achieve ∼7 km/s; 2) the likely extension of present capabilities to ∼7 km/s (if not already achieved); 3) recent relevant technical progress; and 4) investments by other programs in the same technology.

A. Electromagnetic Railguns

Some of the earliest references to electromagnetic (EM) accelerators mention their use for launch to space.[4] A few papers have discussed this possibility (e.g., [1], [2]), but most EM studies and technology development in recent years have been for military applications. A few laboratory experiments have achieved muzzle velocities in the range from 7 to 9 km/s with projectiles of a few grams, showing that no fundamental barriers to very high velocities exist in principle. Scaling up to the launch masses required for this application is a major issue, but may be an opportunity to develop new techniques that are not feasible in small-bore railguns. Other aspects of the railgun launcher and power supply system technology have progressed considerably in recent years. Pulsed power supply technology based on compact rotating machines has made considerable progress with the advent of high-strength carbon fiber composite structures, although a critical issue is how to achieve the extremely high power ratings needed to accelerate the payload to these high velocities. The capability to use existing or dedicated electrical utility supplies to power such a system, and the inherent controllability of an electrical system, are attractive. The cost of electricity for a launch will be negligible, as shown below. Barrel life is central to the successful economics for this system. A research program to address the issues involved in achieving long life is needed.

B. EM Coilguns

Coil-gun technology has the potential advantage that the EM forces on the projectile can be self-levitating so that the projectile need not physically contact the walls of the launch tube. If achievable at the velocities and payloads needed for launch to space, this would be an important benefit—eliminating a potential source of wear that would otherwise limit barrel life. However, to date, coilguns have not exceeded about 1 km/s [3]. A fundamental concern for coilguns is that the EM forces basically act in the radial direction in the launch tube, so that the projectile is "squeezed" in the radial direction to provide acceleration in the axial (launch) direction. Very high switching voltages are necessary to rapidly energize the drive coils while the projectile package is nearby. The coilgun does not offer a proven advantage over the railgun at present.

[3]These are arbitrary values—further studies are required to determine the optimum values for this application.

[4]Dr. Richard A. Marshall notes that Rynin (1929) states that "the Austrian, Heft, in 1895 proposed a solenoid gun for launching interplanetary spaceships."

C. Electrothermal–Chemical (ETC) Guns

Military users are developing the ETC gun, in which electrical energy assists the ignition and burning of a high-density conventional gun propellant (e.g., see [4]). The advantage of this approach for the military is that conventional propellants and gun barrels can be used. However, ETC will not provide the muzzle velocities needed for launch to space.

D. Light Gas Guns

The ultimate performance of conventional guns can be achieved by using hydrogen as the working gas. Guns of this type are used in impact research laboratories to achieve velocities up to 10 km/s with small projectiles. Hunter and Hyde [5] proposed scaling up such a system with a two-stage system fueled by methane–air combustion. The pump piston mass would be 3600 tons for a launch package of 2 tons, and about 150 tons of the methane/air mixture would be consumed per shot. Although such a system may be feasible, it would suffer from a nonuniform acceleration and barrel wear. Hunter and Hyde propose to reduce wear by lowering the peak gun pressure to about 550 MPa. The muzzle blast will also be a very significant noise issue as a result of the leakage of hydrogen after the projectile.

E. RAM Accelerator

The RAM accelerator [6] uses a specially shaped projectile that is launched into a gun tube prefilled with a gaseous propellant mixture to cause shock compression and combustion of the propellant. This creates a traveling pressure zone that accelerates the projectile. Velocities up to 2.7 km/s have been achieved, but there is no substantial investment in this technology at present. To achieve ∼7 km/s, a series of 15 separately pumped explosive gas regions would be needed, according to Knowlen and Bruckner [7]. Half of these regions are thermally choked and half are super-detonative, each with a different fill mixture or pressure. Separating these regions may require rapid-acting valves that are quickly activated as the projectile accelerates through the tube. Refilling all of these compartments every few hours—as required for 2000 launches per year—seems to present formidable difficulties, and this approach does not seem preferable to the railgun.

F. Blast Wave Accelerator

The sequential detonation of high explosives to reach high velocities has been explored for many years. The blast wave accelerator, suggested by Kryukov [8] and investigated recently by Wilson and Tan [9], uses rings of high explosive inside a long barrel that are sequentially detonated to produce acceleration pressures on a projectile. Wilson and Tan [9] showed that 28 700 kg of high explosive would be needed to launch a 1000-kg projectile to 8 km/s. The possibility of rep-rating such a system to provide a shot every few hours seems remote, and the system seems impractical compared with a railgun that uses utility electrical power.

G. Slingatron

The "hula hoop" concept for accelerating a particle inside a hollow ring has been taken to an extreme level with the Slingatron concept [10], [11]. Although no significant velocities have yet been achieved, the construction of a large spiral system weighing thousands of tons that would be vibrated at 1.6 Hz to impart momentum to the launch body has been advocated [12]. At the appropriate instant, the body would be ejected from the launcher. The accelerating force is imparted to the projectile by the mechanical push provided by the inclined wall of the accelerating tube on the rear edge of the projectile. It is difficult to see how a practical projectile can be accelerated without considerable local forces and wear.

H. Lasers

Several concepts for accelerating vehicles into space using a high-power ground-based laser have been discussed (e.g., [13]). If the vehicle carries a liquid or solid propellant, a continuous or pulsed laser can heat and/or ignite the propellant to produce thrust. The capability of pulsed high-power lasers to accelerate lightweight "flying saucer-like" objects up to tens of meters from the ground has been demonstrated recently. This results from heating the air layer underneath the lightweight vehicle plus ablation from the underside by the laser pulse, so that the resulting blast reaction provides the accelerating force. With suitable collimation of the beam and if adaptive optics can minimize atmospheric distortion, the laser system could operate over long distances. Scaling up this approach to multikilogram payload sizes will require lasers having power ratings very much greater than currently available. Kare [14] has estimated that lasers of 50 000 MW, costing tens of billions of dollars, will be required for launch to space. This concept seems so far in the future that it has not been considered further in these studies.

I. Gun Choice

Of the options investigated, only EM railguns seem worthy of further study for this application. This choice was made on the basis that:

- they have already achieved 7 km/s at small scale, and 9 MJ at 2–3 km/s;
- significant development is being funded for military applications;
- they offer the possibility of achieving the muzzle velocities and energies required;
- the potential cost savings seem significant based on our estimates.

Methods of accelerating large masses in large bore railguns will need to be developed, and some concepts are suggested here.

III. RAILGUN LAUNCH-TO-SPACE CONCEPT

A civilian launch-to-space system would be a fixed installation, preferably located at a launch site near the equator and at high altitude. Since there is no requirement for mobility or slewing, the launcher can be of a degree of sophistication that is optimized for this application, rather than the simpler type used for tactical military missions. The energy demands of a high launch mass make it important to maximize the electrical efficiency of the launcher. This can be achieved by modifying the approaches used in military railguns so as to:

1) use *distributed energy supplies* to feed electrical power into the launcher throughout the launch process, rather than by feeding all the electricity from the gun breech;
2) *augment the magnetic field* that permeates the launcher bore by using pulsed external magnets in their vicinity.

These two aspects are combined in the *UTSTAR* concept [15] described below. The following steps illustrate the launch sequence and components.

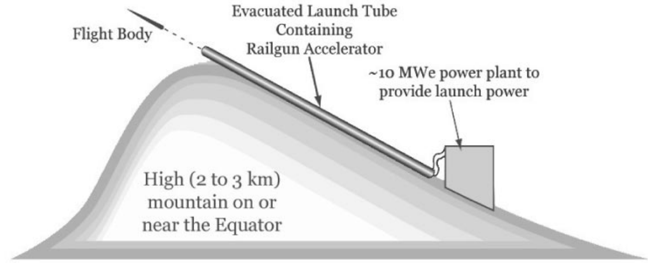

Fig. 1. The preferred launch site layout (after Gasner [16]).

A. Launch Site

The ideal launch site would be situated on or near the equator and at the highest possible altitude. The EM launcher will be fixed and oriented so as to maximize the benefit of the contribution of the Earth's rotation to the launch velocity. A convenient arrangement would be on the side of, or embedded into, a suitable mountain, as shown in Fig. 1 [16]. Having the launch site at high altitude reduces the aerothermal heating load on the flight vehicle nosetip: 2000 m above sea level was assumed in this study. The launch site should also be chosen so that launch noise will not be an issue and so that items disposed after launch will not pose a downrange safety hazard.

B. Launcher

Military railguns designed for ordnance applications are not well matched to the launch-to-space mission. For example, military railguns are usually fed with current from the gun breech. This is convenient for a barrel of moderate length where slewing is needed for target acquisition, but it is unsuitable for a very long launcher because a single current feed point results in high resistive losses. Ordnance railguns also need to be lightweight and are therefore designed with a simple two-rail configuration, thereby accepting the efficiency penalty of using only the self-magnetic field of the propulsive current.

In contrast, the *UTSTAR* concept [15] uses saddle-back augmenting magnets distributed along the launcher (see Fig. 2) to increase the magnetic field in the bore of the launcher only in the vicinity of the launch package. The augmenting magnets produce a magnetic field similar in strength to that produced by the main current. This allows the rail current to be reduced while providing the accelerating force, which is advantageous for the power supply. Also, by reducing ohmic resistive losses, it increases the efficiency of the launch process. Nevertheless, a high current is still required. For one case in this study, it was

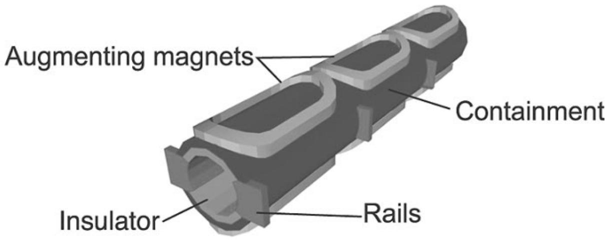

Fig. 2. Three *UTSTAR* modules.

~6.6 MA. For comparison, laboratory railguns have demonstrated muzzle energies of ~9 MJ with 3.4 MA [17].

The augmenting magnets are only energized when the launch package is in the vicinity of the launch package so that electrical energy is expended to create the augmenting field only when the launch package is nearby, rather than filling the entire launcher bore with magnetic field. The magnets are energized sequentially at a rate corresponding to the projectile velocity so that a traveling wave is created that envelops the armature as it accelerates along the launcher. This distributed feed arrangement also ensures that minimum magnetic energy is left in the barrel at projectile launch.[5] A further advantage is that the multiple feeds arranged along the launcher will provide a distributed (staged) power input. This ensures increased efficiency compared with military railguns because the resistive losses associated with current transfer along the rails from the power leads to the armature will be reduced. This is much more important for this mission than for most military applications because the launcher length here is so long that breech fed arrangements would be prohibitively inefficient [18].

The required current and the launch package acceleration are strongly dependent on the barrel length. Longer barrels are more expensive but enable lower currents and accelerations to be used to achieve a specified muzzle velocity. The extended *UTSTAR* launcher concept is shown in Fig. 3. For this study, the acceleration was limited to a modest value (by ordnance standards) of ~2000 gees by using a barrel length of 1600 m. The cost of this long barrel and its associated infrastructure will be offset by the easier operating conditions and the reduced need for maintenance—although the optimum choices depend on a more detailed economic evaluation.

The operating risks will also be reduced compared with ordnance applications by using a modest rail current density of ~6 kA/mm. This is ~15% of the value used for military barrels—thereby reducing heating and stresses in the barrel.[6] No attempt has been made to optimize the operating conditions and risks during this study since the necessary database does not exist.

A high efficiency can be achieved with a long *UTSTAR* system, since energy is fed into each stage only when the projectile is present: 80% was assumed here, and even higher values may be possible. Thus, for a muzzle energy of 35 GJ (1250 kg to 7.5 km/s) the input energy per launch would be about 44 GJ.[7]

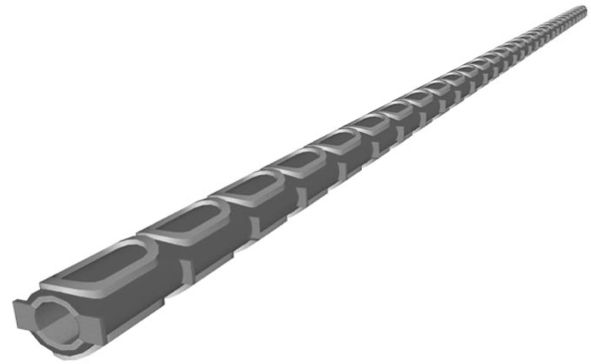

Fig. 3. A long *UTSTAR* launcher section.

At launch, the projectile will be injected into the launcher breech at ~few 100 m/s,[8] and nearby magnets will be energized. Simultaneously, a pulse of high current fed to the rails will initiate the railgun acceleration process. As the launch package accelerates, the breech magnets will be powered down, and magnets further down the launcher will be sequentially energized with current pulses that are timed to maintain spatial synchronicity with the accelerating projectile. Similarly, current will be fed into each section of the launcher from the pulsed power supplies that are distributed along the launcher. The launch velocity will be optimized for the vehicle characteristics. This study has evaluated muzzle velocities in the range from 5500 to 9500 m/s.

C. Electrical Power Input

Having assessed a variety of available energy and power technologies in prior studies [19], our present recommendation is that the energy required for this application would best be provided by multiple high-speed rotating electrical generators. Pulsed generators are being developed for other applications, and significant progress has been made in recent years. Of the options available, the cylindrical drum topology shown in Fig. 4 appears to be the most promising.

Compact generators of this type use high-strength carbon fiber structures that rotate at very high speeds. They provide an ac output that needs to be rectified for application to the dc railgun. For a *UTSTAR* launcher, multiple machines distributed along the launcher would provide the most efficient system. For this study, 100 machines were arbitrarily assumed. Launch to space, in contrast with most military missions, is a relatively infrequent and prescheduled event. Consequently, it will only be necessary for each machine to store the inertial energy required for a single launch—between launches, the energy will be replenished with electric motors that spin up the generator rotors. A spin-up time of a couple of hours would be appropriate for the launch rates assumed in this study, with a

[5]In a simple breech-fed railgun operating at constant current, the magnetic energy left in the barrel at projectile exit equals the muzzle kinetic energy, so that the launch efficiency is limited to a maximum of 50%. In contrast, efficiencies of 80% to 90% are expected for the *UTSTAR* launcher in this application.

[6]Copper rails reach the melting temperature at 44 kA/mm and tungsten at 56 kA/mm.

[7]With energy recovery, not all of this energy may be used—some could be returned to the energy stores.

[8]Preinjection reduces barrel damage in the breech region and improves barrel life.

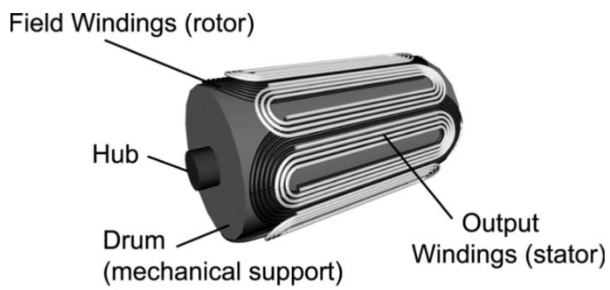

Fig. 4. Pulsed alternator topology.

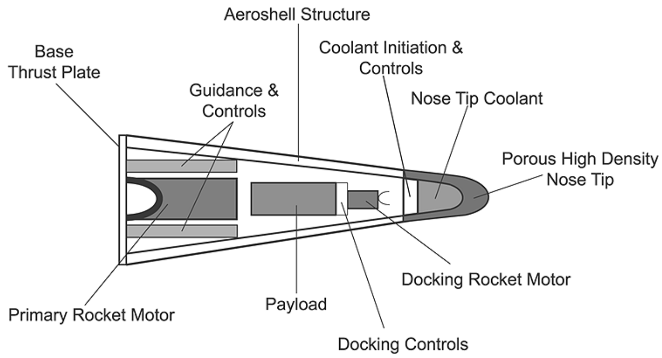

Fig. 5. Flight body concept.

relatively modest power input (<10 MW) that could either be taken from an existing utility grid or from a dedicated site supply. Some power conditioning will be needed between the rotating generators and the launcher to couple the electrical energy effectively and efficiently, especially near the muzzle where the power ratings are very high. Future pulsed power technologies may offer some advantages compared with rotating machines, and the Institute for Advanced Technology (IAT) continues to assess alternative technologies, such as battery-inductor systems.

D. Launch Package

We have assumed that the payload would be launched in a slender Rodman cone. For this study, a 4° half-angle cone was assumed, although other angles may also be considered [16]. A sketch of the launch package concept is shown in Fig. 5, and the arrangement in the railgun launcher is shown in Fig. 6. A nominal mass breakdown for the subcomponents is given in Table I for an assumed total launch mass of 1250 kg. For these calculations, a launch flight body mass of 1000 kg was used. For an average package density of 1000 kg/m^3, the package will be ∼6 m long with a base diameter of ∼1 m. The combined mass of the armature, baseplate, and front scoops is estimated as 25% of the aeropackage mass, based on calculations of the action coefficient for the armature plus engineering estimates. Using the base-push configuration with a muzzle velocity of 7.5 km/s, the base pressure would be ∼55 MPa (∼8 kpsi).

The proposed armature is a hybrid in which a lightweight fiber-reinforced aluminum metallic section is used to transfer the current across most of the bore gap [20]. At the edges of the armature, the current interface with the rails will be provided by a plasma. The armature design will ensure that the current density in the plasma will be at an acceptable level for good operation with low losses. The development of a successful armature of this type for use at these velocities is likely to require significant research and development.

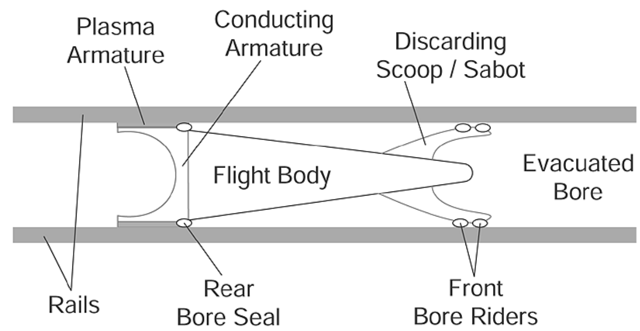

Fig. 6. Launch package concept.

TABLE I
LAUNCH PACKAGE COMPONENTS

Component	Mass (kg)
Payload Docking thruster with fuel	300
Orbit changing rocket motor and fuel Controls and electronics Aeroshell and structure Nosetip and cooling	700
Baseplate Aerodynamic front scoops and bore riders Hybrid armature	250
Total	1250

E. Post-Launch Sequence

After launch, a sequence of events will lead to the successive disposal of most of the launch package components (i.e., the armature, base plate, and sabot/front scoops), until only the slender low-drag shape-stable Rodman cone aeroshell structure (Fig. 5) will remain to transit the atmosphere and reach orbit. This will minimize the energy (fuel) required by the orbit-changing rocket motor—thereby maximizing the payload fraction. The most critical concern during this phase of the flight is aerothermal heating of the nosetip, which will be very extreme at these launch velocities even though the sensible atmosphere will be transited in only a few seconds. Following Palmer and Dabiri [2], Martin's work [21] was used to estimate the amount of coolant required to absorb the nosetip heat flux.[9] This study indicates that this problem is soluble in principle with an acceptable coolant mass penalty.

F. Above the Atmosphere and Into Orbit

Having transited the sensible atmosphere, the nosetip, and any of its remaining coolant plus the coolant control system, may be safely jettisoned, together with the aeroshell and much of the remaining structure.[10] The remaining components (payload, rocket motors, and controls) will continue on a ballistic

[9]For conservatism, a factor of safety of 50% was applied to Martin's estimates.

[10]The possibility of maneuvering in the atmosphere to reduce the rocket impulse required to achieve orbital velocity, as suggested by Gasner [16], was not evaluated here.

trajectory to the apogee of the orbit that can be achieved based on the initial launch velocity.[11] At the apogee, the larger rocket motor will be fired to increase the payload to the orbital velocity at that altitude. For this study, a conventional fuel-specific impulse $(I_{\rm sp})$ of 250 s was assumed. The details of the rocket burn were not addressed in this study, but the results are expected to be accurate to within a few percent. No allowance was made for any translational thrust needed in orbit, although this will eventually need to be addressed.[12]

G. Docking

The final stage of the process will be to use small thrusters to rendezvous the payload to a docking station where the payload can be removed and transferred to the recipients—ISS or other. The docking point could be the low end of a space tether [22]. Once the payload is removed, the disposition of the vehicle structure needs to be addressed. If the cost of getting into near-Earth orbit can be substantially reduced, the items could be disposed of as trash. However, it would seem better on all counts, including safety, to make use of the components in orbit—even as raw materials. After all, having 2000 sets of payload structures, rocket motors, and thrusters as an accessible resource every year should be of value, provided it can be managed successfully.

IV. System Operating Parameters

To provide some insight into the system parameters, several component analyses have been undertaken using simple codes developed at IAT. These separate codes, which do not yet provide an end-to-end evaluation of a launch-to-space system,[13] comprise the following.

1) A calculation that links the muzzle energy requirements for an augmented launcher with the power input.
2) A calculation that estimates the parameters of a rotating machine system. This includes an estimate of the machine sizes and of the prime input power for a specified firing rate.
3) A calculation that estimates the parameters needed to get the launch package from the launcher muzzle to payload in a near-Earth orbit. Aerothermal heating and the mass of coolant required are calculated, as well as the parameters of the rocket motor [23].

A short discussion of the results obtained with these codes follows.

A. Pulsed Power

For this study, it was arbitrarily assumed that 100 pulsed high-speed rotating electrical generators would power the *UTSTAR* launcher stages. For an assumed power system delivery efficiency of 90%, the input energy per launch will be ~50 GJ. Although inertial energy storage in high-speed rotors is very effective, it is not possible to extract all of the inertial energy because the machine output voltage droops as the rotor speed falls, thereby limiting the energy transfer process. To ensure that the machine can deliver an adequate voltage during the output pulse, the rotor of each machine needs to have sufficient inertia. It was assumed here that each machine rotor would store 2.5 times more energy than it delivers in each pulse. Each of the 100 machines assumed here would therefore need to store $50 \times 2.5/100 = 1.25$ GJ. With a rim rotor configuration operating at stress levels that are currently being considered in modern development programs, a future combined flywheel–alternator may operate at tip speeds as high as 750 m/s on the generator portion and 1100 m/s on the flywheel section, so that the rotor mass will be about 3.3 tons and the total machine mass less than 10 tons. For a peak operating magnetic field in the machine of 5 T, the rotor of a typical machine would be about 3 m in diameter and about 6 m in length to deliver a power of about 200 GW.[14] These would be substantial machines, but they are smaller than those used in utility power stations. In the later stages of the launch, it may be necessary to employ other pulse power technologies, since the voltage and power rating will become extremely high. This is because the back-electromotive force generated by the railgun increases with velocity and near the muzzle will reach a value of about 50 kV. Combined with the high-current input, this will necessitate an energy input of over 300 GW [24]. Since rotating generators may not be able to develop this power directly, an intermediate pulse compression stage may be needed. Further studies are needed to assess the best approach, including whether all of the rotating machines would have identical designs (but different pulse compression stages) or whether groups of various designs might be required.

TABLE II
UTSTAR Launcher Parameters

Parameter	Value
Launch mass (kg)	1250
Armature mass (kg) (50% margin)	156
Sabot structure (kg) (estimated)	94
Aerobody mass (kg)	1000
Muzzle velocity (m/s)	7500
Muzzle energy (GJ)	35
Launcher length (m)	1600
Bore height (m)	1.1
Average acceleration (m/s^2)	17,600
Maximum acceleration (m/s^2)	19,500
Launch time (s)	0.43
Inductance gradient (μH/m)	1.0
Linear current density (MA/m)	6.8
Average current (MA)	6.6
Maximum back emf (kV)	50
Launcher efficiency	0.8
Energy input (GJ)	44

B. Launcher

Estimates for the performance of a typical *UTSTAR* concept are given in Table II. This is one of many cases that have been

[11]Less the aerodynamic drag from the atmospheric transit.

[12]This study assumed that the launch would be made from 30° latitude into a polar orbit. This may be unduly pessimistic. Jones [22] has suggested that an equatorial orbit would be used to take maximum advantage of the Earth's velocity and to enhance the opportunity for second or nth orbit retrieval.

[13]The development of a linked code of this type is highly recommended for the future.

[14]The average power level is about 116 GW and the peak power about 330 GW at the muzzle.

TABLE III
TOTAL ENERGY (GJ) REQUIRED TO LAUNCH 500 TONS OF SUPPLIES INTO ORBIT PER YEAR

Launch velocity (km/s)	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
Aero mass (kg)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Launch mass (kg)	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250
Launch energy (GJ)	18.91	22.50	26.41	30.63	35.16	40.00	45.16	50.63	56.41
Breech energy (GJ)	23.63	28.13	33.01	38.28	43.95	50.00	56.45	63.28	70.51
Payload to orbit (kg)	51.29	94.18	142.53	196.44	254.16	314.01	367.99	413.54	437.94
Orbit height (km)	212	264	332	415	544	581	572.5	596	511
Launch angle (deg)	19.5	19.0	18.5	17.9	17.5	15.5	13.225	11.5	9.5
No. launches for 1 tonne in orbit	19.5	10.6	7.0	5.1	3.9	3.2	2.7	2.4	2.3
No. launches for 500 t. in orbit	9,748	5,309	3,508	2,545	1,967	1,592	1,359	1,209	1,142
Launch velocity (km/s)	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
Total energy for 500 tonnes (GJ)	230,384	149,315	115,793	97,438	86,452	79,615	76,695	76,512	80,499

analyzed and is not an optimized system solution, but it provides parameters that can be used to assess the needs of the power supply. For this case, a 1600-m launcher was assumed that had a low-projectile acceleration. This reduces system risk, although at the expense of a greater investment in the launcher. Future optimizations will need to address this issue. However, the results appear to show that the system parameters fall within the bounds of acceptability, with a caveat relating to the power input, as discussed below.

C. Launch to Orbit

Using the code developed by Erengil [23] (which is based on [2]), a series of calculations was performed to assess the tradeoff between launch velocity and energy requirements. This takes into account that as the launch velocity is increased, the energy input has to increase correspondingly, but the amount of rocket fuel required to circularize the orbit decreases, so that the payload increases and fewer launches are needed for a given total mass delivered into space. Details of the calculations are given in Table III, and the results are shown graphically in Fig. 7. The results show that launching at about 9 km/s is the minimum energetically, but that launching at a lower velocity of 7.5 km/s has only ∼13% energy penalty. Clearly, factors other than energy must ultimately be considered in setting the system parameters—chiefly technical feasibility and cost—but this calculation gives some indication of one of the issues involved.

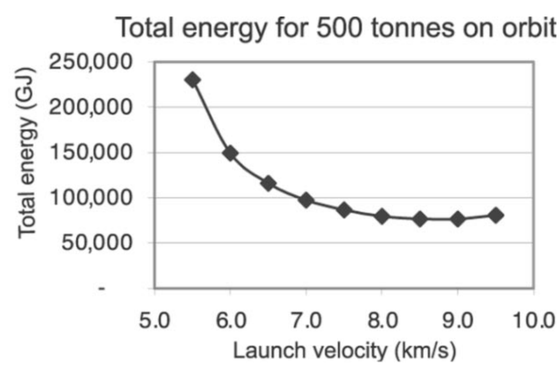

Fig. 7. Variation of total launch energy with launch velocity.

V. COST ESTIMATES

If the technical feasibility of the railgun as a launch-to-space concept can be proven, the next step will be to estimate the financial viability. Unless the railgun has prospects for considerably lower cost than present or competitive techniques, it will most likely not be of interest to NASA. The cost of launching mass to orbit has several components, including the cost of the launch package; the cost of the electrical power for the launch; the cost of operations; and the amortized cost of the capital equipment. Each of these costs is discussed briefly below. However, because we have little insight into items 1) and 3), most attention is given to items 2) and 4). Taking item 4) first, Table IV shows estimated values for each of the railgun launcher components. These estimates assume that reasonable future developments will occur in other funded programs.

The switching estimates are based on scaling up the costs of large diameter silicon thyristors that now can be purchased from commercial sources. There is a good likelihood that, by the time this concept comes to fruition, the introduction of silicon carbide or diamond switches will substantially reduce these costs, especially in the quantities needed here. Similarly, although the generators needed here are larger than needed for other applica-

TABLE IV
CAPITAL COST ESTIMATE

Component	Cost per unit	No. units	Total component cost
AC generators	$5M	100	$500M
Switching	$1.5M	100	$150M
Barrel	$0.1M/m	1600 m	$160M
Pulsed magnets	$1.5M	100	$160M
Busbars & structure			$100M
Civil engineering			$250M
Total			$1320M

tions, they are within the same range. Thus, it seems likely that these costs are likely to be an upper bound to the range of capital investment needed. The total cost is comparable to that for a new Orbiter vehicle.

Assessing the contribution of this cost to each launch requires an estimate of the equipment lifetime. The results discussed earlier show that ∼250 kg of payload may be placed in orbit for each 1250 kg launched. Thus, getting 500 tons of payload into orbit each year would require ∼2000 launches per year.[15] A lifetime of five years has been used as the goal for this equipment—that is, 10 000 launches. This assumption seems quite feasible for the rotating machinery, but the launch tube is more difficult to estimate. No experiments have yet been conducted that have measured the life of barrel components at this level.

The initial goal for a high-pressure high current ordnance gun is hundreds of shots, but this barrel is designed for much lower operating pressures, albeit higher velocities. Clearly, this is an area where further work is necessary. Nevertheless, using this assumption for the lifetime between total replacement or major refurbishment, the contribution of the capital cost of the facility per kilogram in orbit = $1320 M/(10 000 × 250) = $528/kg. This is an attractively small number compared with the shuttle cost (2.4%).

The cost of electrical power can easily be estimated. For an energy input per shot of 50 GJ (=13.9 MWh) at a typical cost of 8¢/kWh, the total cost is about $1100—which is negligible compared with other factors.

In summary, the two cost factors that have been estimated look attractive. The other two major items need further investigation but seem unlikely to alter these conclusions. However, embedded in these items are other factors that require careful evaluation before this concept can be considered practical, including:

1) the choice of a site—preferably equatorial and at high altitude—that will be safe;
2) the effect of jettisoned items—such as armatures—on down-range safety;
3) the safe disposition (preferably the recycling) of orbit circularization components before or after delivery of the payload to the customer location;
4) a hazard analysis for an aborted/reduced velocity launch.

[15]This is eight launches per day for 250 operating days or 5.5 launches per day for 365 days.

VI. CONCLUSION

The focus for this study was to undertake a first level evaluation of an EM railgun that could perform a direct launch to space from the surface of the Earth. The study showed that there do not appear to be any fundamental barriers that would make such a system impossible, although technological advances will need to be achieved in several areas, as discussed below. One important caveat to note is that no attention was given in this study to the considerable issues of flight body aerothermodynamic heating, projectile guidance, and orbit circularization and docking. The design of the sabot/armature for this application will need advances compared with ordnance applications because of the much higher muzzle velocity. Given the large bore diameter, a hybrid plasma–solid armature concept seems most likely to succeed [20]. A further area of major concern is that of the power delivery to the barrel, since the instantaneous power required will become very large as the projectile nears the muzzle of the barrel.

A substantial development program will be required to address these issues, but this will not need to be on the scale of the Apollo program or the Space Shuttle system. The result of a successful program would be substantially reduced costs for shipping material into space and support for manned Mars and other interplanetary missions. The development of a moon-based system for the supply of material would be easier than launch from the surface of the Earth, and an asteroid-based system would be even easier. As near-term "off-ramps" on the way to developing such a system, NASA could take credit for developing techniques for the hypersonic launch of test vehicles in a laboratory situation that could greatly reduce the cost of flight testing.

VII. RECOMMENDATIONS FOR RESEARCH

Before a railgun launch to space system could be considered, a substantial prior development program will need to address many issues, some of which are discussed below. It is important to note that methods of accelerating large masses in large bore railguns will need to be developed for this application. This development will most likely have to be funded by NASA, since no other mission would have these requirements.

A. Railgun Launch to >7 km/s

The most challenging technical issue will be the development of railguns capable of launching large projectiles to >7 km/s with acceptable lifetimes. No other mission needs this capability at present.[16] The first requirement for this research will be to construct a facility that is capable of providing the energy needed to achieve such launches. Even a scaled model would have substantial energy requirements: 10 kg at 7 km/s is a muzzle energy of 250 MJ, and with a launcher efficiency of 80%, an energy input ∼300 MJ would be required. This is comparable to the energy obtained from capacitor modules for the U.S. National Ignition Facility for laser fusion research. As

[16]With the possible exception of an undefined ultralong-range projectile launch for the military.

discussed above, rotating machines may be preferred for this application.

The most difficult aspect of this effort may be obtaining the support to build the facility that will do the research. Unless funding agencies can be persuaded that there is a reasonable chance of success, they may be unwilling to make the necessary investments. The best strategy would be to make staged investments that are dependent upon technical success, such as increasing velocities.

B. Hybrid Armature

A critical aspect of the research will be to develop the hybrid armature concept into a practical operating system for the velocities of interest. The advantage of conducting such research at masses considerably higher than present experiments is that it will be possible to incorporate substantial instrumentation and data transmission packages on-board the projectile. This will allow useful data to be telemetered back to recording and analysis equipment. The small projectile packages used in present research do not allow significant data collection.

C. UTSTAR Launcher

The *UTSTAR* concept relies on transiently inputting energy to the accelerating rails as well as the pulsed augmenting magnets. Strategies for optimizing and controlling the energy flow need to be developed [24]. The Thunderbolt project [25] was intended to study such issues but ended before that could be accomplished. Some development of two key components of the launch system—the pulsed augmenting magnets and the pulsed alternators to power the launcher—is taking place in separately funded programs for other purposes. However, it is necessary to identify the needs for this application and apply dedicated efforts to address those needs.

D. Aeroshell

Although the simple thermal calculations used here indicate that it should be feasible, the design of an aeroshell that can successfully transit the atmosphere at >7 km/s represents a substantial challenge that will require advanced materials and cooling techniques to be developed. Within the aeroshell, the various components that comprise the payload, rocket motor, docking motor, and controls need to be integrated into a compact volume that maximizes the payload fraction. Recent advances in miniaturized and ruggedized components should ensure that railgun-launched rounds will definitely be practical at the modest acceleration levels assumed here.

E. Overall System

It is strongly recommended that the present study be repeated in more detail and extended in scope. Although the focus has been on addressing the EM launcher system, it is clear that the flight of the projectile after launch can have a major impact on the launch system that needs to be considered. One important issue is the possibility of aerodynamically maneuvering the projectile in the upper atmosphere after launch to provide a significant horizontal velocity component, as suggested by Gasner [16]. If feasible, this could reduce the ΔV that has to be provided by the rocket motor and hence can increase the useful payload. It also has an impact on the optimization of the launch angle and velocity, and, hence, on the launcher. Jones [22] has suggested that rendezvous and docking with a tether at a lower altitude than LEO might permit the rocket motor and launch requirements to be eased.

The disposition of the larger rocket motor and associated structure after orbit velocity has been achieved requires consideration. One option would be to use the last of the fuel on board to de-orbit the rocket motor and associated components to burn up in the atmosphere. On the other hand, having used valuable energy to get the equipment into orbit, it would be preferable to collect and utilize these components, provided they can be collected safely.

F. Cost

A necessary condition to start a development program for this system is that it must have a competitive cost for putting payload in orbit. Only a portion of the total cost has been assessed in this study since we do not have the expertise to accurately estimate items such as launch costs. The focus has therefore been on the capital cost of the system and the power costs. The estimated system cost of ~$1.3B and a component life of 10 000 launches without replacement yields a cost of about $530/kg into orbit. It is important to note that this does not include the cost of the vehicle itself or operational costs on the Earth or in space, and these items need to be estimated. We assume that NASA will develop concepts for collecting and distributing the payload in orbit.

G. Alternate Missions

This study evaluated direct launch from the surface of the Earth into LEO. Although several significant technical advances need to be achieved to accomplish this, the benefits seem attractive. Either as an alternative, or as a strategy for the development of the technology in steps that have useful off-ramps, it may be worth considering the development of a moon-based launch system for which the launch velocity requirements would be much less stringent (about 2.5 km/s). Using resources available on the moon, this could serve as the forward base for sending material to Mars in support of a manned mission.[17] A system of this type would have muzzle velocity requirements similar to those for a long-range artillery system. It is therefore possible that a common funding base might be used to construct an experimental test and demonstration facility.

Another alternative would be to locate a system of this type on the International Space Station with the objective of resupply for the Mars Mission or for other interplanetary missions.

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[17] I am indebted to Dr. Hans Mark for this suggestion.

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