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Electromagnetic Railgun Launchers: Direct Launch Feasibility

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Considerable progress in understanding railgun operation, requirements, and limitations has been made. It appears that railguns may have potential application to space propulsion and direct launch. This paper discusses the state-of-the-art and expected capability of railgun systems. It includes the requirements and an example design of an Earth-based system capable of launching projectiles through the atmosphere at velocities greater than 8 km/s. The critical issues and problem areas that require investigation are described.

Introduction

THE feasibility of directly launching projectiles from the Earth's surface to Earth orbit or beyond depends on several factors including 1) the atmospheric drag and projectile erosion and 2) the launcher system size, durability, efficiency, and power requirements.

The magnitude of atmospheric drag experienced by a projectile traversing the atmosphere at velocities greater than 5 km/s has not been experimentally determined. Hence, the minimum-required launch velocity and projectile mass is not firmly established. Calculations of transatmospheric drag forces indicate a wide range of possible requirements. The mass and velocity required to escape the atmosphere at ~ 9 km/s range from a few kilograms[1,2] launched at ~ 10 km/s up to a hundred kilograms[3,4] launched at ~ 30 km/s.

Two basic types of magnetic accelerators have been considered for direct launch. In one case, the accelerating force is generated by a traveling magnetic field interacting with a magnetic dipole. The traveling field accelerator promises high electrical to kinetic energy conversion efficiency, and has been extensively discussed by Kolm,[5] O'Neill,[6] and Chilton.[7]

Here we will consider another type of accelerator—the railgun. It utilizes a very simple geometry and the Lorentz force resulting from current flowing orthogonally to a magnetic field. The railgun can provide very high accelerations and permit the attainment of the required velocities with practical length launchers.

This paper focuses on the potential application of the railgun to directly launch projectiles from the Earth's surface to Earth orbit and solar system escape. It discusses the operation, limiting factors, system requirements, and research status of railguns.

Launch Requirements

To determine the feasibility of launching projectiles into orbit with a railgun, estimates of required projectile mass and launch velocity are needed. These estimates will set the lower limits for railgun performance. The required performance in combination with the limits of operation discussed in the following section will determine the feasibility.

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Buckingham[3] and Park and Bowen[4] have calculated the magnitude of atmospheric deceleration of a low-ablation, hemispherical-nosed, blunt-tailed, cylindrical projectile. Their results indicate that 100-kg mass projectiles launched at 20 km/s would be required to achieve an Earth-orbit terminal velocity, v_T, of 8.8 km/s (see Fig. 1). This combination of mass and launch velocity represents a kinetic energy of 40 GJ. The low-ablation projectile design results in small projectile mass loss ($\sim 5\%$) but very high drag loss.

A more optimistic calculation by Banks and Ford[1] leads to lower required launch velocities and projectile masses. Their calculation is based on a projectile shape described by James.[8] The projectile was experimentally found to have a drag coefficient, C_D, of less than 0.1 at velocities greater than 4 km/s. If we assume 1) a constant drag coefficient of 0.1, 2) a projectile length-to-diameter ratio of 10, and 3) a projectile mass density of 19.3×10^3 kg/m^3 (tungsten), the terminal-versus-launch velocity shown in Fig. 2 will result. In this case, projectile masses of the order of 10 kg will vertically traverse the atmosphere almost unimpeded. Figures 3 and 4 show the required launch velocity and resulting kinetic energy vs projectile mass for two missions, Earth orbit ($v_T = 8.8$ km/s) and solar escape ($v_T = 13.8$ km/s).[9] As the projectile mass is decreased, the required launch velocity increases but the kinetic energy decreases. Ablation will set a lower limit on the mass of the projectile that can traverse the atmosphere and retain most of its original mass. Hence, in this case, we estimate a few kilogram mass projectile launched at a velocity approximately 15% greater than the desired terminal velocity would be needed for direct launch. Table 1 summarizes the direct launch requirements for both types of projectiles.

Precise calculations of projectile ablation and resultant configuration and drag coefficient change remain to be done. The result of such calculations will be the keystone to determining the feasibility of directly launching projectiles through the atmosphere. Furthermore, the presence of ice particles, water droplets, and/or dust in the atmosphere will most probably aggravate projectile ablation and may even limit launch conditions.

Railgun Operation

The railgun is essentially a linear dc motor consisting of a pair of rigid parallel conductors that carry current to and from a small interconnecting movable conductor. The connecting link functions as an armature, while the parallel rails serve as a single-turn field winding in series with the armature (see Fig. 5). The force, F, on the armature is given by

$$F = L_t I^2 / 2 \tag{1}$$

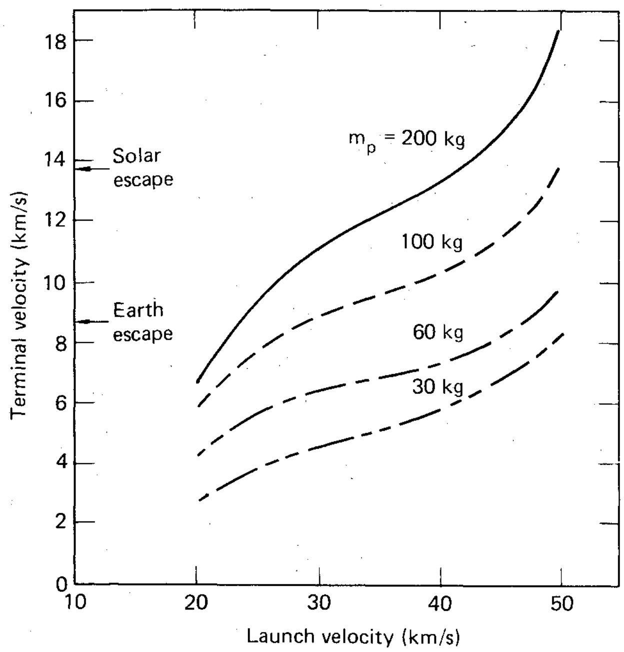


Fig. 1 Terminal velocity as a function of launch velocity and projectile mass based on Buckingham's calculations for low-ablation, hemispherical-nosed, cylindrical projectiles.[3] These results indicate that projectile masses of 100 and 200 kg would be required for Earth orbit and solar escape missions, respectively.

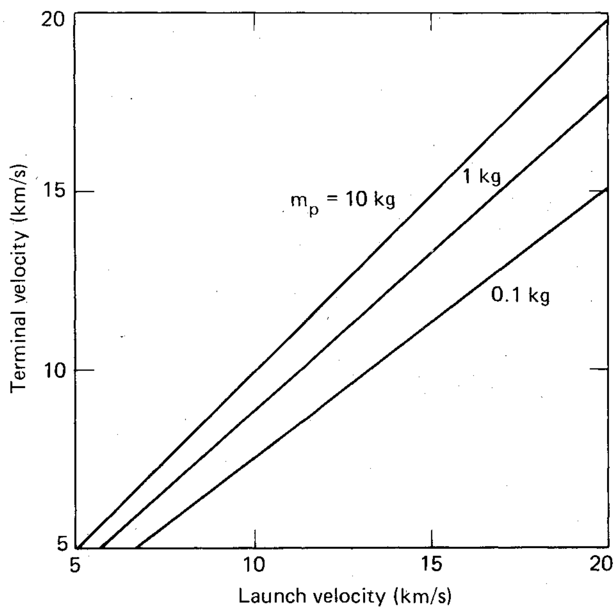


Fig. 2 Terminal velocity as a function of launch velocity and projectile mass based on a low-drag coefficient (0.1). These results[1] indicate that projectile masses in the 1-10 kg range may be capable of efficiently traversing the atmosphere provided excessive ablation does not occur.

Table 1 Required launcher performance for Earth orbit and solar escape

Requirements	Low-ablation, hemispherical-nosed cylinder[3] Earth orbit	Solar escape	Low-drag, fin-stabilized projectile[1,8] Earth orbit	Solar escape
Projectile mass, kg	100	200	4	4
Launch velocity, km/s	28	42	9.5	14.8
Kinetic energy, GJ	39	176	0.18	0.44

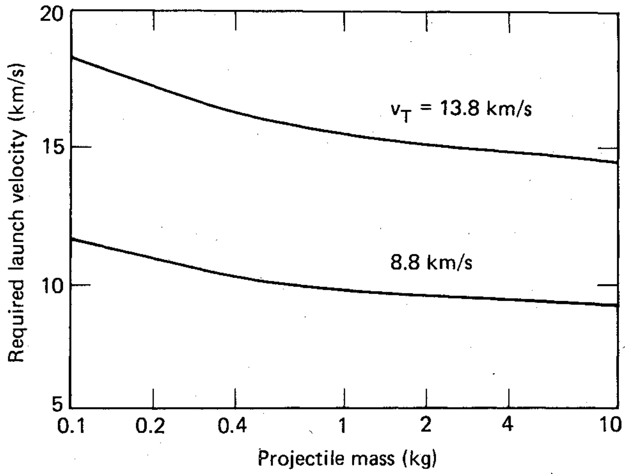


Fig. 3 Required launch velocity as a function of projectile mass for Earth orbit and solar system escape based on a drag coefficient of 0.1. Both Earth orbit and solar escape missions require less than 8% greater launch velocity than terminal velocity for projectile masses greater than 4 kg.

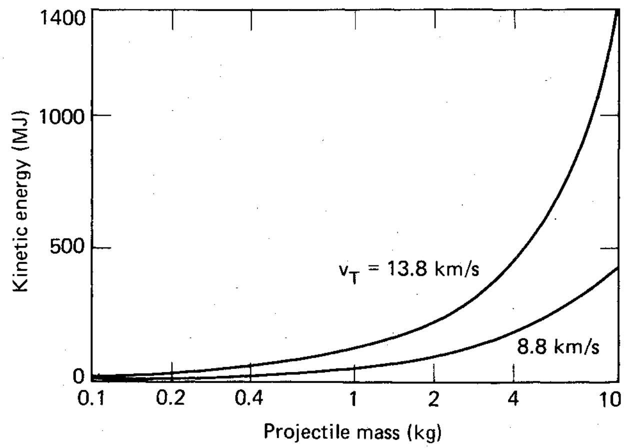


Fig. 4 Required kinetic energy of projectile as a function of projectile mass for Earth orbit and solar escape based on a drag coefficient of 0.1. Projectile kinetic energies of about 180 and 440 MJ are required to launch 4-kg projectiles for Earth orbit and solar escape missions.

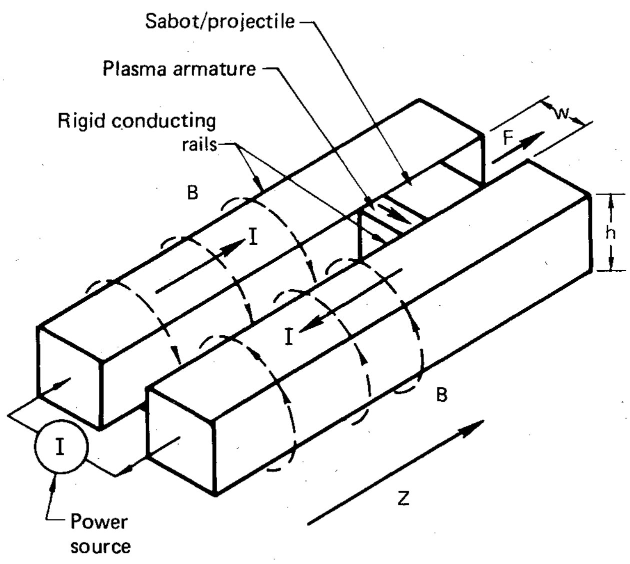


Fig. 5 A railgun accelerator utilizes a power source that supplies the current to generate a magnetic field which, in combination with the armature current, exerts a propulsive force on the backside of the sabot containing the projectile.

where I is the armature and field current and L_l is the inductance gradient (inductance per unit length of the rail pair).

It is not necessary that the armature be a solid metallic conductor. Brast and Sawle[10] and Marshall[11] demonstrated that an arc discharge initiated across the base of a dielectric projectile can also act as an armature if it is confined behind the projectile. The confinement is provided by the conducting rails on two sides and dielectric rail spacers on the other two sides. A plasma arc armature removes limitations resulting from sliding contacts and permits higher velocity launches.

A variety of power sources can provide the high current and long pulse durations needed to accelerate projectiles to hypervelocities. In the past, railguns have been powered by battery (J. Hansler's early 1940's railgun research in Berlin, Germany was reported in Ref. 12), capacitor bank,[10] homopolar generator (HPG),[11,13] and magnetic flux compression generator (MFCG).[14,15]

Limiting Factors That Influence Launcher Design

The design and operation of a railgun is restricted by practical limits.[16] These limits result from the properties of the rail and projectile materials, interior ballistics of the projectile, sustainable voltage without spurious arcing, and power supply characteristics.

Solid Armature Melting

It has been shown that in most cases, resistive heating would cause a solid metal armature to melt prior to attaining a velocity of ~10 km/s. Furthermore, a solid armature would require current flow to be maintained through sliding contacts with the rails. Such contacts are limited to even lower operating velocities (1-3 km/s). For launch velocities of 15 km/s, a plasma arc armature will be required for at least the latter portion of the acceleration.

Rail Melting

Not only is melting of the rails undesirable, but high temperatures decrease their strength. Melting of the rails can be caused by two mechanisms in railgun operation. One is the heating caused by the current flowing in the rails. This mechanism is most severe when the projectile is moving at a high velocity and rapidly exposing the rails to intense current that has little time to diffuse into the rails. Hence, the current is initially localized to a thin region on the interior surface of the rails. The resulting temperature rise of the rail surface, ΔT, can be approximated by[17,18]

$$\Delta T \simeq \frac{2\mu_0 I^2}{\pi \rho C_v h^2} \ln\left[1 + \frac{\pi}{2}\sqrt{\frac{\rho C_v \eta_0}{\mu_0 k}}\right] \tag{2}$$

where μ_0 is the permeability, ρ is the density, C_v the specific heat, k the thermal conductivity, η_0 the resistivity of the rail material, and h the width of the rail (see Fig. 5). We have concluded[16] that for a copper rail system initially at room temperature, the current concentration will be limited to about 43 kA/mm of rail width.

Plasma bombardment is the other mechanism that can cause rail melting and damage. The plasma arc erodes the rails in much the same manner as in switch contractors used to interrupt current flow. This effect is most severe when the projectile and plasma are slow-moving or stationary, providing a long time for the erosion to occur.[19,20] To operate a railgun repetitively at megampere currents, one or a combination of several techniques will be required. Use of erosion-resistant materials for rails in the breech region, hybrid solid/plasma armatures, current pulse shaping and/or rapid projectile injection will be necessary. Furthermore, if the repetitive launching is rapid, heat removal during operation would be required.

Launcher Stress

The railgun structure is subjected to a complex set of loads and mechanical deformation that results from intense-pulsed magnetic fields, high-temperature gradients, and sliding-contact-induced shear. It is necessary to determine the stress states of each component because in many cases each must function in a dual (or multiple) role. For example, while the primary function of the rails is to conduct the armature current, the rails must also guide and perhaps contain the projectile, as well as provide a thermal conduction path for the heat generated by the current in the rail surface. Similarly, the dielectric region surrounding the rails provides not only electrical insulation but also mechanical support for the rails and guidance for the projectile. Thus, it is necessary to consider both the direct and indirect influences of each perturbation.

The stress P on the rails generated by the magnetic field B, interacting with the rail current, can be estimated by[21]

$$P = \frac{\mu_0 I^2}{2\pi h^3}\left[2h\tan^{-1}\frac{h}{w} - w\ln\left(\frac{w^2+h^2}{w^2}\right)\right] \tag{3}$$

where w is the rail spacing. For a square bore, Eq. (3) reduces to

$$P = 0.44(\mu_0 I^2/\pi h^2) \tag{4}$$

In this case, a stress equal to the elastic limit of steel will be reached with a current concentration (I/h) of about 100 kA/mm. This value is less severe than the expected limit imposed by rail melting; the stresses, however, are complex and important to consider. In addition to the magnetic stress, the plasma arc exerts a pressure on the rails and dielectric as well as the projectile. The duration of the arc pressure on the rails and dielectric is limited to the passage of the arc, whereas the magnetic pressure on the rails is exerted throughout the launch.

Projectile Stress

As with the rails and their support structures, the projectile will deform according to the waveshape, amplitude, and distribution of the applied stress, and the flow characteristics of the sabot and projectile materials. Buckingham[22] has calculated the drag and heating losses caused by sliding friction, solid deterioration at the surface, and the liquid and gaseous boundary layers between the sabot and the launcher walls.

When the acceleration stress causes sufficient deformation of the sabot, it will be in rubbing contact with the bore of the gun. The sliding friction will result in considerable drag and heating of the sabot. If the elastic strength of the sabot material were zero, it would be totally plastic and the amount of energy dissipated by drag could be of the order of 2-10% or more of the kinetic energy, depending on the geometry of the sabot and the coefficient of sliding drag.

Whenever the elastic strength is greater than the acceleration stress, the sabot can be self-supporting and not require the gun bore to constrain its shape. Calculations have indicated that in this case the energy lost to drag can be negligible up to velocities in excess of those considered here. To limit the acceleration stress (assumed to be uniform) to less than the elastic strength of the sabot, the maximum allowable acceleration a_M is

$$a_M = \sigma_y A / m_t \tag{5}$$

$$= L_l I_M^2 / 2m_t \tag{6}$$

where σ_y is the dynamic elastic strength of the sabot, A the bore area, m_t the total mass of the combined projectile and sabot, and I_M the maximum allowable current. From Eqs. (5)

and (6), we find

$$I_M/[A]^{1/2} = [2\sigma_y/L_l]^{1/2} \tag{7}$$

For a sabot made of a composite of resin and graphite fibers with an elastic strength of 1.4 GPa, and at least an equally strong projectile, the maximum value of $I_M/[A]^{1/2}$ is 80 kA/mm.

In-bore Projectile Stability

Consideration of rail heating, magnetic, and plasma arc stresses leads one to the conclusion that, for a given projectile mass, the launcher performance will increase with increased bore size. However, the mass of the sabot will increase with bore size unless the sabot length can be decreased to compensate. The length can be decreased until the length-to-width or length-to-diameter ratio (i.e., aspect ratio) of the sabot is so small that it can tumble or wedge in the bore. Barber[23] discusses this problem from the standpoint of Taylor instabilities and thereby estimates a minimum ratio of 0.64. Experience with the 8-km/s, two-stage, light-gas gun at Lawrence Livermore National Laboratory has been that an aspect ratio as low as 0.67 is acceptable.[24] For the direct-launch mission, projectiles will require aspect ratios of 10-15 for flight stability and drag reduction. This will, in turn, lead to large aspect ratios for the sabot, or a sabot that will provide guidance at the fore and aft positions of the projectile with minimal material between.

Postlaunch Projectile Stability

Stable projectile flight through the atmosphere is required in order to minimize projectile drag and erosion and to achieve accurate orbit or payload delivery. Stable flight can be obtained in two ways. Fins on the projectile can be used and are compatible with a square-bore launcher. Stabilization can also be achieved by spinning a round projectile. Spin stabilization would be easiest to achieve with round-bore launchers. In this case, the sabot and projectile could be spun during or after, but most probably before, acceleration.

Hence, railguns appear to have no inherent restrictions that would prevent the launching of projectiles that are either spin or fin stabilized.

Spurious Arcing Between Rails

If the railgun is to operate effectively, it is important that the moving arc or metal armature be the only conduction path across the rails. Hence, conditions that could develop secondary arcs must be avoided.

To avoid secondary arcs in front of the projectile, the pressure should be below 10^{-4} Torr, thereby avoiding excessive drag and possible collisional ionization of gas.

The largest voltage developed across the rails occurs at the breech and is the sum of the arc, inductive, and resistive voltages along the rails. The gaseous components and pressure remaining behind the plasma arc may require modification or purging.

After the acceleration is completed, however, it is possible to launch the projectile into the atmosphere by use of a thin diaphragm, differential vacuum region, or fast-opening shutter.

Available Energy

In addition to all of the above considerations, the performance of a railgun launcher determines the amount of energy required. The maximum input energy to the railgun is equal to the energy stored in a primary energy storage device (PESD) less the energy loss in transfer from the PESD to a pulse-shaping and/or energy-transfer network and then to the launcher. A variety of potential power sources are currently being developed for railgun launchers. The energy and power output of all of the power sources are influenced by the operational characteristics of the railgun. Therefore, the railgun and its power supply must be considered as a combined system. An example system is discussed in the following section.

Launcher Design

The two estimates of required launch velocities and masses listed in Table 1 lead to the required launcher performance. The required kinetic energies and resulting electrical power needed for the hemispherical cylinder projectile are, by contemporary pulsed-power standards, very large. Therefore, an example launcher design will be considered only for the low-drag projectile.

Launcher Length

For an Earth-based system, a minimum length launcher is desired. The required acceleration, current, and stress on the sabot, projectile, and launcher increase as the launcher length is decreased. As the current is increased, the current concentration limit leads to an increase in bore size, sabot size, total mass, and required energy.

Three limits on current concentration for a square-bore railgun are:

1) rail melting (copper)—43 kA/mm
2) launcher stress (steel)—100 kA/mm
3) projectile stress (graphite fiber composite)—80 kA/mm

The most restrictive limit results from rail melting. As the launcher length z is varied, the required acceleration a is

$$a = v_L^2/2z \tag{8}$$

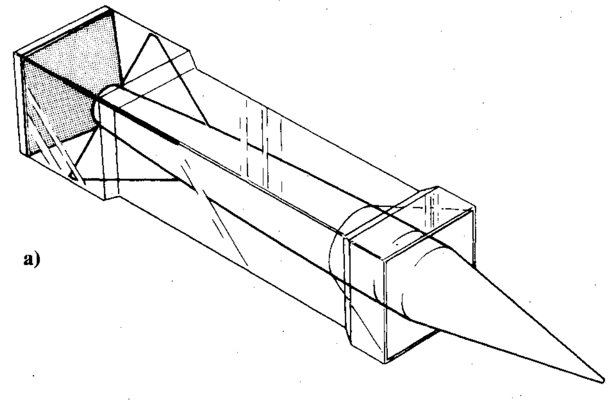
where v_L is the launch velocity. The required current is

$$I = [2m_t a/L_l]^{1/2} \tag{9}$$

where m_t is the combined mass of the projectile m_p and sabot m_s.

Figure 6 illustrates a finned projectile mounted in a sabot for a square-bore launcher. To remain below the maximum current concentration κ, the bore size (and sabot cross section)

a)



b)

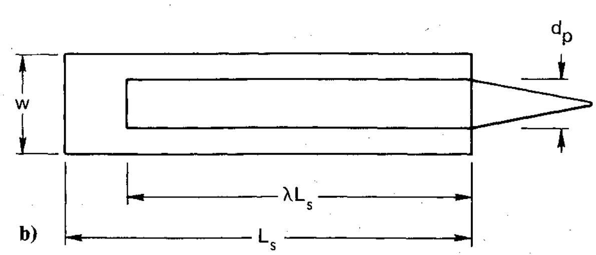


Fig. 6 A finned projectile can easily be encased in a sabot for a square-bore launcher (a). A simplified equivalent projectile/sabot combination (b) was used for the example calculations.

must increase with current, i.e.,

$$h = w = I/\kappa \tag{10}$$

The mass of the sabot shown in Fig. 6b is

$$m_s = \rho_s L_s [hw - (\lambda \pi d_p^2/4)] \tag{11}$$

where ρ_s is the sabot material density, L_s the sabot length, d_p the diameter of the projectile engaged in the sabot, and λ the fraction of sabot length engaged by the projectile. Combining Eqs. (9-11), we find

$$I = \left[\frac{2m_p - (\lambda\pi/2)\rho_s L_s d_p^2}{(L_l/a) - (2\rho_s L_s/\kappa^2)} \right]^{1/2} \tag{12}$$

Table 2 lists the parameters used to calculate the current, bore size, and sabot mass as functions of launcher length. The results are shown in Figs. 7a and 7b for launch velocities of 9.5 and 14.8 km/s, respectively.

In the case of the Earth-orbit mission, it would be excessively difficult to use a launcher of less than 100 m where the sabot mass would be equal to or greater than the projectile mass. At the other extreme, a bore size of much less than 4 cm will not accommodate the projectile fins; hence, a launcher length of greater than 360 m will not reduce the sabot mass. A 200-m-long launcher would have a bore size of 5.8 cm, operate with a current of 2.5 MA, and launch a 4-kg projectile with a 1.3-kg sabot at 9.5 km/s.

Similarly, in the case of the solar escape mission, launcher lengths in the range of 250-770 m would be reasonable. A 440-m-long launcher would also have a bore size of 5.8 cm, operate with a current of 2.5 MA, and launch a 4-kg projectile with a 1.3-kg sabot at 14.8 km/s.

The above discussion serves as a guide. The launcher length one would select would depend on a variety of factors including efficiency, structure cost, and power supply characteristics.

Table 2 Parameters used to calculate current, bore size, and sabot mass

Parameter	Definition	Value used
κ	Maximum current concentration	43 kA/mm
ρ_s	Sabot material density	$2.2(10^3)$ kg/m^2
L_s	Sabot length	0.21 m
λ	Fraction of sabot length engaged by projectile	0.9
d_p	Projectile diameter	0.03 m
m_p	Projectile mass	4 kg
L_l	Railgun inductance gradient	$4(10^{-7})$ H/m

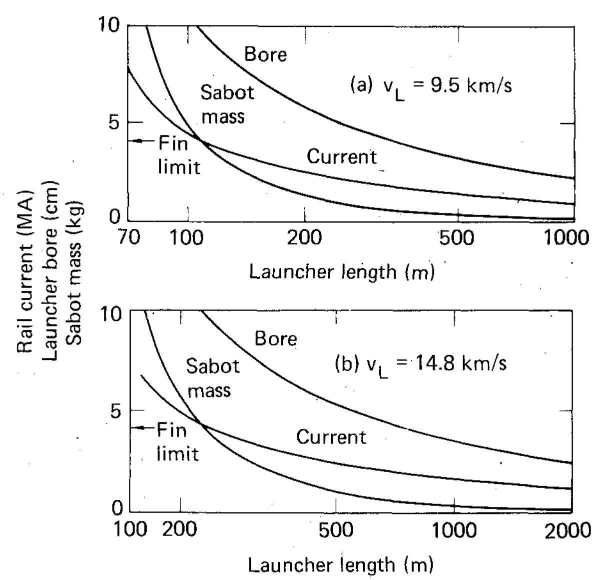


Fig. 7 Rail current, launcher bore, and sabot mass as functions of launcher length for achieving a) 9.5-km/s or b) 14.8-km/s launch with the constraints listed in Table 2. Lengths shorter than a) 100 m or b) 250 m lead to sabot masses greater than the projectile and result in excessive wasted energy. Projectile fins restrict the minimum size of bore, and hence, negate any advantage to launchers longer than a) 360 m or b) 770 m.

Efficiency

The energy conversion efficiency of a single-stage, constant-current railgun is easily calculated. The energy delivered to the railgun is distributed to kinetic energy of the projectile/sabot, dissipated in the rails and plasma arc, or stored in the magnetic field.

The energy dissipated E_R in the rails is[25]:

$$E_R = \frac{32}{15hI} (\pi\mu_0\eta)^{1/2} \left(\frac{m}{L_l}\right)^{3/2} v_L^{5/2} \tag{13}$$

where μ_0 and η are the permeability and resistivity of the rails, respectively. In this case, the energy stored in the magnetic field is equal to the kinetic energy E_p. Hence, neglecting the energy dissipated in the plasma arc, the efficiency, ϵ, is

$$\epsilon \cong E_p/(2E_p + E_R) \tag{14}$$

Table 3 summarizes the results for the example calculations above. The gross electrical-to-kinetic conversion efficiencies of the combined projectile and sabot launch are 11% and 9.5% for the Earth orbit and solar escape, respectively. The net launch efficiencies of the projectile alone are 8.3% and 7.2%. Considering the length of the single-stage launcher, these efficiencies are very encouraging. Multistage railguns will lead to higher efficiencies.[25] The energy lost in the rails decreases approximately with the square root of the number of stages. Hence a 10-stage accelerator would have gross efficiencies of 24% and 21% for the combined sabot and projectile and net efficiencies of 21% and 16% for the

Table 3 Example launcher design for Earth orbit and solar escape missions

	Earth orbit	Solar escape
Launch velocity, km/s	9.5	14.8
Projectile mass, kg	4	4
Sabot mass, kg	1.3	1.3
Total mass, kg	5.3	5.3
Total kinetic energy, MJ	240	580
Acceleration time, ms	42	60
Launcher length, m	200	440
Bore, cm	5.8	5.8
Current MA	2.5	2.5
Single-Stage Launcher		
Energy lost in rails, MJ	1630	4930
Gross launch efficiency, %	11	9.5
Net launch efficiency, %	8.3	7.2
Energy input, GJ	2.2	6.1
Power input, GW	52	102
Ten-Stage Launcher		
Energy lost in rails, MJ	515	1560
Gross launch efficiency, %	24	21
Net launch efficiency, %	18	16
Total energy input, GJ	1.0	2.8
Total power input, GW	24	46

projectile alone at $v_L = 9.5$ km/s and $v_L = 14.8$ km/s, respectively.

The efficiency could be increased by recovering some of the energy stored in the magnetic field of each stage and used in a succeeding stage. Overall system efficiency will be less than described above due to additional losses in the power supply and power delivery system.

Power Supply

The power supply system must provide a considerable amount of energy in a relatively short period of time. Table 3 includes the required energies and power for each of the above examples. In all cases, the required power input greatly exceeds the direct output of contemporary electrical power-generating facilities (~1 GW). Therefore, an energy cumulation technique will be required to store one or more gigajoules of energy and rapidly transfer it to the railgun. Capacitor banks, homopolar generators, compulsators, inductive storage, and chemical explosives can be used for large-scale energy storage.

A 25 MJ capacitor bank has been operating for several years, and an 80 MJ bank is being constructed for laser fusion research.[26] Ten such banks could be used to power a 10-stage railgun. Therefore, a capacitive-energy-storage power supply is feasible but expensive.

Fifty MJ homopolar generators (HPG's) have been built and operated at full energy. A 500 MJ HPG has been constructed and operated at 380 MJ.[27] Usually, HPG's provide low-voltage outputs and cannot be used to directly power a railgun; however, it can be used to energize a storage inductor, which can then be used to power a railgun.[23] The size and cost of HPG's are considerably smaller and cheaper than capacitor banks.

Stored magnetic energy in an inductor can be used to power a railgun. The inductors can be superconducting or normal conducting. Both are comparable in size but not cost. Superconducting inductive storage has the advantage of storing energy indefinitely without loss and can be energized over a long period of time; however, it is difficult to extract the stored energy rapidly. Whereas a normal-conducting inductive storage device can rapidly deliver energy, it resistively consumes energy rapidly enough that it must be energized in a short time. Hence the time compression of energy storage into energy discharge is limited but might be adequate. The size of both types of inductive storage is dictated by the strength of materials. Up to about 10 MJ/m^3 can be inductively stored.

Compulsators are rotating, compensated, inductive devices that can store large amounts of energy and provide 10-kV pulses at megampere currents for millisecond durations. These devices have great potential; however, the largest that has been built is 200 kJ and the largest to be designed is 10-20 MJ.[26]

The energy stored in chemical explosives can be converted into electrical energy by way of magnetohydrodynamic generators and/or magnetic flux compression techniques. TNT contains 4.2 GJ/Mg. Conversion efficiencies as high as 20-25% might be possible. Thus, this type of energy storage could provide the required energy and power to demonstrate the feasibility of direct launch, but isn't likely to be used on a routine basis.

Hence, although the energy and power required to launch projectiles directly into space are large, they appear to be within the realm of feasibility.

Complex Projectiles

After the projectile has been launched and has traversed the atmosphere, many applications, including Earth-orbit missions, would require a means to alter the trajectory. Projectiles may require movable fins and/or propellant. It can be envisioned that such complex payloads could be designed to survive the launch process, but the mass of the projectile may need to be greater than the 4-kg example discussed here.

Status of Railgun Research—1981

Experimental research on railguns began in 1944 with the launch of a 10-g projectile at ~1 km/s.[12] In 1963, a 0.2-g mass was accelerated to an estimated 9.5 km/s.[14] Since then, there have been several concentrated efforts to develop railguns for a variety of applications.

Australian National University

Recent interest in railguns was stimulated by a research program at the Australian National University in Canberra.[11,13,23] 3-g cubes made of polycarbonate plastic were accelerated and launched at velocities as high as 5.9 km/s in a 5-m-long, 12.7-mm square-bore railgun powered by a homopolar generator and inductive storage device. The higher-velocity projectiles were driven by a plasma arc armature. Railgun research at Canberra has been terminated, but a new program was recently started at the Australian Materials Research Laboratory in Melbourne[28] using a capacitor bank as the prime power source.

Los Alamos-Livermore

In another program, a joint team of researchers from the Los Alamos National Laboratory and the Lawrence Livermore National Laboratory fired a number of railguns powered by explosive magnetic flux compression generators.[15,19] A 12.7-mm, square-bore, 3-g polycarbonate cube was launched at a velocity of 5.5 km/s with a 2-m-long railgun. Figure 8 is an x-ray radiograph of the projectile in free flight. During acceleration, the projectile was subjected to an average stress of five or six times the static yield strength. This may have contributed, along with atmospheric ablation, to the development of the mushroomlike shape of the projectile after it left the gun muzzle.

At higher current levels, velocities as high as 10 km/s were indicated by analysis of the current records and by interior ballistic diagnostics in the early stages of acceleration. The projectiles did not appear on the postlaunch x-ray radiographs. It was concluded that because the projectiles were still being accelerated and highly stressed, they broke into pieces as they left the muzzle of the gun.

Preliminary experiments have been started to accelerate more massive projectiles. In one experiment, a 165-g, 50-mm polycarbonate cube was accelerated to a velocity of 350 m/s. The railgun was only 30 cm long, but the accelerating current reached a value of nearly 2 MA. The projectile was recovered intact.

Research is currently directed toward increasing the capabilities of explosive generators, improved railgun and projectile design, improved diagnostic techniques, improved mathematical modeling, and exploring and demonstrating military and scientific applications.[16,29,30]

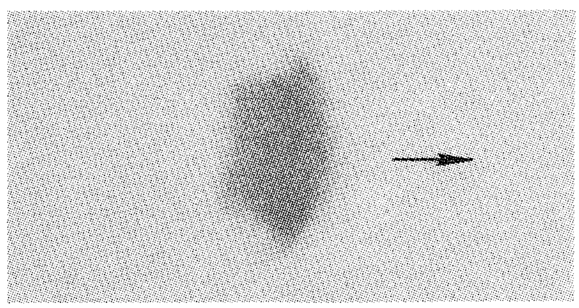


Fig. 8 X-ray radiograph of 12.7-mm cube of polycarbonate (Lexan) launched at 5.5 km/s with a 2-m-long railgun. After launch, the projectile had traveled ~25 cm in vacuum, punched through a 0.25-mm-thick mylar diaphragm, and traveled through ~30 cm of atmosphere causing the ablation of the projectile nose.

The railguns fired thus far have been extensively damaged by the plasma arc armature and the intense magnetic fields. Therefore, another important goal is to develop railguns with multishot capability. Longer railguns are being built at both laboratories. Calculations that have been performed and experience gained in previous railgun shots give the team confidence that, in the future, intact projectiles will be launched at velocities in excess of 10 km/s.

At Los Alamos, a two-stage railgun (called an integral railgun) powered by an external explosive generator and a second explosive generator built into the railgun itself[31] is being developed.

University of Texas

At the University of Texas at Austin, a railgun with capacitor bank power supplies distributed along the length of the gun is being developed.[32] A powder gun has been used to inject projectiles into the railgun in order to reduce the plasma arc damage to the rails. A 50-MJ, homopolar, pulsed-power facility is being planned and will be used to power railguns in a few years.[33,34]

Westinghouse Corporation

The Westinghouse Corporation is building a large-bore railgun powered by a 15-MJ homopolar generator to accelerate 300-g projectiles to 3 km/s.[35,36] They have been using a capacitor bank for small-bore testing.

General Dynamics

The General Dynamics Corporation has initiated a program to assess the feasibility of upgrading the radar-controlled U.S. Navy PHALANX ship defense gun system with a railgun.[37] In collaboration with LLNL, saboted Al and W projectiles were launched with a railgun in March 1981.

Tokyo Institute of Technology

In Japan, a railgun program for high-pressure research has been initiated at the Tokyo Institute of Technology.[38] They plan to use a two-stage gas gun to first accelerate projectiles to ~5 km/s and then further accelerate them with a railgun.

Optimism is high in the railgun community that the future will see rapid advances in railgun technology.

Conclusions

We have concluded that an electromagnetic railgun will be capable of directly launching projectiles from the Earth's surface into Earth orbit and beyond, provided low-drag projectiles of a few kilograms of mass are capable of traversing the atmosphere at velocities between 10 and 15 km/s without devastating erosion or deceleration. For a projectile with a drag coefficient of about 0.1, a 9.5-km/s launch will be adequate to emerge from the atmosphere at 8.8 km/s and, with proper trajectory modification, would be adequate for maintaining an Earth orbit. A low-drag projectile launched at 14.8 km/s would be capable of emerging from the atmosphere at 13.8 km/s, and by using the sun's gravitational pull, escape the solar system.

In an example calculation, we found that a 4-kg, fin-stabilized projectile, mounted in a 1.3-kg sabot, could be accelerated to launch velocities of 9.5 and 14.8 km/s by 5.8-cm square-bore railguns of lengths 200 and 440 m, respectively. The operation of the railgun was assumed to be limited by several factors, the most restrictive being that imposed by melting of the rails. The efficiency of converting the electrical input energy into projectile kinetic energy is expected to be in the vicinity of 10-20%. Hence, the power supply will need to deliver about 1-6 GJ at a rate of 20-100 GW. The power level will require the use of an energy storage device. It appears that capacitor banks, homopolar generators, explosive generators, and possibly compulsators could adequately power the railgun.

The state of railgun technology indicates definite promise for achieving direct launch. Much more research and development is needed in order to extend the launch capability to larger projectile mass and kinetic energy. Even further development will be required in order to insure the survivability of the launcher system for repeated operation.

Recent Results

Significant progress in railgun and pulse power technology has been made since April 1981.

The Los Alamos-Livermore team has obtained a flash x-ray radiograph of a tantulum disk accelerated by a polycarbonate sabot and launched at about 11 km/s.

The Westinghouse Corporation has successfully demonstrated the launch of a 317 g projectile at about 4.2 km/s.

Railgun research and technology development has commenced at Boeing Aircraft Corporation in Seattle, Washington, Vought Corporation in Dallas, Texas, and Physics International in San Leandro, California.

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