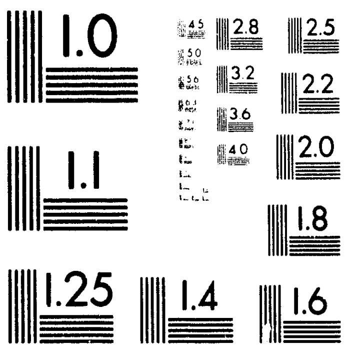
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THE CONTINUING CHALLENGE OF ELECTROMAGNETIC LAUNCH*

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1. BACKGROUND

Interest in launching payloads through the atmosphere to ever higher velocity is robust. For hundreds of years, guns and rockets have been improved for this purpose until they are now considered to be near to their performance limits.

While the potential of electromagnetic technology to increase launch velocity has been known since late in the nineteenth century, it was not until about 1980 that a sustained and large-scale effort was started to exploit it.[1] Electromagnetic launcher technology is restricted here to mean only that technology which establishes both a current density, J, and a magnetic field, B, within a part of the launch package, called the armature, so that $J \times B$ integrated over the volume of the armature is the launching force. Research and development activity was triggered by the discovery that high velocity can be produced with a simple railgun which uses an arc for its armature.[2] This so called "plasma-armature railgun" has been the launcher technology upon which nearly all of the work has focused. Still, a relatively small parallel effort has also been made to explore the potential of electromagnetic launchers which do not use sliding contacts on stationary rails to establish current in the armature. One electromagnetic launcher of this type is called an induction coilgun because armature current is established by electromagnetic induction.

In this paper, we first establish terminology which we will use not only to specify requirements for successful endoatmospheric launch but also to compare different

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launcher types. Then, we summarize the statuses of the railgun and induction coilgun technologies and discuss the issues which must be resolved before either of these launchers can offer substantial advantage for endoatmospheric launch.

2. DEFINITION OF TERMS AND REQUIREMENTS

2.1 The Launcher Equation

The kinetic energy of the launch package, $mv^2/2$, at the muzzle of any launcher or gun may be written as follows:

$$\int_o^L F(x)dx = \frac{mv^2}{2} \quad , \tag{1}$$

where F(x) is the net, forward-going force on the launch package, and L is the length of the barrel. This may also be expressed using an average force, $\overline{F}$ (averaged over L), as follows:

$$\overline{F}L = \frac{mv^2}{2} \quad . \tag{2}$$

If we divide both sides of (2) by the cross-sectional area of the bore and the bore diameter, d, we obtain the launcher equation:

$$\overline{P}\ell = \rho^* \frac{v^2}{2} \quad , \tag{3}$$

where

$\overline{P}$ = net, average, forward-going "pressure" ,

ℓ = launcher length in calibers (L/d) ,

ρ^* = effective density of the launch package ,

$\rho^* = 4m/\pi d^3$ (round bore) , and

$\rho^* = m/d^3$ (square bore) . (4)

For EM launchers, the forward-going force is actually distributed within a volume of the armature so that $\overline{P}$ is then an "effective" pressure.

One of the expected advantages of EM launchers is that $\bar{P}\ell$ will not depend on ρ^* or ℓ as it does for gas-dynamic launchers. In Fig. 1, we show a plot of $\bar{P}\ell$ vs. ℓ for a hypothetical EM launcher which achieves a value of $\bar{P}$ given by $\bar{P}$ = 2 kbar (2×10^8 Pa) for any barrel length, ℓ . For comparison, we also show an example of the way $\bar{P}\ell$ depends on both barrel length, ℓ , and effective density, ρ^*, for conventional guns. The two curves for $\rho^* = 10^3$ and 10^4 kg/m^3 were calculated for an idealized gun with an infinitely long powder chamber and for a nitrocellulouse propellant at an initial pressure of 5 kbar, using a model from [3]. Both curves indicate asymptotic limits on $\bar{P}\ell$ (or v^2). Even with infinitely long barrels, maximum velocity would be limited to about 2.3 km/s for $\rho^* = 10^4$ kg/m^3 and to about 4 km/s for $\rho^* = 10^3$ kg/m^3.

2.2 Endoatmospheric Launch Requirements

In order for a projectile to have adequate aerodynamic performance, it must be long compared to its diameter and have fairly high density (> 10^3 kg/m^3). Although compromising trade-offs may be necessary, a reasonable requirement is that projectile "effective" density, ρ^* (4), be given by

$$\rho^* \geq 10^4 \text{ kg/m}^3 \quad . \tag{5}$$

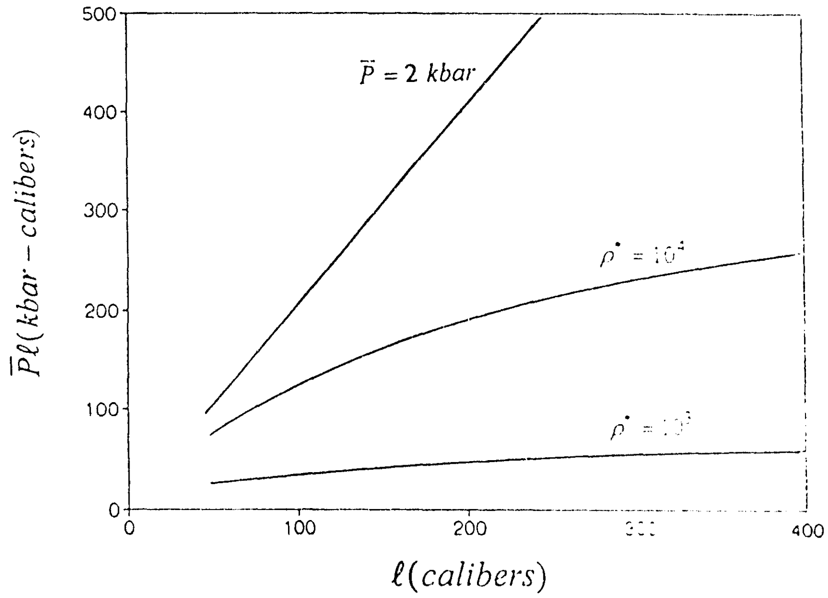

Figure 1. Hypothetical EM launcher with $\bar{P}$ = 2 kbar compared to conventional gun with launch package, ρ^*, values of 10^4 and 10^3 kg/m^3.

For minimum-caliber launch of a projectile, the launch package and projectile must have the same diameter so that the $\bar{P}\ell$ requirement for the launcher from (3) and (5) is given by

$$\bar{P}\ell \geq 50\ v^2 \text{ kbar calibers} \ , \qquad (6)$$

where v is expressed in km/s. Thus, the conventional gun modeled in Fig. 1 could not make minimum-caliber launch at velocity greater than about 2.3 km/s due to its asymptotoic limit on kbar calibers at $\rho^* = 10^4$.

However, the same conventional gun might launch an aerodynamically adequate projectile to higher velocity by using sabot technology. To do this, both the diameter, d, and mass, m, of the launch package are increased, but in such a way that d^3 increases faster than m (4). Still, penalties for using sabots can be severe in terms of mass increases of both the gun and the launch package.

3. THE RAILGUN

3.1 Evaluation of the Physical Model

The seminal paper on the plasma-armature railgun [2] assumed that the forward-going force, F, was always electromagnetic in nature and was simply expressed by the following equation:

$$F = \frac{1}{2} L' I^2 \ , \qquad (7)$$

where L' is the inductance per unit length of the railgun, and I is the current. On this basis, very high velocities for large masses were deemed possible according to [2].

In the early 1980's, it was found that railgun experiments designed by this simple theory were not delivering expected velocities. It was proposed [4] that the short-fall in performance was due to wall ablation, viscous drag, and "secondary" arc formation. These ideas were generally accepted by the railgun community, and drag terms for both ablation and viscosity were added to most railgun codes. It was reasoned that better materials could reduce ablation and high velocity (50 km/s) could still be achieved. Still, the experimental results continued to fall short of expectations. In fact, as better materials were used to control ablation, performance actually degraded. Relatively recently, a new physical model of the plasma-armature railgun has been emerging [5,6] which accounts at least qualitatively for the experimental disappointments of more than a decade.

It has been pointed out [5,6] that the plasma-armature railgun, like several other similar plasma devices, can have two different modes of operation. In one mode, a current sheath accelerates plasma like a fast, solid piston, while in another, the current structure remains relatively stationary and accelerates plasma like a quasi-stationary pump. In the "piston mode," the plasma can provide electromagnetic-like force on a tightly-fitting, plastic projectile. However, this mode is unstable and quickly gives way to the "pump mode." A recent study of railgun data [7] indicates that this change in mode occurs when an "action" per unit volume for the plasma armature, given by the cube of the linear current density over the time-rate-of-change in current, exceeds a certain value as follows:

$$\frac{I^3}{h^3 \dot{I}} \geq 1.7 \times 10^{13}\,A^2 s/m^3 \quad . \tag{8}$$

High performance railguns exceed this action well before peak current is reached. The current structure begins to grow in length toward the breech by development of parasitic discharges. This first accelerates and then releases gas to cross a currentless zone and impact the projectile. Momentum exchange decelerates the current structure and accelerates the projectile. Clearly, this physical process leads to gas-dynamic rather than electromagnetic acceleration of the projectile. As we will show in the following section, a gas-dynamic model is more consistent with experimental results.

3.2 Railgun Data

Table 1 lists data from ten shots of eight, well-known plasma-armature railguns. These are "best performance" data. Most had the launch package injected with an initial velocity. One, CEM-UT, attempted solid armature operation. The shots are numbered 1 through 10 and will be referred to by these numbers. Table 2 lists for the same experiments the values of ρ^*, $\bar{P}\ell$, ℓ, and $\bar{P}$, none of which depend on scale. Notice that four railgun shots with $\ell \doteq 100$ calibers (5, 7, 8, and 10) produced an average value for $\bar{P}\ell$ of $\bar{P}\ell \doteq 100$ kbar calibers while three shots with $\ell \doteq 400$ calibers (1, 2, and 3) had an average value of $\bar{P}\ell \doteq 140$ kbar calibers. This indicates a diminishing return for increased barrel length similar to that for gas-dynamic guns (Fig. 1). Data from three long guns (1, 2, and 5) show that acceleration actually ended at 180 ± 20, 170 ± 20, and 140 ± 10 calibers, respectively, even though heavy current was still being applied at the breech.[2,8,11] Comparing shots 7 and 8 which are from the same railgun, one sees that $\bar{P}$ also depends on ρ^*. As in gas dynamic guns, lighter, faster projectiles experience less forward-going pressure than slower, heavier ones.

In Fig. 2, we plot $\rho^* v$ vs. ρ^* for all ten railgun experiments. In addition, we show four points, labeled G, for a 300-caliber, two-stage, light-gas gun. These four points were calculated by an experimentally verified code.[15] The two curves from (3) are for constant $\bar{P}\ell$ of 200 and 50 kbar-calibers. This shows that the long railguns (1, 2, and 4) came close to the performance of the light-gas gun for a range of ρ^* from 504 to 1220 kg/m^3. To establish the minimum-caliber launch capabilities of railguns will require that experiments employ much heavier launch packages than in the past.

Table 1.

Shot #	Railgun	Insulator Material	Bore Size (mm)	Barrel Length (m)	Projectile Mass (kg)	v (km/s)
1	R&M [2]	Asbestos-Reinforced Resin	12.7 (square)	5	$2.5/3.1 \times 10^{-3}$	5.9
2	LLNL [8]	Poly-Carbonate	12.8	5.2	1×10^{-3}	6.6
3	LLNL [8]	G9 Epoxy-Fiber Glass	11.5	5.2	1×10^{-3}	4.6
4	HYPAC [9]	Poly-Carbonate	13	1.86	0.87×10^{-3}	7.5
5	CHECMATE [10]	G9 Epoxy-Fiber Glass	51 (square)	5	93×10^{-3}	4.2
6	Thunderbolt [11]	Boron Nitride	56	12	77×10^{-3}	5.3
7	Maxwell [12]	G10 Epoxy-Fiber Glass	92	8	1.1	3.6
8	Maxwell [12]	G10 Epoxy-Fiber Glass	92	8	1.58	3.3
9	ACB [13]	Epoxy Fiber Glass	92	7	1.59	2.6
10	CEM-UT [14]	Epoxy Fiber Glass	100	10	2.44	2.6

Table 2.

Shot #	Railgun	ρ^* (kg/m^3)	$\bar{P}\ell$ (kbar-calibers)	ℓ (calibers)
1	R&M	1220	212	390
2	LLNL	607	128	406
3	LLNL	837	89	452
4	HYPAC	504	140	143
5	CHECMATE	706	62	98
6	Thunderbolt	554	75	214
7	Maxwell	1800	113	87
8	Maxwell	2590	137	87
9	ACB	2580	87	76
10	CEM-UT	3300	110	100

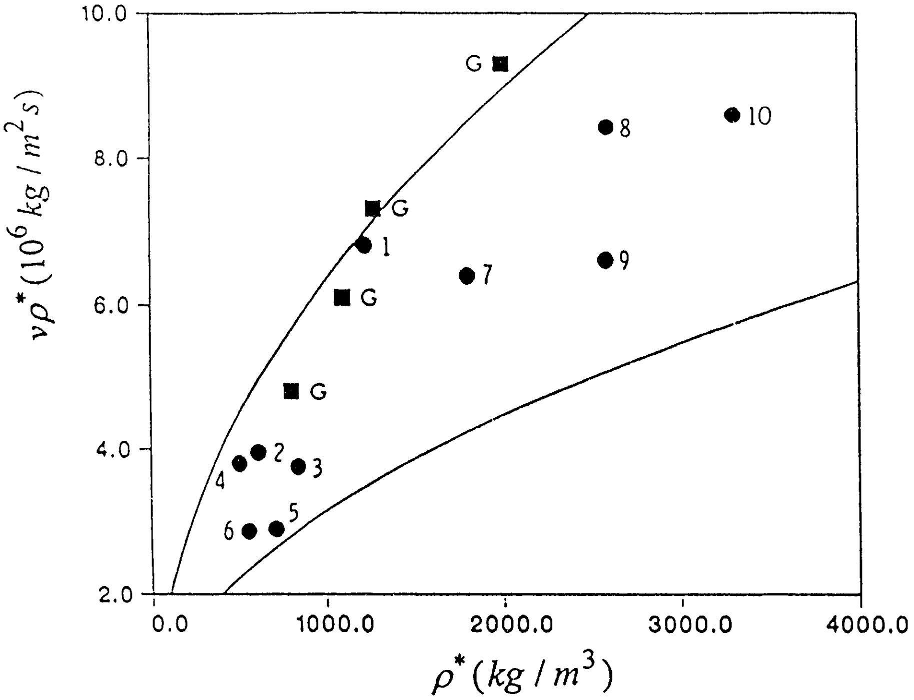

Figure 2. Comparison of railgun data (Tables 1 and 2) with calculated performance of a 300-caliber, light-gas gun. Upper and lower curves are for constant $\overline{P}\ell$ of 200 kbar calibers and 50 kbar calibers. Dots are railgun data, and squares are light-gas gun calculations.

3.3 Railgun Status

Experimental results strongly indicate that high performance railguns are electrically-powered, gas-dynamic rather than electromagnetic guns. This would mean that the physical model used since 1980 is incorrect and that theoretically sound modeling is yet to be done. At velocities above 3 km/s, railgun experiments show a diminishing return for increase in barrel length with total loss of forward-going pressure before a length of 200 calibers. To launch a projectile with adequate ballistic performance with a minimum caliber launch-package at 3 km/s requires 450 kbar calibers (6). Even with a 200-caliber long gun, this specifies a net, average, forward-going pressure of 2.25 kbar. This is about two times the experimentally achieved value at $\ell = 200$ calibers; however, the high performance experiments have launched packages with relatively low effective density (low ρ^*) compared to that for a minimum caliber launch of a practical projectile.

Experimental results suggest that railguns could launch projectiles with good ballistic performance to high velocity by using sabots with highly oversized caliber. This was a technique used for conventional guns in the HARP experiments.[16]

4. THE INDUCTION COILGUN

4.1 Background

Induction coilguns consist of a linear arrangement of many electric coils which form a "barrel" and a metallic armature which must be part of the launch package. Both the current and magnetic field within the armature which produce the launching force are established and maintained by energizing each barrel coil only during the time that the armature is in close proximity. No sliding, electrical contacts are used.

Compared to railguns, induction coilgun hardware is relatively complex ,and high performance is not possible with small caliber and low ρ^*. Therefore, high-velocity experiments are relatively expensive. However, induction coilguns are true electromagnetic launchers that can be accurately modeled.[17,18] Several different concepts have been proposed for induction coilguns,[19-24] but experimental demonstration has been relatively limited. The highest experimental velocity and kinetic energy produced have been 1 km/s and 280 kJ in two different experiments.

4.2 A Potentially Successful Concept

We have studied the proposed concepts for induction coilguns and have concluded that only one has potential to offer substantial advantage over conventional guns. This scheme allows two different geometries, cylindrical or plate, as shown in Fig. 3. The cylindrical geometry has one coil per stage, while the plate geometry may have two or more. Each of these geometries has an outstanding advantage and disadvantage. The cylindrical armature can be incorporated conveniently into a flight package, but axial coil-to-coil forces and radial forces on the armature and coils are greater than the launch forces. In plate geometry, launch forces are the highest forces, but it is difficult to utilize the kinetic energy of the armature.

The coil stages (stages) are separately powered by capacitor banks. Two closing switches are used with each power supply; one to fire the stage, and one to crowbar it at peak current. The stages are fired in simple sequence by a fire-control system as the armature reaches the proper position with respect to each stage. Armature position and velocity must be measured continuously by sensors and that information must be provided to logic circuits in the fire-control system. Each stage is fired when the measured armature position matches the one pre-assigned for that stage. For fault protection, launcher operation may be shut down when armature velocity fails to fall within a pre-assigned range at any stage. Both fiber optic sensors and laser rangers have been successfully employed to measure position and velocity.

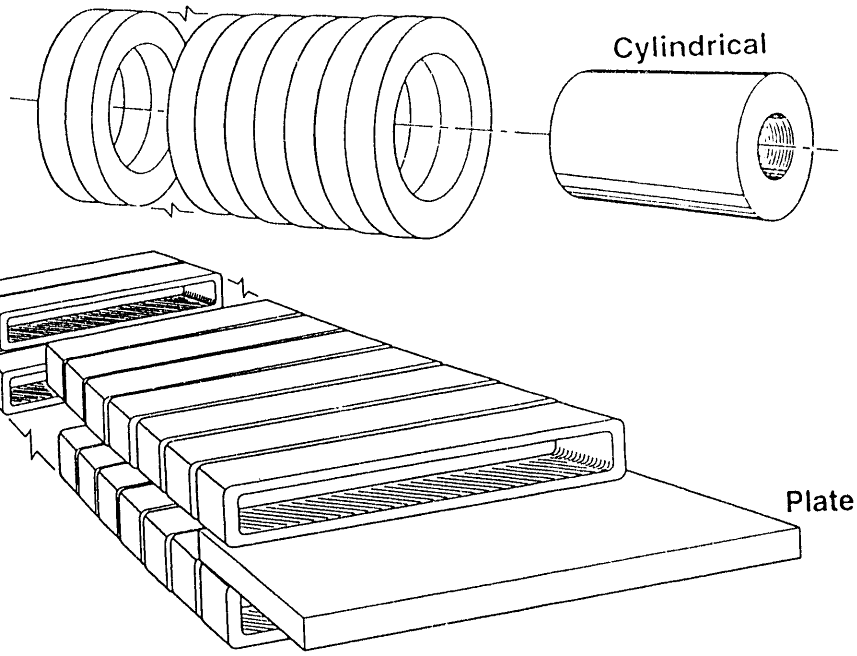

Figure 3. Cylindrical and plate geometries of the induction coilgun.

The armatures may be either solid or wound. In either case, we have found by many code runs that certain geometrical features are required. Both the length and separation of the stages must be made as small as possible and the armature relatively long. This limits high-frequency modulation of armature current which can cause serious heating. It also provides a time for current rise in a stage given by λ/v where λ is a length of armature that maintains nearly constant coupling with a stage as it passes with velocity, v. Thus, the longer the armature, the lower the required power. The increasing power requirements from breech stages to muzzle stages are met by decreasing either capacitance of the power supplies or inductance (turns) of the coils or both. Only a few discrete changes are needed in practice.

Induction coilguns may be operated either with or without both "slip" and "current reversal," giving four possible modes of operation. We will clarify what we mean by these terms. Since induced armature current dies away at some rate, the accelerating force on the armature will too unless something is done. By making the armature long enough to advance or "slip" the induced current into "new metal" as current in "old metal" decays, armature current and accelerating force can be maintained at nearly constant value. To accomplish this, the later a stage is fired, the more its firing position with respect to the armature is advanced toward the muzzle. The cost of this procedure is an additional length of armature. Because of ohmic heating, current may be slipped through the armature only once. If slip is not used, the rate of decay of accelerating force must be satisfactory for the application.

"Current reversal" refers to an intentional change of current direction in the stages. After an appropriate number of stages (determined by code calculation) have been fired with current in one direction, a significant amount of flux from the stationary coils has diffused into the armature. Then, by firing another number of coils with current in the opposite direction, one can take advantage of this diffused-in, antiparallel flux to make important improvements in performance.[25] Since current reversal exacerbates ohmic heating, it may be done no more than two or possibly three times during high-performance launch with wound aluminum armatures.

Code runs have taught us several other things about the cylindrical induction coilgun. With solid aluminum armatures starting at room temperature, the only practical operating mode is with slip and without current reversal. Properly wound armatures can control heating well enough and can have enough time constant to operate in the "no slip-current reversal" mode. With medium bore size (100-200 mm) and high launch "pressure" (~ 2 kbar), efficiency (kinetic energy/stored energy) can be in the 40-50% range for this mode.[25] Due to the large build required for high-pressure coils that produces relatively poor coupling with the armature, much higher efficiency is unlikely. With lower launch pressure and the large scale required for earth-to-orbit launch, efficiencies could approach 80%.

4.3 Induction Coilgun Data

We have built three induction coilguns during the process of learning requirements for competitive performance. Table 3 summarizes their features and performance data. Our first launcher reached the highest velocity but had few of the operational or geometrical features described above that we now know are required for high performance. Our second launcher was our first cylindrical design and the first to incorporate most of the required geometrical features. The third, shown in Fig. 4, is a test bed to develop high-pressure coils for a following launcher that will demonstrate

Table 3.

Coilgun	Bore Size (mm)	Barrel Length, ℓ (m), (calibers)	Projectile Mass (kg)	v (m/s)	ρ^* (kg/m^3)	$\bar{P}$ (kbar-cal)	Efficiency (%)
14-Stage/Plate	131 × 6.5	2.4, 83	0.150	1000	6,100	31	13
6-Stage/Cylindrical	140	0.82, 5.9	5.0	350	2,300	1.3	23
40-Stage/Cylindrical	50	1.6, 34	0.35	770	4,300	12.7	16

Figure 4. The 40-stage, induction coilgun which operates as a testbed for development of high-field coils.

3 km/s or more with competitive forward-going pressure.

Our experimental launchers have used only solid armatures, but wound ones are being developed.

4.4 Induction Coilgun Status

Since armature current is not required to flow through arcs or plasma, operation of an induction coilgun may be accurately simulated without adjustable parameters by fully self-consistent circuit codes such as WARP-10 or its user-friendly successor, SLINGSHOT.[17,18] These codes have correctly predicted results of all our experiments including those which measured armature heating. Still, since code verification extends only to 1 km/s, there remains the physics issue of whether projectile-barrel interactions could create troublesome plasma at higher velocity. Code verification needs to be extended to velocities of interest for applications.

Output from SLINGSHOT may be used with static or dynamic structural codes to calculate stresses and strains on the armature and coils. This has been done recently with the static JAC and the dynamic PRONTO structural codes, and experimental verification has been reasonably successful (measurements within 25% of code predictions). Thus, the necessary computational tools are only now in place to allow design of coils and armatures which are strong enough to produce competitive forward-going launch forces. Such robust coils and armatures are needed not only to compete with powder guns for applications but also to control costs of high-velocity demonstrations. Our present experimental program has a goal of demonstrating a value of 1 kbar for net, average, forward-going "pressure" [$\overline{P}$ of (3)]. To achieve this value with the cylindrical geometry presently being used requires that the coils and armatures be designed to survive much higher axial coil-to-coil and radial coil and armature pressures. This is not the case for plate geometry where the forward-going pressure is the highest pressure produced. Meeting the engineering challenge associated with coils and armatures which produce $\overline{P}$ values of 2 kbar or higher is the key to the eventual utility of induction coilguns.

The armature alone will have a ρ^* value of $\rho^* \sim 4 \times 10^3$ kg/m^3 which can account for a large fraction of launch-package mass. For this reason, it may be appropriate to deliver the armature to the target within the aeroshell of the projectile. Only cylindrical geometry makes this convenient; however, plate geometry may allow much higher $\overline{P}$ values ($\overline{P} \approx 6$ kbar).

5. SUMMARY AND CONCLUSIONS

If electromagnetic guns are to offer substantial advantages over gas-dynamic alternatives for high-velocity endoatmospheric launch, they must be able to produce a substantially larger value for the product of average launch pressure times barrel length for velocities of interest. Since very long barrels are impractical for many applications, the net, average launch pressure, $\overline{P}$, should be as high as possible. A competitive goal is $\overline{P} \geq 2$ kbar (2×10^8 Pa).

Railguns do not appear to offer a clear advantage over gas dynamic-guns. In fact, when they are operated for high performance, they show launch pressure limitations which are more gas dynamic than electromagnetic in nature. Since solid armatures transfer their current to an arc, there is no successful theory which has established the railgun as a true electromagnetic launcher.

The induction coilgun is the only electromagnetic launcher that we know of with a sound theoretical basis to offer substantial advantage over gas-dynamic launchers. However, there are challenges to be overcome before this potential is realized. Most formidable of these are the engineering challenges associated with building coils and armatures that survive the high mechanical and electrical stresses required for competitive launch pressures.

When high launch pressure (~ 2 kbar) is required, the efficiency of induction coilguns will not exceed ~ 50% for bore size less than 200 mm and for aluminum armatures starting at room temperature. Much higher efficiency is possible with modest launch pressures (0.5 kbar) and much larger scale as in the earth-to-orbit application.

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