COILGUN LAUNCHER FOR NANOSATELLITES

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Abstract

Nanosatellite space launches could significantly benefit from an electrically powered launch complex, based on an electromagnetic coil launcher. This paper presents results of studies to estimate the required launcher parameters and some fixed facility issues. This study is based on electromagnetic launch, or electromagnetic gun technology, which is constrained to a coaxial geometry to take advantage of the efficiency of closely-coupled coils. A baseline configuration for analysis considers a payload mass of 10 kg, launch velocity of 6 km/s, a second stage solid booster for orbital insertion, and a payload fraction of about 0. 1. The launch facility is envisioned as an inclined track, 1 - 2 km in length, mounted on a hillside at 25 degrees aimed in the orbital inclination of interest. The launcher energy and power requirements fall in the range of 2000 MJ and 2 MW electric. This energy would be supplied by 400 modules of energy storage and magnetic coils. With a prime power generator of 2 MW, a launch rate of some 200 satellites per day is possible. The launch requires high acceleration, so the satellite package must be hardened to launch acceleration on the order of 1000 gee. Parametric evaluations compare performance parameters for a launcher length of 1 - 2 km, exit velocity of 4 - 8 km/s, and payloads of 1 - 100 kg. The EM launch complex could greatly reduce the amount of fuels handling, reduce the turn-around time between launches, allow more concurrence in launch preparation, reduce the manpower requirements for launch vehicle preparation and increase the reliability of launch by using more standardized vehicle preparations. Most importantly, such a facility could reduce the cost per launch and could give true launch-on-demand capability for nanosatellites.

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Introduction

The use of an electromagnetic launcher for propelling small satellites to orbit has the potential for greatly reducing the cost and complexity of space launch (Lipinski, et al, 1991). An electromagnetic launcher, which produces a high initial launch velocity, could reduce the size of the launch vehicle by eliminating the first stages of a conventional booster. A launcher facility has the additional advantage of being fully reusable and quickly prepared for the next launch. The most efficient use of the launcher is to operate at an exit velocity in the range of 6 km/s, with a small solid-motor booster to achieve final orbit. Hypersonic launch of a satellite into space poses many challenges. The most significant are: (1) high acceleration loads on the payload, (2) thermal management of the projectile while penetrating the densest portion of the atmosphere at high speed; (3) energy storage and high power switching, (3) mechanical and electrical stresses on coils. Less critical challenges include: (1) high-speed projectile drag; (2) sonic effects on both the environment and the projectile; (3) stability and control of the projectile; (4) the ability for the vehicle to rendezvous with targets already in orbit; and (5) cost effectiveness.

Electromagnetic launch should prove cost-effective for any application which requires frequent launch of small payloads, provided the payloads can be hardened against the acceleration of launch. A gun launcher would be suitable for deployment and replenishment of constellations of low-earth orbit communication satellites, "over-night" delivery of small packages to the space station, launch of station-keeping fuel and other supplies for the space station, and launch of low-altitude, rapid-response military sensors or environmental monitors.

Electromagnetic Coilgun Launcher

An electromagnetic coilgun is an attractive option for the electrically powered launcher because it accelerates its payload with pulsed magnetic fields, without a tight, abrasive fit in the barrel, and without direct electrical contacts that generate arcing. A coilgun operates by inductive forces. It consists of a series of solenoidal coils which are energized at the appropriate time by computer control. Figure 1 shows a longitudinal cross-section of the armature and surrounding solenoidal coils. The armature, which pushes the flight package is a thick-walled aluminum cylinder and may have an internal shell of graphite epoxy or ceramic for compressive strength. When a coil is energized with the armature inside it, the rising magnetic field induces a circular current in the armature. The interaction of the armature current with the radial component of the coil magnetic field drives the armature and flight package forward.

In order to propel the armature continuously forward, each coil must be energized synchronously with the armature. The propulsive force is created by the mutual repulsion between a pulsed solenoidal magnetic field and the induced currents in a conductive armature, as shown in Figure 1. Continuous acceleration of the armature is achieved by sequential switching of energy storage modules into successive coils to create a magnetic traveling wave that propels the armature and the entire launch vehicle forward. Switch synchronization and control can be achieved by a sense and fire control system, such as a laser ranger-based system that was used in previous demonstration experiments. In experiments with a 1 km/s launcher at Sandia (Kaye, et al. 1994), this sense and fire control system was based on a laser range-finding beam injected through the gun to determine the location of the launch package. A benefit of this real-time sensing and firing technique is the ability to accurately control the exit velocity of the flight package. Given the high degree of repeatability achievable with the system, however, a preprogrammed firing sequence may be adequate. The strength of the magnetic field seen by the armature is a sine function with quarter wavelength equal to about half the armature length, and magnitude approximately 20 Tesla. This wave is nearly frozen in the rest frame of the armature (although it is made to drift forward slowly by advancing the timing of the coils slightly). This operational technique reduces oscillating currents on the surface of the armature and reduces the heat load to the armature.

Figure 2 is a schematic drawing of the launcher facility for 10 - 100 kg payloads launched at initial velocity of 6 km/s at 25 degree elevation angle. The facility would consist of a coilgun launcher, the associated support buildings, energy storage system, launch packages, launcher support systems, and the control and monitoring systems. Ideally, this facility would be located at high altitude to minimize air drag, and have a large downrange area for safety restrictions.

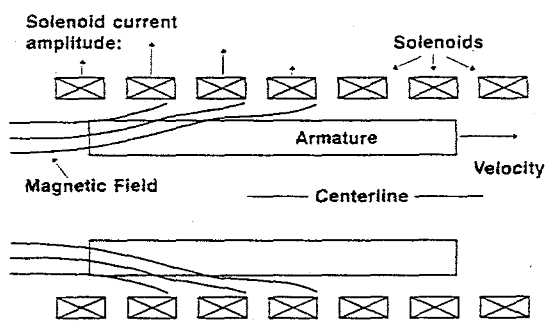

Figure 1. Cross-section of a cylindrical armature inside solenoidal coils in a coilgun.

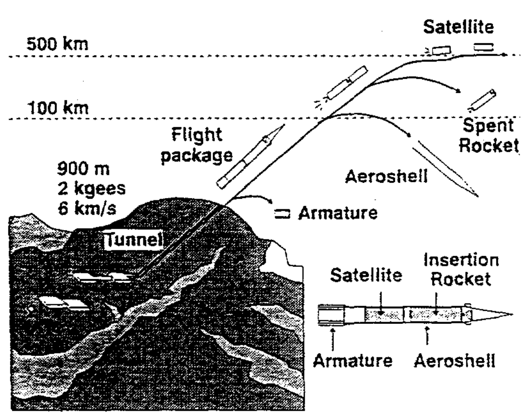

Figure 2. Overview of the hypervelocity coilgun launcher concept.

Each coil has its own energy storage module, so the energy to be imparted to the launch package is distributed along the entire length of the launcher. Since the launcher is modular, the launcher pieces can be mass-produced in large numbers, which will reduce their cost and risk. Maintenance of a damaged section or coil also is simplified by this modularity.

To reduce drag and shock effects of supersonic flight within the launcher, the flight package travels through an evacuated flyway tube to an exit velocity of 6 km/s. This flyway tube is constructed of fiber-reinforced plastic, and serves the added function of alignment and stabilization during launch. A thin foil breakaway window is located at the exit. The flight package consists of the satellite, an orbital insertion rocket, guidance, and an aeroshell, and is pushed through the coilgun by an armature. After launch, the armature separates, slows and falls to the earth within a few miles because of its poor aerodynamic shape. The flight package is designed for atmospheric penetration, essentially a low drag supersonic projectile shape with ablative heat shield construction. The aeroshell protects the package from atmospheric heating, and then is petaled open and ejected. Once open, the pieces of the aeroshell are much less robust against atmospheric heating and thus burn up upon re-entry. The insertion rocket then ignites and circularizes the orbit of the satellite. The rocket detaches from the satellite and makes a final small braking burn to assure that it reenters the atmosphere.

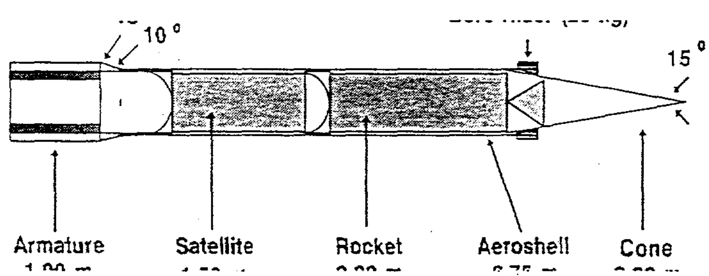

Figure 3. Baseline Launch Package Configuration.

Launch Package Concept

The launch package is shown in Figure 3. The launch package consists of the armature, aeroshell, orbital insertion rocket, satellite, and nose bore-rider (sabot). The flight package is the launch package minus the armature and the bore-rider. Flight stability of the launch vehicle is achieved by either passive or active means. Having passive stability, which cannot be achieved with rockets, is desirable, in that the inherent stability of the vehicle would reduce the uncertainty in trajectory, and could reduce the complexity of launch vehicle control and safety assurance. In order to achieve passive stability (i.e., a static margin of at least 7%), the heavier and denser masses must be near the front of the package, as shown in Figure 3. The forward section of the vehicle must be a conical or ogive shape for aerodynamic drag reduction. A hollow frustum or a large flare is needed at the tail of the package to move the center of pressure behind the center of mass.

A concern for all forms of gun launch is the high acceleration. The satellite and the flight package both must be acceleration-hardened to withstand about a thousand times the force of gravity (one kilogee). However, this can be done by proven techniques such as tying down loose wires, potting electronics in plastic, avoiding cantilevered elements, and making the structure as compact as possible. Military shells are trending toward greater complexity and already have demonstrated the ability to be hardened against acceleration at levels of more than 10 kilogees.

Hypervelocity transit through the lower atmosphere requires an ablative heat shield (Lipinski, et al 1991). The heat loading on the aeroshell during the flight through the atmosphere was determined by experimentally validated codes used at Sandia (Blackwell and Kaestner 1970). These codes were then used to determine the appropriate thickness of heat shield needed. The highest temperature experienced inside the aeroshell is about 30 C. This temperature is reached in about 35 seconds.

Launch Parameter Study

In this section, we evaluate the performance of the electromagnetic launcher over the 1-100 kg payload range, varying the exit velocity over the range for launch velocities 3 to 10 km/s. The following analytical approach is used (Turman,1994). (1) The velocity lost from atmospheric drag is first calculated for the given initial launch velocity, using an estimated hypersonic drag derived from the vehicle shape (Lipinski, et. al. 1991). (2) Additional equations yield the velocity and altitude at the apogee of the ballistic arc, and from this the incremental velocity needed to attain the desired orbital altitude is calculated. (3) This delta-v is used to size the rocket booster, using an assumed solid-motor of 290 seconds specific impulse. (4) Aeroshell mass is calculated on the basis of the size of the vehicle and the ablative thickness required for transit through the atmosphere. (5) The mass of the armature is calculated from the vehicle size, the thickness needed to support the induced eddy currents, and the limits of structural strength of the material. (6) These calculations thus give the mass of the complete launch vehicle. The kinetic energy is calculated from the launch velocity and vehicle mass. The conversion efficiency from electrical energy to kinetic energy is assumed to be 64% (Zabar, 1989). (7) Acceleration through the launcher will be uniform. (8) Incremental launch costs were based on the cost of booster rocket, armature, and aeroshell (based on material and fabrication costs). (9) The facility cost was scaled from the cost estimates made for the capacitor system point design discussed in the previous section.

Table 1 summarizes important parameters for the launcher, for a base case of 10 kg launched to 500 km orbital altitude. Figures 4 – 7 show variations around these base parameters. A fixed launcher length of 2 km is assumed, so a lower launch velocity implies a lower acceleration. Note that the launch vehicle kinetic energy is in the range of 1 to 12 GJ and is not a strong function of the launch velocity. This is due to the fact that more rocket booster mass must be launched at reduced launch velocity. Vehicle acceleration varies from 400 to 6000 gees.

A key question is of course the cost of such a facility and the incremental launch costs. These costs can be estimated from the vehicle cost and facility cost. The launch parameter optimization includes a first order design for the vehicle, based on a 20:1 length/diameter ratio, the component masses, and thickness based on structural strength and temperature requirements. Vehicle component costs are calculated with these assumptions (Lipinski, 1991): aeroshell- \$1000/kg, solid rocket booster- \$300/kg, armature- \$100/kg. Launch vehicle costs per satellite mass are in the range of \$1000 - \$20,000 /kg, with the lower costs coming from the higher initial launch velocity, as shown in Figure 8.

Facility cost estimates are given in Table 2. Here the energy storage cost is based on a value of \$0.05/J, a value consistent with today's cost of capacitive energy storage. Power conditioning/switching is based on 20% of the energy storage cost, and the other items are scaled from cost evaluations conducted by Lipinski, et al, 1991. The total cost estimate is thus about \$760 M for a 10 kg launcher, and about \$1380M for a 100 kg launch capability. A cost per launch estimate is shown in Figure 9, where the facility cost is prorated over a 50,000 shot lifetime assumption. In this case, then, the cost per launch is in the range of \$2000/kg for a 100 kg satellite, and \$10,000/kg for a 10 kg satellite. These numbers are of course only approximations, and should be used for qualitative, not quantitative comparisons.

TABLE 1. Baseline Launcher Technical Specification.

Satellite Mass (kg)	10
Equatorial launch	
Orbit altitude (km)	500
Launch velocity (km/s)	6
Launcher length (m)	2000
Ave. acceleration (gee)	900
Launch duration (s)	0.67
Inclination (degrees)	25
Launch altitude (m)	3000
Launch mass (kg)	144
Flight vehicle mass (kg)	139
Armature mass (kg)	5
Armature diameter (m)	0.24
Flight vehicle length (m)	2.30
Electrical efficiency	0.64
Launch kinetic energy (GJ)	2.60
Initial stored energy (GJ)	4.10

Table 2
Launcher Facility Cost Estimate

Component	10 kg Satellite	100 kg Satellite
Energy storage and switching	$370 M	$950 M
Controls	$ 50 M	$ 50 M
Prime Power (50 MW)	$100 M	$100 M
Coils and launch structure	$100 M	$ 120 M
Buildings	$140 M	$160 M
Total	$760 M	$1380 M

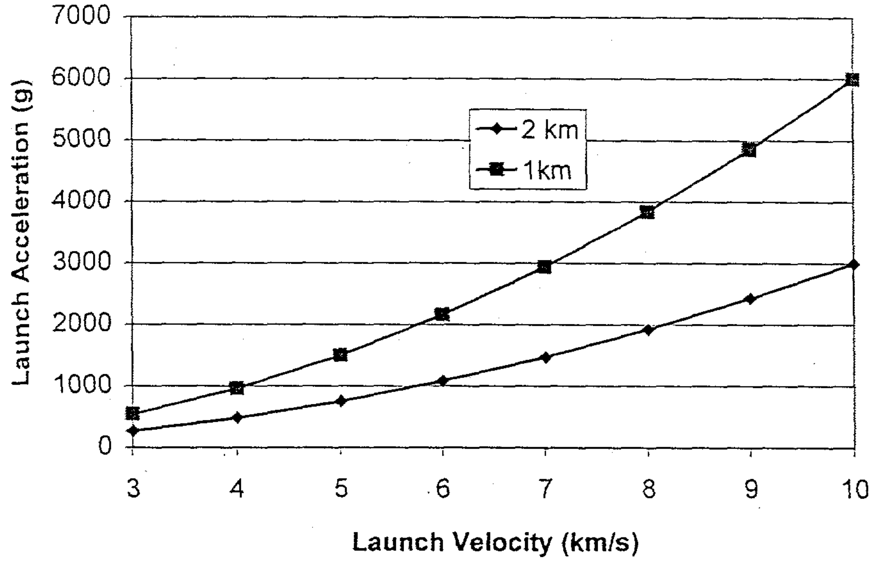

Figure 4. Launch acceleration versus launch velocity.

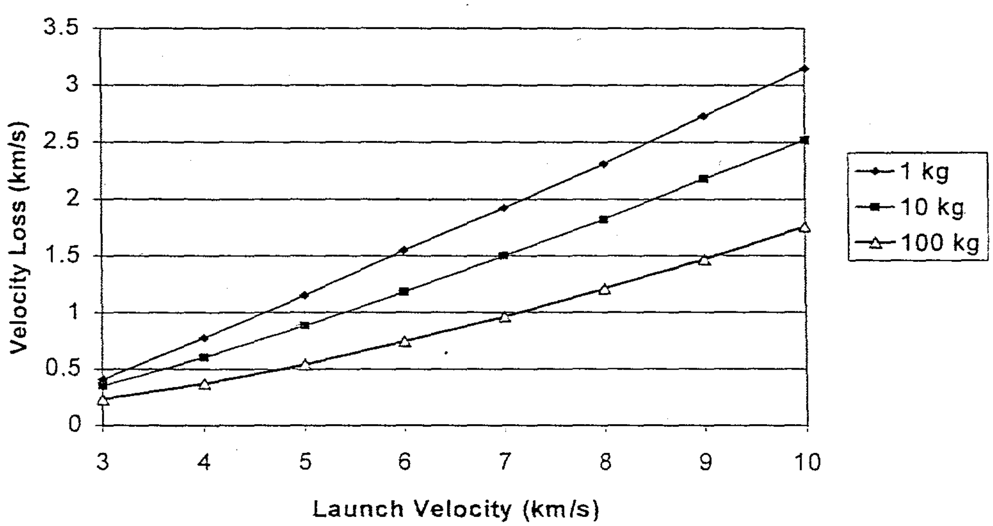

Figure 5. Velocity loss due to drag, versus launch velocity.

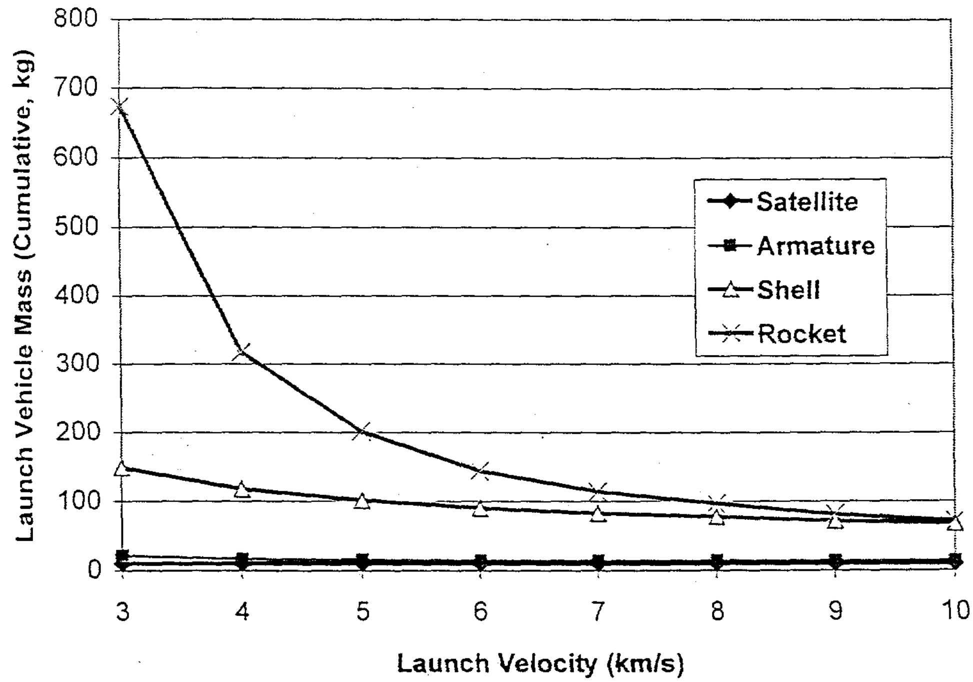

Figure 6. Launch vehicle mass versus launch velocity.

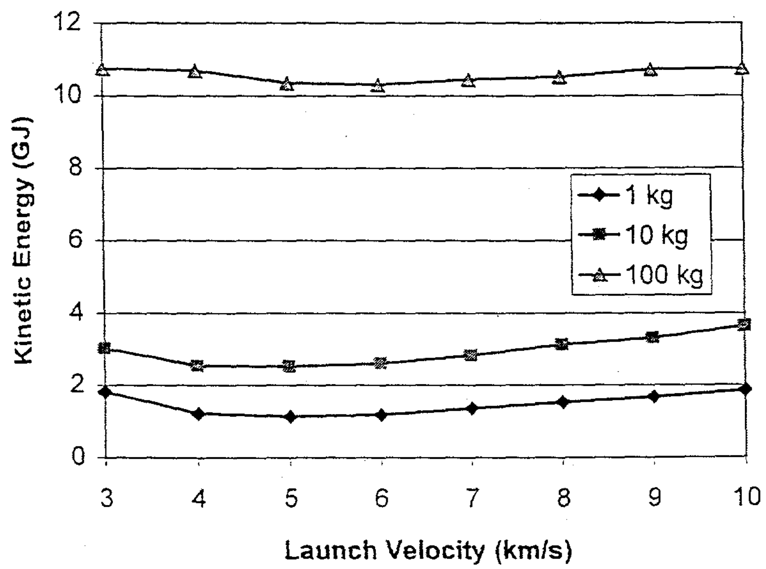

Figure 7. Kinetic energy versus launch velocity.

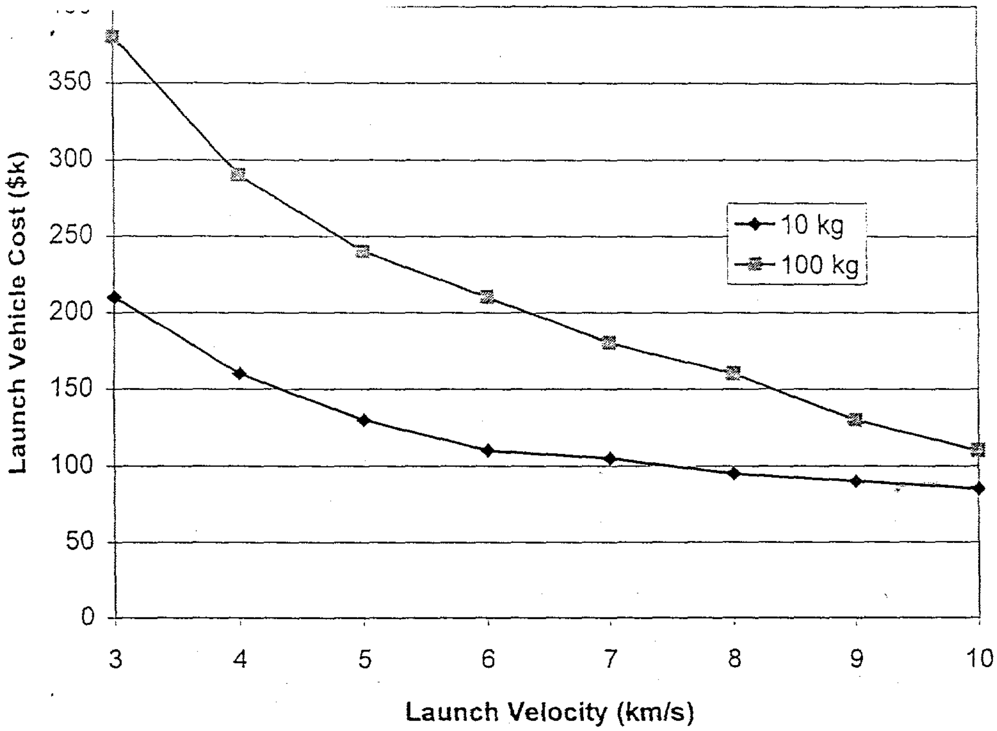

Figure 8. Launch vehicle cost estimates

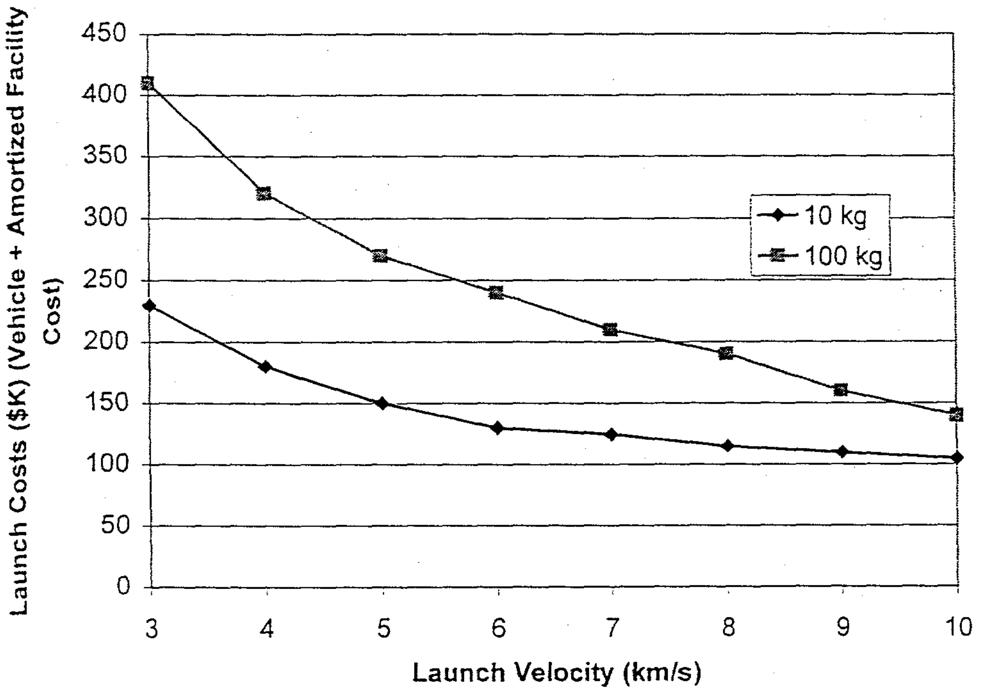

Figure 9. Incremental launch cost, including launch vehicle and prorated facility cost.

Conclusions

For a satellite payload of 10-100 kg, the launcher electrical energy requirement is 2-12 GJ, and the peak power requirement is 6 - 30 GW. At these power levels, a system of energy storage and fast switching will be needed. In the baseline concept, the temporary energy storage is accomplished with capacitors. Energy from the capacitors is switched into the propulsion coils on the microsecond time scale. With 9000 propulsion coils, each coil is energized with 1 MJ of energy. The technology for such capacitor-coil combinations is available now, and has been demonstrated in high-velocity launcher experiments at the level of 60 kJ electrical energy (Kaye, et al, 1994). The capacitor cost is a major portion of the total launcher cost.

The launcher energy requirement is a weak function of launch velocity over the range from 3-10 km/s, because the rocket mass increases as launch velocity is reduced. Facility cost is also a weak function of launch velocity, since facility cost is dominated by the energy requirement. For 100 kg launch capability, the total facility cost is estimated to be about $1.4 B, and $0.8 B for a 10 kg launch capability. The incremental launch cost increases as launch velocity is reduced, driven by the increased mass and cost of the booster rocket. The incremental cost for 100 kg at 6 km/s is about $2500/kg ($1200/lb), and for a 10 kg satellite the incremental cost is about $10,000/kg ($4,500/lb). This compares favorably to present-day launch costs of some $10,000/kg.for a heavy booster, and $50,000/kg for a Pegasus launch. Thus the ease and simplicity of a standardized "factory" operation, and launch-on-demand capability for single or multiple small satellites can be achieved at, or possibly below, the launch cost of heavy lift boosters.

With a 2 km launcher, the peak acceleration is 1000-6000 gee's. The payload must be hardened to this acceleration, but such hardening is now within the state-of-the art for hardened military weapon electronics.

The lower incremental launch cost, ease, and simplicity of the totally reusable launcher and drastically reduced chemical propellants offer an attractive potential for launching satellites with missions that require a large number of launches. Further development work is required to determine in greater detail the optimum design for the launcher, including the proper choice for power technology.

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