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Maglev Launch: Ultra Low Cost Ultra/High Volume Access to Space for Cargo and Humans

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Abstract. Despite decades of efforts to reduce rocket launch costs, improvements are marginal. Launch cost to LEO for cargo is ~$10,000 per kg of payload, and to higher orbit and beyond much greater. Human access to the ISS costs $20 million for a single passenger. Unless launch costs are greatly reduced, large scale commercial use and human exploration of the solar system will not occur. A new approach for ultra low cost access to space – Maglev Launch – magnetically accelerates levitated spacecraft to orbital speeds, 8 km/sec or more, in evacuated tunnels on the surface, using Maglev technology like that operating in Japan for high speed passenger transport. The cost of electric energy to reach orbital speed is less than $1 per kilogram of payload. Two Maglev launch systems are described, the Gen-1System for unmanned cargo craft to orbit and Gen-2, for large-scale access of human to space. Magnetically levitated and propelled Gen-1 cargo craft accelerate in a 100 kilometer long evacuated tunnel, entering the atmosphere at the tunnel exit, which is located in high altitude terrain (~5000 meters) through an electrically powered "MHD Window" that prevents outside air from flowing into the tunnel. The Gen-1 cargo craft then coasts upwards to space where a small rocket burn, ~0.5 km/sec establishes, the final orbit. The Gen-1 reference design launches a 40 ton, 2 meter diameter spacecraft with 35 tons of payload. At 12 launches per day, a single Gen-1 facility could launch 150,000 tons annually. Using present costs for tunneling, superconductors, cryogenic equipment, materials, etc., the projected construction cost for the Gen-1 facility is 20 billion dollars. Amortization cost, plus Spacecraft and O&M costs, total $43 per kg of payload. For polar orbit launches, sites exist in Alaska, Russia, and China. For equatorial orbit launches, sites exist in the Andes and Africa. With funding, the Gen-1 system could operate by 2020 AD. The Gen-2 system requires more advanced technology. Passenger spacecraft enter the atmosphere at 70,000 feet, where deceleration is acceptable. A levitated evacuated launch tube is used, with the levitation force generated by magnetic interaction between superconducting cables on the levitated launch tube and superconducting cables on the ground beneath. The Gen-2 system could launch 100's of thousands of passengers per year, and operate by 2030 AD. Maglev launch will enable large human scale exploration of space, thousands of gigawatts of space solar power satellites for beamed power to Earth, a robust defense against asteroids and comets, and many other applications not possible now.

Keywords: Maglev, space launch, superconductor.
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I. GOING BEYOND ROCKETS

Space exploration and commerce have been limited by the high cost of launching people and payloads into orbit and beyond. Placing a kilogram of payload into low Earth orbit (LEO) costs almost $10,000, while a human at the International Space Station costs 20 million dollars. Payloads to GEO costs an order of magnitude more, while to the moon and Mars, the costs are much greater still. Over the last 40 years, efforts to develop lower cost launch systems, including fully reusable launch vehicles, scramjets, single stage to orbit, etc have failed. No realistic approaches for large reductions in launch costs, using chemical propellants, have been found.

The recent NASA panel on the future of NASA's Constellation program recommends not proceeding with the proposed return to the Moon. The high cost and complexity of rocket launch appear to rule out affordable and effective human exploration of space beyond the ISS.

II. STARTRAM – A NEW ROAD TO SPACE

The energy cost to deliver payloads to orbit is tiny, if directly applied to the payload itself. At 8 kilometers per second, the kinetic energy of a kilogram of mass is only 32 megajoules, or 8.9 kilowatt hours. At 6 cents per KWH, the average US electrical production cost, this is only 53 cents per kilogram of payload – 10,000 times smaller than present launch costs. On an airless planet, launching heavy payloads into space would be incredibly cheap and easy. Using Maglev (Magnetic Levitation), heavy vehicles are magnetically levitated above a guideway without mechanical contact or friction, and magnetically propelled at high speeds. Maglev systems already operate in Japan and other countries for passenger transport and levitate hundreds of tons. Vehicle speeds of 360 mph are achieved, limited only by air drag. In low pressure tunnels, vehicle speed is virtually unlimited. Instead of rockets, the StarTram system magnetically levitates and accelerates spacecraft to orbital speeds, ~8 km/sec, in evacuated tunnels in elevated terrain. They then enter the atmosphere at reduced air density, and coast upwards to orbit. A small ΔV burn by a compact, attached rocket finalizes the spacecraft's orbit.

Conventional rockets locate their expensive, complex equipment on the launch vehicle. StarTram locates its expensive, complex equipment on the ground. With a simple low cost launch craft, StarTram reuses its ground equipment for many launches. World rocket launches are only a few hundred tons of payload annually. A single StarTram facility can launch hundreds of thousands of tons of payload per year, at a cost of only \$50 per kilogram. StarTram will vastly increase space exploration and commerce, including manned bases on the moons and Mars, exploration of the moons of the giant planets, interstellar probes, multi-gigawatt space power satellites that beam power to Earth, space hotels and tourism, space manufacturing, worldwide continuous environmental monitoring, high bandwidth communications, etc. A single StarTram facility could deploy 100 gigawatts(e) of space solar power satellites per year at a launch cost of only 200 dollars per KW(e), a small fraction of Earth based power plant costs. In only a decade 1 billion KW(e) of space solar power could be deployed, a third of the World's need. With only 3 StarTram launch facilities, all of the World's electric power needs could be met by space solar power in just 10 years.

III. MAGLEV TECHNOLOGY

StarTram spacecraft are magnetically levitated and propelled in an evacuated acceleration tunnel at ground level using the superconducting Maglev system invented by Powell and Danby in 1966 (1) for transport of passengers and freight. Based on their inventions, Japan Railways (JR) is operating superconducting Maglev trains on a 21 kilometer test track in Yamanashi Prefecture with total levitation weights up to 200 metric tons in multi vehicle consists. Speeds of 360 mph are achieved, limited only by air drag. Figure 3.1 shows a JR Maglev vehicle on the Yamanashi guideway, with Mt. Fuji in the background. Since its inauguration in 1997, JR Maglev has carried over 50,000 passengers without problems, and accumulated running distances of over 300,000 kilometers. Table 3.1 summarizes the features and capabilities of the JR Maglev system.

Figure 3.1 Maglev with Mt. Fuji.

Table 3.1 Japanese Maglev System Features and Capabilities.

Japanese Maglev System Features and Capabilities

- Based on Powell-Danby Maglev inventions in 1960's/70's
- Uses superconducting (SC) magnets on vehicle and normal aluminum loops on guideway
  - SC magnets induce currents in aluminum guideway loops to levitate moving
  - Levitation is automatic and inherently strongly stable in all directions
  - Vehicle is levitated 10 cm above guideway
  - Vehicle is magnetically propelled by AC current in Linear Synchronous Motor (LSM) windings on guideway
  - Vehicle speed controlled by AC frequency
- Japanese Maglev System has demonstrated
  - Speeds up to 360 mph (limited by air drag)
  - Levitated vehicle weights up to 200 metric tons
  - Carried over 50,000 passengers
  - Accumulated running distance >300,000 km
- Japan plans 500 km Maglev route between Tokyo and Osaka to carry >100,000 passengers daily

StarTram spacecraft are levitated and accelerated using technology similar to the JR Maglev system. Superconducting (SC) magnets on the moving spacecraft induce currents in ambient temperature ordinary aluminum loops on the acceleration tunnel walls. The induced currents magnetically interact with the SC magnets on the spacecraft, levitating it with a clearance from the wall of 10 centimeters, and automatically magnetically stabilizing it vertically and horizontally so that it cannot contact the wall. A separate set of aluminum loops on the tunnel wall carries an AC current that magnetically pushes on the vehicle's SC magnets, accelerating it. The spacecraft is phase locked into the AC current wave and travels at its speed, increasing speed as the AC frequency increases.

Powell and Danby have developed and successfully tested components for an advanced 2nd generation Maglev-2000 system that is much cheaper to construct than the Japanese system, with much greater capability. The M-2000 vehicles operate on an elevated monorail guideway at 300 mph for high speed intercity transport. When the vehicles reach the suburban and urban regions of a city, they switch to levitated travel along existing railroad tracks modified for Maglev travel (conventional trains can still use the RR tracks, given appropriate scheduling), avoiding expensive and disruptive new construction in heavily populated areas.

IV. THE GEN-1 AND GEN-2 MAGLEV LAUNCH SYSTEMS

Two types of StarTram systems are possible (Table 4.1). Gen-1, the first generation system, is a high g cargo launch system. After reaching orbital speed, the Gen-1 cargo vehicle leaves the acceleration tunnel at a high altitude, still at ground level. The vehicle then coasts up to orbit through the remaining atmosphere, experiencing strong but manageable aerodynamic heating and deceleration forces. Due to the low energy cost per kilogram, large amounts of protective coatings and coolants for the cargo craft do not significantly increase launch cost.

The second generation StarTram system, the Gen-2, launches both passengers and cargo. Gen-2 spacecraft accelerate at only 2 to 3 g instead of 20 to 30 g for Gen-1, in a longer acceleration tunnel. To avoid the high aerodynamic heating and deceleration forces experienced by Gen-1 cargo craft, the Gen-2 spacecraft transitions from its ground level evacuated acceleration tunnel into an evacuated magnetically levitated launch tube that ascends to very high altitude, e.g., ~20 km (65,000 feet), where it enters the atmosphere. At this altitude, air density is only a few percent of that at ground level, resulting in low aerodynamic heating and deceleration forces.

The technology base for Gen-1 StarTram systems – Maglev, superconductors and vehicle structures capable of withstanding high heating rate – already exists. A Gen-1 facility could begin operation in the next 10 to 20 years. The Gen-1 and Gen-2 StarTram systems (2, 3, 4, 5) use the same approach for levitating and accelerating spacecraft to orbital speed, with the principal difference being the acceleration level. At the Gen-1 tunnel exit, the StarTram cargo craft enters the atmosphere through a "MHD window". A mechanical shutter closes off the evacuated tube between launches, opening a few seconds before the launch, minimizing air leakage through the MHD window. To reduce aerodynamic drag and heating of the StarTram craft as it travels in the atmosphere, the altitude of the exit point should be as high as possible; typically, in the range of 4000 to 8000 meters (13,000 to 26,000 feet). Analyses of atmospheric drag and heating indicate that the cargo craft can coast up to orbit without damage.

The larger, lower g Gen-2 passenger/cargo StarTram spacecraft enter an evacuated, magnetically levitated tube and coast upwards to ~20 km (65,000 feet) where they enter the atmosphere. The launch tube has high current superconducting (SC) cables that magnetically interact with a second set of high current SC cables on the surface beneath, creating a levitation force of several metric tons per meter of tube length. The levitation force is greater than the weight of the launch tube plus its SC cables and tethers, resulting in a net upwards force on the tube. In turn, the levitated tube is anchored to the ground by high tensile strength, lightweight Kevlar or Spectra tethers. (Figure 4.1) For insertion into LEO orbit, the required ΔV of 0.34 km/sec is easily supplied by a small rocket on the StarTram spacecraft. For a GEO orbit, the ΔV burn is somewhat larger, 1.5 km/sec. Figure 4.2 shows the ascent trajectories to LEO and GEO orbits.

The sonic boom of StarTram spacecraft can be a problem if launched over a populated area. Using the approach of Carlson (6), sonic boom overpressure at sea level was calculated. For launch conditions of 22 km altitude and a launch velocity of 7 km/sec, the sonic boom overpressure is 80 Pa. (To put this in context, Ishmael reported (7) that up to sonic boom overpressures of 35 Pa, none of the population was annoyed. At 48 Pa, 10% of the population was annoyed. Above 142 Pa, all were annoyed.) Clearly StarTram cannot be located in a populated area, such as Cape

Canaveral. It could overfly a downrange populated area (based on noise considerations only) because when the vehicle reaches an altitude of 30 km, the overpressure is only 35 Pa, where none of the population is annoyed. Thus, from the sonic boom standpoint remote sites of the StarTram are desirable.

Table 4.1 Two StarTram Systems.

Two StarTram Systems

Gen-1 System	Gen-2 System
Cargo only, non reusable vehicle	Passenger & cargo reusable spacecraft
High acceleration (30 G)	Low acceleration (~2 to 3 g)
Short acceleration tunnel (~100 km @ 8 km/sec)	Long acceleration tunnel (~1000 km @ 8 km/sec)
Launch from surface into atmosphere @ high elevation (≥ 4000 meters)	Launch into atmosphere @ ≥ 20 km altitude
Coast upwards thru atmosphere to orbit	Coast upwards thru magnetically levitated, evacuated launch tube to ≥20 Atm before entering atmosphere
Substantial aerodynamic deceleration (~10 G) and heating rates (~25 KW/cm^2 at Stagnation Point)	Modest aerodynamic deceleration (~1G) and heating rates (~3 KW/cm^2 at Stagnation Point)
Near term (next 10 to 20 years)	Longer term (20 to 30 years)

Between the implementation of the Gen-1 cargo launch system and the more challenging Gen-2 passenger launch system, an intermediate passenger system, called Gen-1.5 may be desirable. It would launch passenger spacecraft from the surface at less than 8 km/sec orbital speed, say 4 km/sec, in high altitude terrain, e.g., 6000 meters. The resultant maximum deceleration of ~2 g for a few seconds as the spacecraft ascended through the atmosphere would be acceptable. No levitated launch tube would be needed. A rocket ΔV burn of ~4 km/sec would be necessary, but the amount of propellant needed would be much less than needed for a rocket only launch. Access of 100's of thousands humans to space would not be practical, using Gen-1.5, but it would enable very robust human exploration of space.

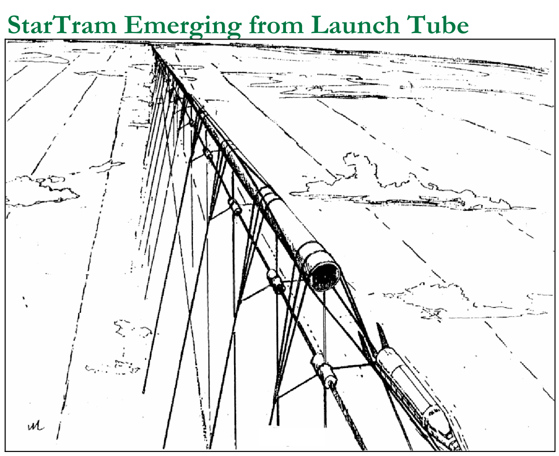


Figure 4.1 StarTram Emerging from Launch Tube.

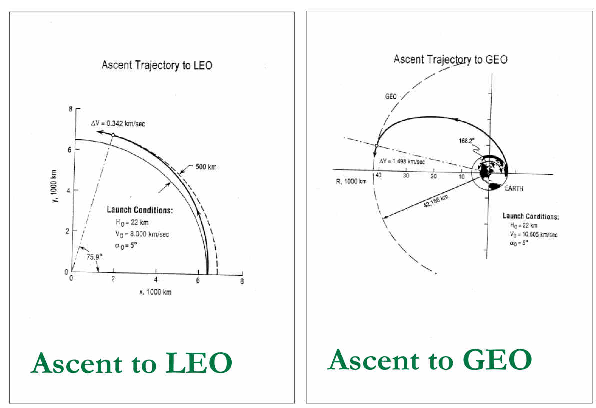


Figure 4.2 Ascent to LEO and Ascent to GEO

V. DESIGN, PERFORMANCE AND COST OF THE GEN-1 SYSTEM

The Gen-1 system does not use a magnetically levitated evacuated launch tube, but launches cargo craft directly into the atmosphere from the end of the ground acceleration tunnel. The StarTram cargo craft can be designed to handle their aerodynamic heating and deceleration forces. Table 5.1 summarizes the principal features and capabilities of the Gen-1 StarTram system. The cargo craft has a nominal diameter of 2 meters and a length of 13 meters, with a total weight of 40 metric tons comprising a 35 ton payload and 5 ton structural weight. The cargo craft has 12 lines of superconducting (SC) loops, with each line of loops occupying a 30 degree section of the surface. Each line has

12 independent SC loops of alternating magnetic polarity. Each loop has a width of 0.50 meter and a length along the cargo craft of 1.0 meter. Figure 5.1 shows the Gen-1 cargo craft in the acceleration tunnel.

Table 5.1

Gen-1 StarTram Features and Capabilities

- Gen-1 Maglev levitation and LSM propulsion design based on Powell-Danby inventions and Japanese operating Maglev system
- Uses mature reliable, low cost Nb-Ti superconductor and cryogenic system technology
- Electrical launch energy generated by conventional power plant and stored for acceleration in Superconducting Magnetic Energy Storage (SMES) loops
  - Stored DC energy converted to AC power for LSM propulsion during acceleration using electronic inverter devices
- Exit of evacuated acceleration tunnel is closed to atmosphere by mechanical shutter and outer thin plastic film
  - After Gen-1 cargo craft exits external air leakage into tunnel while shutter is closing is minimized by "MHD Pump" that forces ionized air outwards
- Gen-1 cargo craft reference design
  - 2 meters OD, 13 meters long, 8 km/sec launch velocity
  - 40 metric ton total weight, 35 ton payload
  - 10 launches daily, 128,000 tons of payload per year
  - 30 G acceleration

Layout of Cargo Craft Geometry

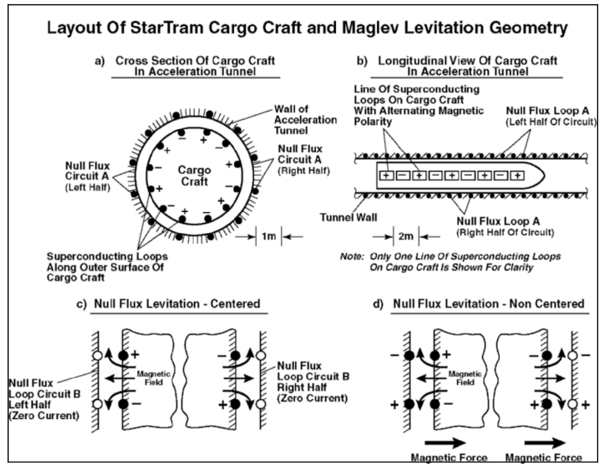


Figure 5.1 Layout of Cargo Craft Geometry

Located on the acceleration tunnel wall are ambient temperature, non-superconducting, null flux aluminum loops. Currents induced in the loops by the magnetic fields of the SC loops on the moving cargo craft interact with the SC loops to levitate and stabilize it. Any displacement of the cargo craft from its centered position in the tunnel automatically generates a very strong magnetic opposing force (~2 g per centimeter of displacement) that pushes the craft back to its centered position.

Because of the magnetic fields from the crafts SC loops are very strong, the currents in the aluminum loops on the tunnel wall are very small. For a restoring force of 2 g, only 9000 amps flows in the aluminum null flux loops. There is a very small I^2R loss in the aluminum loops due to their non-zero electrical resistance. To magnetically levitate the 40 ton cargo craft ~200 kilowatts of power is required, assuming a 1x1 inch aluminum conductor. This power corresponds to a magnetic retarding force $<10^{-3}$ g on the craft at 8 km/sec, negligible compared to the 30 g magnetic acceleration force. The temperature rise in the aluminum conductors as the craft passes is less than 10^{-2} K. The cargo craft is magnetically accelerated by an AC current in a second set of aluminum loops on the wall that push on the SC loops on the craft, producing a magnetic force in the direction of motion (Figure 5.2). The cargo craft "rides" the AC current wave, much as a surfer rides a water wave, and moves at the speed of the wave. The AC frequency increases with time, accelerating the cargo craft. This method, termed the Linear Synchronous Motor (LSM), propels the Maglev vehicles now operating in Japan.

At 8 km per second, the 40 metric ton cargo craft has a kinetic energy of 1280 gigajoules, corresponding to 20 minutes of output from a 1000 MW(e) power plant. At 6 cents per KWH, the energy cost is just $0.50 per kilogram of payload, and only $21,000 for the 40 ton cargo craft. Storing and delivering the energy in less than 30 seconds to the cargo craft as it accelerates at 30 g to orbital speed is the challenge. The average electric power demand during acceleration is 47 gigawatts, with a peak power of 94 gigawatts when orbital speed, 8 km/sec, is reached. (Figure 5.3) Such large power demands rule out conventional generation methods, though pulsed MHD generation might be an option. Superconducting magnetic energy storage (SMES) is the best approach. SMES systems have operated, though not yet at the scale required for StarTram. However, recent advances in superconducting and cryogenic technology make it attractive for the Gen-1 system. A circular loop of superconducting (SC) cable 250 meters in diameter carrying 10 megamp turns of current stores ~50 gigajoules of electrical energy. 60 such loops would store 3000 gigajoules, almost 3 times the energy needed to accelerate the 40 ton Gen-1 cargo craft to 8 km/sec.

The SC energy storage loops would be distributed along the acceleration tunnel, to deliver stored energy to the LSM windings propelling the cargo craft. The total current of 10 megamp turns would be carried by multiple independent superconducting circuits positioned on a cylindrical support tube. Current densities in commercially available superconductors are millions of amps per cm^2. The engineering current density, including substrate and thermal stability material is about ~100,000 amps per cm^2. The total length of the 40 SC energy storage loops for the Gen-1 system is ~50 kilometers. This appears comparable in length to the rings of SC magnets in high energy particle accelerators. The operating energy doubler at Fermi Lab, for example has two rings of SC magnets, each 5 kilometers in length. The Large Hadron Collider at CERN, which will soon begin operation, has 54 kilometers of SC magnets. The Superconducting Super Collider (SSC), if it had been built, would have had 144 kilometers of SC magnets. The SC magnets in these facilities are much more complex and technically challenging than the StarTram SC energy storage loops, requiring extremely precise field homogenity, conductor positioning, reproducibility, higher fields, and much more stringent thermal insulation conditions. The thousands of SC magnets in the many kilometer long particle beam line must all function perfectly; otherwise, the facility could not operate.

Cargo Craft Acceleration

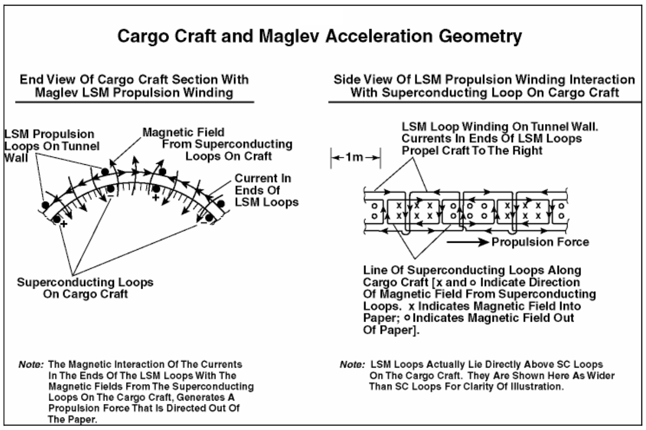


Figure 5.2 Cargo Craft Acceleration

Speed and Acceleration Geometry

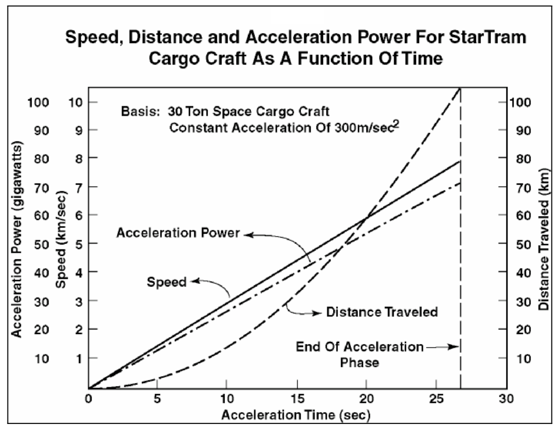


Figure 5.3 Speed and Acceleration Geometry

The superconductor cost for the Gen-1 energy storage system is very low. At \$2 per kiloamp meter, which is probably high, multi-filament NbTi SC would cost ~one billion dollars. Amortized over 10 years, with 10 launches per day of 35 ton payload per launch, this is only \$0.50 per kg of payload. The refrigeration cost for the SC energy storage loops is even smaller. Using multi-layer thermal insulation (MLI) with conductivity of $0.5x10^{-6}$ w/cm K, and a 10 cm thick MLI layer between a 77 K liquid N_2 shield and the 4 K superconductor, total heat leak into the SC region for the 50 km long Gen-1 SC energy storage system would be ~5 kilowatts(th), based on a 0.8 meter diameter support tube for the SC circuits. At 500 watts(e)/watt(th), refrigeration power would be 2.5 MW(e), and the equipment cost at \$2000 per watt(th), only 10 million dollars. Amortized over 10 years, the refrigeration equipment would cost only 5 cents per kg of payload, and the refrigeration power, at 6 cents per KWH, only 1 cent per kg of payload.

As the Gen-1 cargo craft exits the acceleration tunnel and climbs to orbit, it experiences strong aerodynamic heating and deceleration forces. The heating rates and deceleration forces depend on 3 factors: 1) altitude of atmospheric entry, 2) cargo craft nose geometry, and 3) launch velocity. Figure 5.4 shows the deceleration rate of the 2 meter diameter, 13 meter long, 40 ton Gen-1 cargo craft as it ascends through the atmosphere, as a function of launch velocity and altitude. Figure 5.4A uses a relatively blunt nose (r = 14.4 cm), while Figure 5.4B uses a sharp nose (r = 0). The effective drag coefficient for the blunt nose is 0.090, while for the sharp nose, the drag coefficient is 0.044. The corresponding stagnation point heating rates are shown in Figure 5.5 for the blunt nose (Figure 5.5A) and sharp nose (Figure 5.5B). At a launch velocity of 8 km/sec and a launch altitude of 8000 meters, the blunt nose results in a deceleration rate of 12g, while the sharp nose results in a deceleration rate of 6g. The peak heating rate at the stagnation point is 20 KW/cm^2 for the blunt nose, and 100 KW/cm^2 for the sharp nose. Deceleration and heating are greater at lower launch altitudes, in the denser atmosphere. At 4000 meters launch altitude, the ratio of atmospheric densities, $\rho(4000)/\rho(8000)$ is 1.56, proportionately increasing the deceleration rate. The increase in heating rate is somewhat smaller, about 30%.

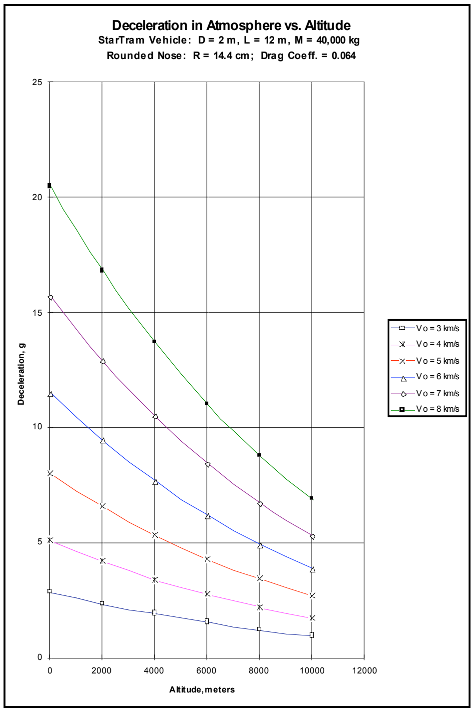


Figure 5.4 Deceleration in Atmosphere vs Altitude for Rounded Nose

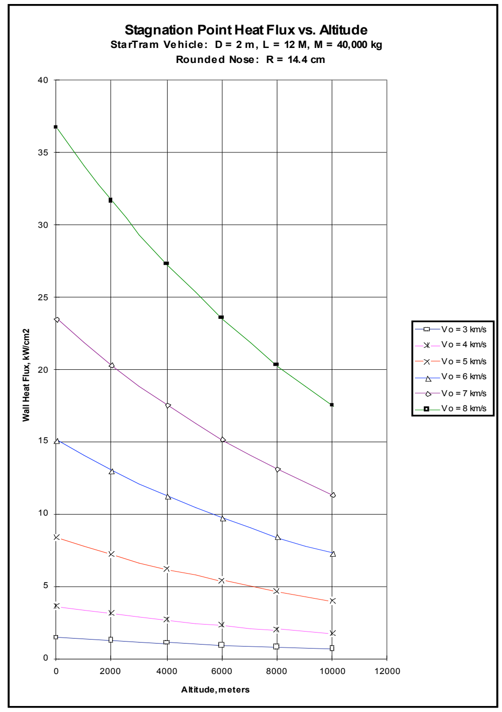


Figure 5.5A Heating Rate at Stagnation Point In Atmosphere vs Altitude for Rounded Nose

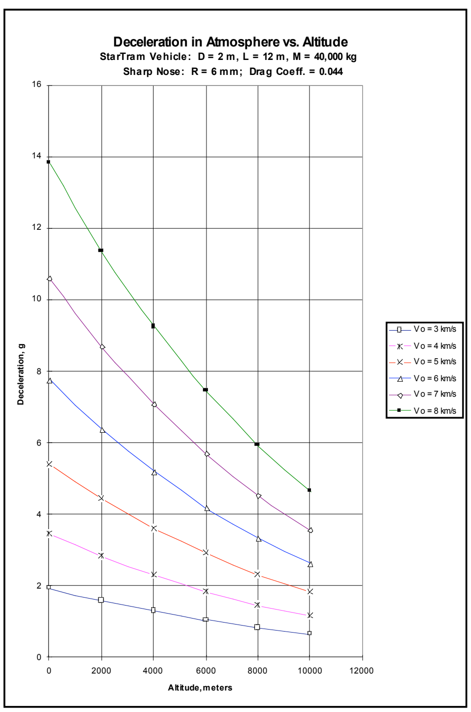


Figure 5.4B. Deceleration in Atmosphere vs Altitude for Sharp Nose

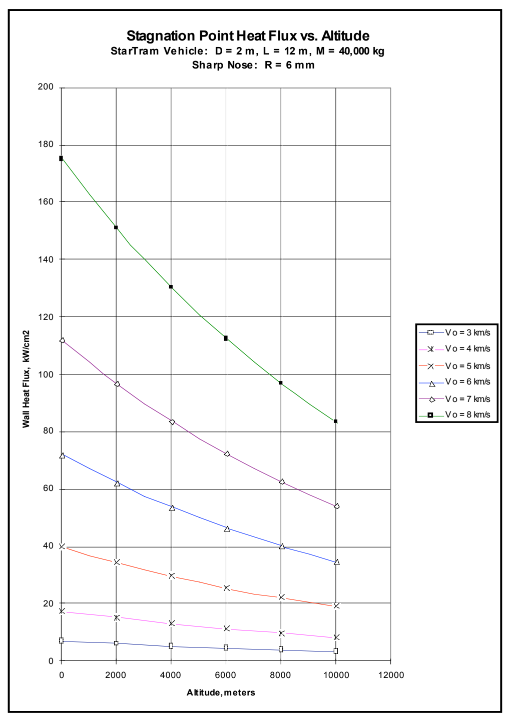


Figure 5.5B. Heating Rate a Stagnation Point In Atmosphere vs Altitude for Sharp Nose.

The cargo craft will lose some ΔV as it ascends to orbit because of aerodynamic drag. The ΔV loss depends on 4 factors: 1) launch altitude, 2) launch angle, 3) drag coefficient, and 4) launch velocity. To reach the desired orbital altitude, the cargo craft needs the necessary velocity as it leaves Earth's atmosphere. For insertion into LEO, the required velocity is ~8 km/sec. There are 3 approaches to achieve 8 km/sec at the top of the atmosphere: 1) Launch at 8 km/sec at ground level, and do a controlled ΔV rocket burn as the cargo craft ascends at a constant velocity of 8 km/sec; 2) Launch at 8 km/sec and do a ΔV rocket burn after the cargo craft reaches the top of the atmosphere; 3) Launch at (8+ΔV) km/sec, with sufficient ΔV so that the cargo craft velocity is 8 km/sec after it passes through the atmosphere.

Optimization of the Gen-1 design requires extensive trade studies. Below are results for a promising sub-set of design factors. 1) Blunt nose geometry, with an effective drag coefficient of 0.09; 2) Launch at 2 different possible altitudes (4000, 6000, and 8000 meters) corresponding to potential StarTram facility locations; 3) Launch at 10 or 15 degrees relative to ground surface; 4) 8 km/sec velocity at top of atmosphere using 3 different approaches to compensate for the ΔV loss during ascent through the atmosphere; 5) 40 ton cargo craft, 2 meter diameter, 13 meter long.

Table 5.2 summarizes the ΔV requirements for the various cases. A number of important conclusions can be drawn:

(1) The aerodynamic deceleration of the cargo craft is acceptable, ~10 to 20g, depending on launch altitude.
(2) The maximum aerodynamic heating rate at the stagnation point is high, ~20 to 30 KW/cm^2, but manageable using transpiration cooling. Heating rates at the stagnation point of more than 10 KW/cm^2 only last ~3 to 10 seconds. The amount of water coolant for transpiration cooling of the nose will be very small. With evaporation, the water consumption rate is only 10 cm^3/cm^2 of area per second at 25 KW/cm^2. The heating rate for most of the nose is much smaller than at the stagnation point. Even if the entire frontal area of the cargo craft experienced 25 KW/cm^2 for 10 seconds, which is far too pessimistic, the weight of water would be only 3 metric tons, easily carried by the cargo craft.
(3) Launch altitudes as low as 4000 meters (13,000 feet) are practical. Higher altitudes reduce the deceleration, heating rate, and ΔV loss. Launching at 8000 meter altitude, reduces ΔV loss by almost a factor of 2.
(4) The optimum launch angle is in the range of 10 to 15 degrees. Both result in acceptable ΔV loss. Less than 10 degrees results in a considerably larger ΔV loss, while much greater than 15 degrees requires a large ΔV burn for orbit insertion.
(5) The simplest way to compensate for the ΔV loss is to accelerate the cargo craft to (8+ΔV) km/sec in the tunnel. The additional ΔV acceleration is modest, and eliminates the compensating rocket motor on the cargo craft.

Table 5.2. StarTram Cargo)V Loss Through the Atmosphere as a Function of Launch Altitude, Launch Altitude, and ΔV Compensation Approach.
Basis: 40 metric ton cargo craft, 2 meter diameter, 13 meter length; Blunt nose geometry, C_D = 0.09; 8 km/sec velocity at top of atmosphere

	Launch Altitude, Meters					
	4000		6000		8000	
Parameter	10° Angle	15° Angle	10° Angle	15° Angle	10° Angle	15° Angle
Deceleration @ 8 km/sec, g	19	19	15	15	12	12
Stagnation point heat rate, KW/cm^2	27	27	24	24	20	20
Rocket ΔV Burn During Ascent						
Launch velocity, km/sec	8	8	8	8	8	8
ΔV burn during ascent, m/sec	985	661	745	500	558	374
Rocket ΔV Burn at Top of ATM						
Launch velocity, km/sec	8	8	8	8	8	8
ΔV burn at top of Atm, m/sec	924	634	630	484	542	364
Extra ΔV Provided by LSM in Acceleration Tunnel						
Launch velocity, km/sec	9.04	8.67	8.78	8.50	8.58	8.37
Extra ΔV above 8 km/sec in acceleration tunnel, m/sec	1037	671	779	505	578	374

Based on these studies, parameters for a reference Gen-1 system are given in Table 5.3. At 10 cargo craft per day, one Gen-1 facility could launch 128,000 tons of payload per year. With launch rates of 20 per day and a somewhat heavier vehicle, a Gen-1 facility could launch 300,000 tons annually, sufficient to meet any foreseeable space commercialization and exploration requirements not involving large numbers of humans going into space as tourists and colonists.

Table 5.3. Parameters for the StarTram Gen-1 Reference Design.

Parameters	Reference Design Value	Range of Potential Designs
Cargo craft diameter, meters	2	1.5 to 2.5
Cargo craft length, meters	13	10 to 15
Cargo craft total weight, MT	40	30 to 50
Cargo craft payload weight, MT	35	25 to 45
Cargo craft acceleration, g	30	20 to 50
Launch velocity, km/sec	8.78	8 to 10
Altitude @ entry into atmosphere, meters	6000	4000 to 8000
Launch angle, degrees	10	10 to 15
Acceleration tunnel length, km	130	100 to 150
Cargo craft velocity @ 30 km altitude, km/sec	8	7 to 10
Drag coefficient	0.09	0.05 to 0.12
Deceleration rate @ atmospheric entry, g	18	15 to 25
Nose heating rate @ atmospheric entry, KW/cm^2	30	20 to 40
ΔV loss thru atmosphere, meter/sec	780	400 to 1000
Launch rate, #/day	10	5 to 20
Average power generation, MW(e)	210	100 to 400
Electrical energy per launch, GJ(e)	1540	1000 to 3000
Acceleration time, seconds	30	20
# of superconducting storage loops	40	30 to 80
Maximum AC frequency of LSM power, kilohertz	4.4	4 to 6
Payload launched per year, MT	128,000	50,000 to 300,000

Before describing the economics of the Gen-1 and Gen-2 Maglev Launch Systems, it is useful to provide an overview of the present technology status and representative costs of the various sub-systems that make up Gen-1 and Gen-2.

The Gen-1 Maglev Launch System has the following principal sub-systems:
- 110 km, 3 meter diameter evacuated acceleration tunnel
- Aluminum guideway loop assemblies in acceleration tunnel
- Superconducting energy storage and refrigeration
- Power conditioning/switching for Gen-2 acceleration
- Superconducting loops on Gen-1 cargo craft
- Gen-1 cargo craft structure
- MHD window sub-system for entry into the atmosphere
- Cooling system for ascending cargo craft as it ascends

The Gen-2 Maglev Launch System has the same sub-systems as Gen-1 with the addition of the:
- Levitated launch tube
- Superconducting cable systems to levitate the Gen-2 launch tube to high altitude
- Re-usable passenger/cargo spacecraft

The Maglev cargo craft accelerates in a long straight underground tunnel. Long tunnels are practical and their cost for a Maglev launch system is modest. The Large Hadron Collider (LHC) particle accelerator at CERN has a tunnel circumference of 27 kilometers. The planned Japan Railways Maglev route between Tokyo and Osaka is 500 km in length, 300 km in deep tunnels. The 72 km SSC tunnel, of which several km was constructed, had a diameter of 5 meters, compared 3 meters for the Gen-1 tunnel. The projected SSC tunnel cost was about 2 billion dollars. The cost of the 110 km mile Gen-1 tunnel will be comparable; while somewhat longer (110 km vs 72 km), its diameter is smaller (3 meter vs 5 meter). The present Japanese undersea railway tunnel between Honshu and Hokkardo is 50 km in length.

The aluminum guideway loops are similar to those used in the Japanese Maglev System operating in Yamanashi. Even at the very conservative figure of $20/kg, 10 times greater than commercial aluminum, they cost only 0.4 billion dollars. The total circumferential length of the 60 superconducting (SC) loops in the Gen-1 energy storage system is 50 kilometers, less than the 54 km length of SC magnets now installed in the Large Hadron Collider (LHC). The SSC would have had a total magnet length of 144 km. The SC magnets for the LHC and SSC are much more complicated and difficult than the Gen-1 SC loops. The LHC and SSC magnets require extremely high magnetic field precision, and substantially higher field strength than the Gen-1 SC loops. In addition, their refrigeration requirements are considerably greater, since their thermal insulation is much thinner than that for the Gen-1 SC loops. The LHC uses liquid helium cooled superconductor which operates at 1.7 K, with very high refrigeration power requirements. The Gen-1 SC energy storage loops operate at 4.2 K with much lower refrigeration power required. The superconducting loops on the Gen-1 cargo craft use high temperature superconductor. They are cooled down just prior to launch, with a small quantity of stored coolant to keep them cold during the few minutes, that it takes to position the craft in the tunnel and accelerate it. The thermal insulation requirements are very modest. High temperature YBCO SC magnets have already been used on the Japanese Maglev vehicles. The Gen-1 cargo craft structure is costed at $100 per kg, which appears conservative. It would use a high strength, high temperature composite material, probably with an inner shell of stainless steel or titanium shell.

The MHD window uses technology like that for the 1960's large MHD generators, except that it functions as a pump to prevent atmospheric air from entering the evacuated tunnel, instead of as a generator, with hot combustion gases flow through a transverse magnetic field to generate electric power. In the MHD window, applied DC electric current flows through ionized air in the pump region, pushing it outwards to prevent it from entering the acceleration tunnel. The air would be seeded with a small amount of alkali metal vapor, e.g., cesium, ionized by a RF input and I^2R losses from the DC. The MHD window is a conventional MHD generator, run with input power to make it a pump. Cooling the Gen-1 cargo craft as it ascends through the atmosphere would use technology like that for intercontinental re-entry missiles. Missiles traverse the full atmosphere, while a Gen-1 cargo craft traverses about ½ of the atmospheric. Moreover, the much heavier Gen-1 cargo craft can carry large amounts of transpiration coolant; unlike re-entry missiles. It will be much easier for Gen-1 cargo craft to traverse the atmosphere than re-entry missiles. The Gen-1 launch facility cost will be very small compared to its economic benefits. Consider launching space solar power satellites, which are not economically practical using rockets. Launching 50 GW(e) per year (5000 launches/year) of SPS satellites would enable 1000 GW(e) of electric power in space after 20 years. At 6 cents per KWH, the annual revenues from the SPS satellites would be 500 billion dollars. Over 20 years, total revenues would be ~5,000 billion dollars, 250 times greater than the projected construction cost of 20 billion dollars for the Gen-1 facility. Even if the Gen-1 facility cost was double or triple, which is very unlikely, it would be tiny compared to its economic benefits.

The Gen-2 system is much more technically challenging than the Gen-1 cargo only system, and more expensive. The levitated launch tube uses existing superconductors, but will require considerable development. Gen-2 would enable large scale human activities in space, including tourism, manufacturing and exploration. Large scale human activity in space is not economically possible using rockets. Whether to develop Gen-2 to let large numbers of humans live and work in space, and to experience its beauties depends on ones values. We believe that the cost is worth it, whether it is 100 billion dollars or even 300 billion (which is only 1% of annual World GDP). It is part of human destiny.

The cost per kilogram of payload depends on three factors:1)Construction cost of the facility and amortization period; 2) Payload tonnage launched annually; 3) Operating cost and payload per launch. Construction and operating cost can be projected by estimating the individual costs of the various materials and operations involved based existing experience as benchmarks. A launch rate of 130,000 tons per year appears. A 10 year amortization period is assumed. Table 5.4 shows the projected construction and operating costs for the first Gen-1. There are two acceleration tunnels enabling one to shut down for maintenance and repairs, while the other continues operating. Each tunnel is 110 km in length, with an interior diameter of 3 meters. Added to this is 47 km of energy storage tunnels for the 60 superconducting energy storage loops. [Only 40 loops would be in use at any one time, with the other 20 in reserve.] Total tunnel length is then ~265 kilometers. Total excavation volume would be 1.9 million cubic meters. The projected excavation cost for the 72 km, 5 meter diameter Superconducting Super Collider (SSC) was ~$1000 per cubic meter. Several miles of tunnel were excavated before the SSC project stopped. The Gen-1 excavation cost is taken as $1500 per cubic meter, corresponding to 17 million dollars per mile of 3 meter (10 feet) diameter tunnel. [The cost also includes a vacuum liner for the tunnel wall.]

For the superconductor in the energy storage loops, a cost of $2 per kiloamp meter is projected, based on current commercial practice. Superconductor cost should decrease substantially in the future, due to advances in technology, and the economics of large scale production. The major contributor, ~½ of the total 20 billion dollars construction cost, is the power conditioning system that converts the DC energy stored in the superconducting energy loops to kilohertz frequency AC power that accelerates the launch vehicle. The projected unit cost for the electronic switches, controls, etc. is $100/KW(e), for a total cost of ~10 billion dollars. The power conditioning sites will be located along the 2 acceleration tunnels, which will share the equipment. Handling the enormous power load of 10's of gigawatts of AC power during the 30 second acceleration period will require many distributed electronic units operating synchronously in parallel. The full assembly will be highly reliable, since if some individual units were to fail, other units would take over their load.

Table 5.4. Projected Capital and Operating Costs for Gen-1 StarTram System.
Basis: 35 ton payload per launch; 10 launches per day.

Capital Cost Component	Cost (Billion $)
Excavate/line 2 acceleration tunnel and 60 energy storage tunnel (265 km, 3 meter, $1500/m^3)	3.00
Aluminum guideway loop @ $20/kg (incl. placement)	0.44
Superconductor for energy storage loops (60 loops @ 250 meter diameter, $2/KA meter)	0.94
SC cable & cyropipe manufacture and installation	0.94
Power conditioning, DC to AC @ $100/KW(e)	10.00
Vacuum & monitoring equipment for tunnels	1.00
Refrigeration systems	0.03
Prime power plant, 300 MW(e) @ $3000/KW(e)	0.90
Launch buildings & operational facilities	2.00
Total construction cost	19.25 B$
Operating Cost Rev Launch of 35 Ton Payload	**Cost (Million $)**
Cargo craft structure (5 MT) @ $100/kg	0.50
Superconducting loops on craft @ 2$/KA meter	0.43
Personnel @ 50 man days @ $500 per day	0.025
Energy operating cost @ 6 cents/KWH	0.021
Total operating cost/launch	0.98 M$
10 year amortized capital cost (3650 launches/year)	0.52 M$
Total cost/launch	1.50 M$
Total cost/kg of payload	43 $/kg

The 20 billion dollar Gen-1 facility cost has an amortized cost of ~15 $ per kg of payload for a launch rate of 128,000 tons annually. Adding the cost of the cargo craft structure and its superconducting loops, energy and operating personnel – the facility would have a staff of approximately 1000 – total unit cost is $43 per kg of payload launched. The 20 billion construction cost, is small compared with other government programs. The NASA Constellation program for the return to the Moon is ~100 billion dollars. Gen-1 is approximately 2 weeks of the US defense budget. The economic benefits will greatly outweigh its cost.

The capital cost for the Gen-2 system is projected at 67 billion dollars, over 3 times the cost of the Gen-1 system, even when large reductions in component costs are projected. For example, the superconductor in the levitated SC cables attached to the evacuated launch tube is projected at only 0.2$ per KA meter, compared to the present 2$ per KA meter. Such large reductions appear possible using thin film High Temperature Superconductors (HTS) which have current densities of over 10 million amps per cm^2 in the superconducting film. The launch volume for the Gen-2 system is enormous – over 300,000 tons of cargo and 400,000 passengers annually. Even so, with a World population of 9 billion persons in 2050 AD, this corresponds to only 1 person in 500 going into space once during a 50 year period of their lifetime. In practice, probably many more would want to experience spaceflight. Over a 50 year period, $13,000 cost per trip would only be an annual equivalent of $650 – well within the reach of ordinary people.

VI. StarTram Gen-1 Applications

Figures 6.1 and 6.2 show some potential applications for the Gen-1 Maglev launch system. The amounts of payload using Maglev launch are much greater than present rocket systems can provide. Besides reducing the launch cost per kilogram to less than 1/100th of present costs, Maglev launch will also greatly reduce the manufacturing cost of space hardware. The very high launch cost forces the hardware to be very reliable, ultra-lightweight, and operate close to its limits, "one of a kind" systems with extremely expensive engineering and quality control. With very low cost, unlimited launch capability, space hardware could be much cheaper using existing, heavier components instead of new one-of-a-kind. Hardware would not have to operate close to failure limits.

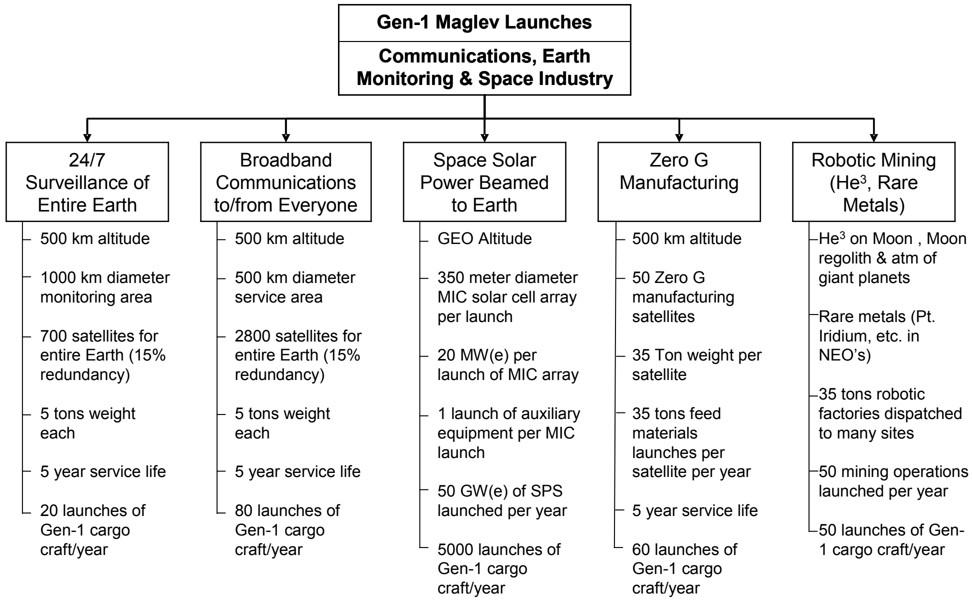
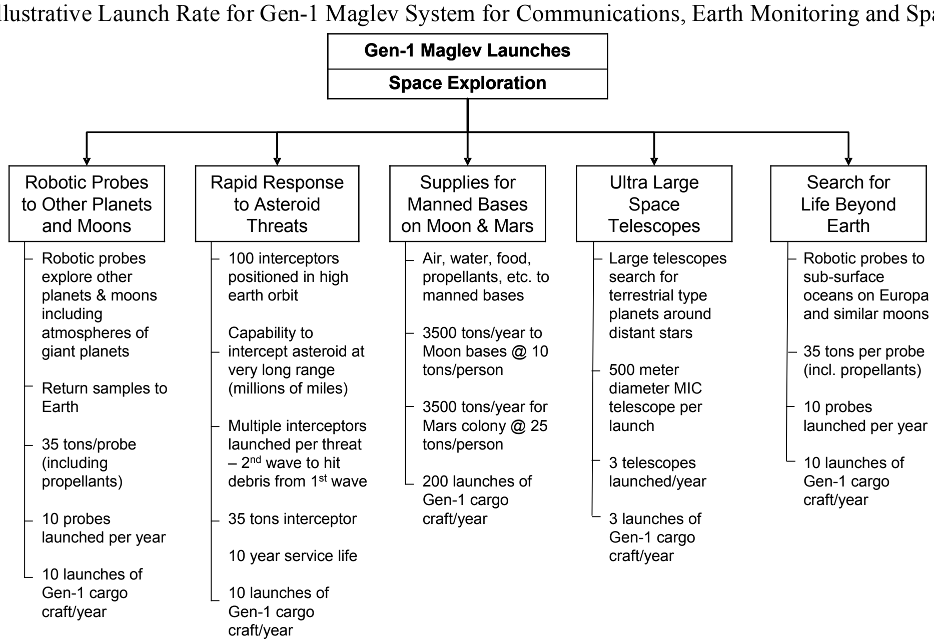


Figure 6.1 Illustrative Launch Rate for Gen-1 Maglev System for Communications, Earth Monitoring and Space Industry.



Basis: 35 tons payload/launch; 5210 launches/year; 180,000 tons launched/year.

Figure 6.2. Illustrative Launch Rate for Gen-1 Maglev System for Space Exploration.

Basis: 35 tons/launch; 233 launches/year; 8200 tons launches/year.

Space solar power satellites are the largest industrial market for Maglev launch. To launch 50 GW(e) per year, about 2% of present world electric generation, a launch rate of 5000 SPS satellite cargo craft per year would be required, at a specific weight of 4 kg/KW(e) for SPS units. SPS satellites can potentially supply almost all of Earth's needs for clean, non-polluting energy. However, the high cost of rockets prevents SPS's from being practical. Even with an unrealistically low specific mass of 1 kg/KW(e) for the satellites, placing a SPS in GEO would cost $100,000 per KW(e) assuming $100,000/kg of payload to GEO, compared to ~3 thousand dollars per KW(e) for fossil and nuclear plants on Earth. A new concept (8) for very large, self deploying solar power satellites, termed MIC (Magnetically Inflated Cables), combines high current superconducting (SC) and tensile Kevlar type tethers to create very lightweight, very large, very strong and rigid structures. MIC would be launched as a compact package of coiled cables and tethers.

Once in orbit, the SC cables would be electrically energized. The outward magnetic forces on the SC cables cause MIC to expand to full size, with its shape determined by the tensile tethers restraining the outwards magnetic forces on the SC cables. For solar electric power MIC can be a simple circular loop with a planar 2-D tether network restraining the outwards radial forces on the SC cable. The solar cell array is the planar 2-D tether network. With multi SC cables, MIC can be a curved solar reflecting mirror, using thin aluminized film supported by the tether network to concentrate and focus sunlight onto a smaller solar cell array. Each cargo craft MIC launch would produce a solar collector unit of ~330 meters in diameter. At a solar cell efficiency of 20%, each unit could generate ~20 MW(e). For each MIC solar collector launch at 2 kg/KW(e), there would be one launch of auxiliary equipment at 2 kg/KW(e). The MIC solar modules would launch to LEO, and self deploy to full size. A number of modules would then attach together to form a larger power unit, which would then transfer to GEO to beam power down to a designated location on Earth. A 20 module unit would beam down 400 MW(e), for example; a 50 module unit would beam down 1 GW(e). Launched from an equatorial location (e.g., in the Andes or Africa) the Gen-1 cargo craft could directly reach GEO at a launch velocity of 10 km/sec, followed by a 1.5 km/sec rocket burn to circularize the GEO orbit (Figure 4.2). Launched into a polar LEO orbit the Gen-1 payload could use a solar powered high Isp thruster (MHD or other type) to ascend to GEO. Using a high Isp thruster, the ~5 km/sec ΔV transfer to GEO would take a few weeks. At 5000 launches per year, a Gen-1 facility could deploy 50 GW(e) of solar power annually or 500 GW(e) over a decade. At 6 cents per KWH, the present US average production cost, the power production from 500 GW(e) of SPS satellites would be worth 260 billion dollars per year. For 10,000 launches per year, the resultant annual power production would be worth over 500 billion dollars with 1000 GW(e) deployed in 10 years. The corresponding annual cost for Maglev launch is only 10 billion dollars.

Gen-1's ability to launch massive amounts of supplies and construction material would greatly expand space exploration. Figure 6.2 outlines the exploration capabilities made possible by Gen-1, including large manned bases on the Moon and colonies on Mars. Robotic probes would explore all the planets and moons in the solar system, searching for evidence of past or present life in the oceans of Europa and other Jovian moons, and long term flight in the atmospheres of Jupiter and the other giant planets, using nuclear powered ramjets. Large samples from the other bodies in the solar system could be returned to Earth. Ultra large MIC telescopes with diameters of several hundred meters, could provide detailed images of terrestrial type planets around distant stars.

A very important application is the positioning a fleet of high velocity interceptor rockets in orbit to quickly intercept asteroid threats far from Earth. Rapid response and multiple interceptors to ensure intercept, is crucial to protect Earth from catastrophic impact events. The asteroid defense fleet needs to intercept dangerous debris from the initial intercept, using second and third waves of interceptors. The Gen-2 system has the capabilities of the Gen-1 system, plus the ability to launch tens of thousands of travelers into space per year at affordable cost. The travelers could visit space hotels in Earth orbit, or bases on the Moon.

For the Gen-1 StarTram system, the potential sites should meet the following criteria: 1) Launch altitudes of 4000 meters or more; 2) Remote location with very low population density; 3) Minimum flight length over land. Criteria #1 minimizes aerodynamic drag and heating, and ΔV loss during ascent through the atmosphere. Criteria #2 avoids disturbing people with the very intense sonic booms that would accompany launches. Criteria #3 minimizes hazards to population from debris if a cargo craft disintegrates during its ascent to orbit.

For high resolution environmental monitoring and broadband communications polar LEO orbits continuously cover all Earth. Moon and Mars base supply and robotic space exploration missions could be carried out from polar orbits as well as equatorial orbits. If the Gen-1 system launches into polar orbit, the only areas significantly impacted by the ΔV for orbital plane changes are the SPS and ISS supply applications. The SPS application would transfer MIC-SPS modules from LEO polar orbit to GEO equatorial orbit. The low launch cost of the propellant for the orbit transfer, and the high Isp of the solar powered orbit transfer make the operation practical. Similarly, the ΔV required to transfer supplies destined for the ISS from a polar orbit launch is practical using Gen-1.

VII. POTENTIAL STARTRAM LAUNCH SITES

An ideal site for polar orbit launch is Antarctica. The Vinson Massif in Marie Bryd Land reaches 5140 meters altitude. From there a launch vehicle would travel over the open Pacific to Alaska – halfway around the World before passing over land. There is no local population and no objection to sonic booms. The only drawback is its isolation from existing World transport routes, though the large container ships that already carry massive amounts of freight halfway around the World at low cost could service Antarctica. Four other possible isolated sites for polar launch are described in Table 7.1. The exit altitude of the acceleration tunnel will be significantly below the top of the mountain range that houses it. A value of 500 meters (1650 feet) is assumed for the altitude difference, which appears sufficient. The Gen-1 acceleration tunnel is at a constant altitude relative to sea level, and then curves upwards to the exit. Three of the Gen-1 sites – Alaska, Greenland, and Kamchatka, have very long downrange flights over the ocean, i.e., 14,000 km or more, before reaching Antarctica. After Antarctica they have 1000's of miles additional flight over the ocean before reaching a second land mass. For the Kamchatka site, the second land mass is Greenland, with a flight distance of 20,000 kilometers before reaching it.

There are few high altitude locations for an equatorial launch. Launch altitudes of 6000 meters appear possible in the Andes. Africa's launch locations are at lower altitudes, ~4000 meters. For Gen-2, the exit of the acceleration tunnel can be at low altitude since the magnetically levitated evacuated launch tube exits at high altitude. Low population density, isolated land areas are desirable for Gen-2, with long down range flights over the ocean. Antarctica and Greenland are attractive, as are sites in Alaska, Kanichatka, Northern Siberia, Australia, Brazil, Argentina, etc. Using two different Gen-2 sites, it could launch into both polar and equatorial orbits.

Table 7.1. Features of Potential Sites for a Gen-1 StarTram Facility.

Feature	United States	Russia	China	Greenland (ECl is Host)
Name/location of mountain peak	Mt. St. Elias, Alaska	Klyudevskaya Sopka, Kamchatka Peninsula	Gongga Shan Szechwan Province	Highest point in Greenland ice sheet
Altitude of peak, meters	5489	4750	7556	3220
Altitude of exit point from acceleration tunnel, meters	4989	4250	7050	3220
Launch angle (LA), degrees	10	10	$10 \leq LA \leq 15$	10
Flight distance to reach first land flyover beyond host country	15,000 km flight over Pacific Ocean	14,000 km flight over Pacific Ocean	600 km flight over China	18,000 km flight over Atlantic Ocean
Location of first land flyover	Rockefeller Plateau Antarctica	Wilkes Land, Antarctica	Vietnam	Filchner Ice Shelf, Antarctica
Notes:	Second land flyover is 13,000 km farther downrange (Africa)	Second land flyover is 20,000 km further downrange (Greenland)	Second land flyover is 3000 km further downrange (Indonesia)	Second land flyover is 5000 km further downrange (Australia)

VIII. DEVELOPMENT OF THE GEN-1 AND GEN-2 LAUNCH SYSTEM

Superconducting Maglev has been demonstrated as practical by the Japan Railways passenger route in Yamanashi Prefecture. JR vehicles achieve 360 mph, limited only by air drag. In evacuated tunnels, JR Maglev vehicles could reach orbital speeds. JR has operated 5 vehicle consists with a total levitated weight of ~200 metric tons. Table 8.1 lists the four main technology issues for Maglev launch to space. All appear solvable, given the existing technology base developed in other experience. MHD generators have operated at more stressing conditions than the MHD window. Superconducting magnetic storage units have operated successfully, though with much smaller amounts of stored energy. However, there should be no problem in scaling them up for Maglev launch.

Table 8.1. Technology Issues and Development Requirements for Maglev Launch Systems.

Technology Issue	Requirement	Currently Demonstrated	Development Path
High G Magnetic Propulsion	30 to 50 G	~0.2G	• Static tests of High G magnetic forces on superconducting magnets. • Dynamic tests of High G acceleration on levitated sub-scale vehicles
Superconducting energy storage with fast discharge capability (~10^{-2} sec)	400 MJ/unit (~1000 units for full system)	~10 MJ (slow discharge)	• Build and test several different designs of superconducting energy storage/discharge units at sub-scale size. • Build and test optimized full scale prototype unit
Minimization of air leakage into end of evacuated tunnel, using combination of gas jet ejectors and MHD pump	Air leakage from 1 Atm ambient = <0.1 kg/m^2 sec	MHD generators operating @ ~1 to 10 Atm	• Build and test several different designs for gas jet ejector/MHD pump. • Build and test optimized full scale prototype unit.
High heating rate on nose of cargo craft as it ascends through atmosphere	Peak heating ~10 Kw/cm^2 for ~2 seconds	>>10 Kw/cm^2 for RV's	• CFD analyses of alternative transpiration cooling designs • Sub-scale tests in wind tunnel of both cooling operations

Development cost for the Japanese Maglev System was ~2 billion dollars. Development cost for the Gen-1 Maglev technology will be roughly the same. The development costs for the superconducting energy storage system, the power conditioning system, the MHD window, and the Gen-1 cargo craft are additional. The superconducting energy storage and power systems are modular, with approximately 60 modules for the Gen-1 facility. This greatly reduces development cost, since the whole system is not developed as a single unit. After the module is developed, it can be replicated for the full launch facility. Its projected development cost is 2 billion dollars. The MHD window can be tested at sub-scale, and then scaled to full size. MHD development cost is estimated to be about 1 billion dollars. The development cost for the cargo craft is projected as 5 billion dollars. The cargo craft is much simpler than a rocket. There is no engine, only superconducting cables, and no propellant. Moreover, its weight is not constrained as in rockets, since the launch cost is much less, enabling a cheaper structure and lower development cost. Total development cost for Gen-1is projected to be 10 billion dollars - very tiny, on the order of 1/1000th of the economic benefits from just one application, e.g., solar power satellites.

IX. SUMMARY AND CONCLUSIONS

A new way to launch large amounts of payloads into orbit and beyond is described. The StarTram Maglev launch system uses magnetically levitated vehicle technology similar to that now operating for passenger transport in Japan. Two Maglev launch systems are described. The near term Gen-1 system launches 40 ton cargo craft at high altitude (≥4000 meters) and ~8 km/sec from an evacuated acceleration tunnel. The cargo craft then coast up to space through the atmosphere. Aerodynamic heating and deceleration loads are acceptable. A Gen-1 facility can launch 100,000 tons or more of payload annually, at a unit cost of less than $50 per kilogram. The long term Gen-2 system would launch humans and cargo into space, using an evacuated magnetically levitated launch tube that ascends to an altitude of ~20 km where the passenger/cargo craft enter the very low density atmosphere at that altitude.

Applications for Maglev launch are assessed, including commercial, and space exploration. The major application is solar power satellites that beam continuous electric power to Earth from GEO orbit. Maglev launched SPS satellites could beam hundreds of gigawatts of power to Earth at less cost than fossil fuel and nuclear power plants. Maglev launch would enable large manned bases on the Moon and colonies on Mars. Using low cost robotic probes, the outer solar system could be explored in great detail, and samples returned to Earth for analysis. Maglev launch would provide a very robust defense against impact events from asteroids and long period comets.

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