StarTram: A New Approach for Low-Cost Earth-to-Orbit Transport

James R. Powell, George Maise and John Paniagua
Plus Ultra Technologies, Inc., P.O. Box 547, Shoreham, New York 11786, USA
(631) 744-5707
maglev2000@aol.com
and
John D.G. Rather
Karmanos Cancer Institute, Wertz Cancer Center, 4100 John R, Detroit, Michigan 48201, USA

Abstract - StarTram is a revolutionary concept for low-cost, high volume Earth-to-Orbit transport of passengers and/or cargo. StarTram is an evacuated launch tube that is magnetically levitated above the Earth's surface, up to a maximum altitude of ~18 km above the local terrain. Although the concept is advanced, it is within the limits of existing technology. The launch tube is levitated by the magnetic repulsive force between a set of superconducting (SC) cables attached to the tube and a set of SC cables on the ground beneath. A total current of 14 mega-amps in the levitated cables and an oppositely directed current of 280 mega-amps in the ground cables, produces a repulsive force of 4 tonnes/m at an altitude of 22 km above sea level (18 km above local ground level). These forces levitate a robust 7 meter diameter launch tube with an adequate margin of safety. The launch tube is stabilized, both vertically and horizontally, against the net upwards magnetic force and wind forces, by an array of high tensile strength (e.g., Kevlar) tethers that are anchored to the ground. Traveling inside the launch tube is a reusable StarTram Space Vehicle (SSV) that is magnetically levitated and accelerated to near orbital velocity in an evacuated tunnel at ground level. The SSV carries a set of lightweight SC magnets that inductively interact with a guideway of simple normal aluminum loops that operate at ambient temperature to stably levitate the moving vehicle. A separate AC current winding in the guideway pushes on the SSV's SC magnets, accelerating it. After the SSV reaches 8 km/sec at the end of its 1280 km long acceleration tunnel, it transitions into the ascending, magnetically levitated 220 km long launch tube, in which it coasts upwards to the launch point at an altitude of ~22 km. The SSV then enters the upper atmosphere at a launch angle of 5 degrees. A subsequent 0.34 km/sec ΔV burn by a conventional LOX-kerosine rocket engine on the SSV inserts it into orbit. For a high-traffic system, StarTram can deliver payloads into orbit at a projected cost of \$30 per kilogram. This includes amortization of the launch complex, vehicle, and energy costs.

0-7803-6599-2/01/\$10.00 © 2001 IEEE

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StarTram is a new concept for launching heavy payloads into orbit at much lower cost and much greater volume than now possible. Spacecraft are magnetically suspended and accelerated to orbital velocity, ~ 8 km/s, in a long evacuated tunnel at ground level. They then coast upwards inside a magnetically levitated evacuated launch tube to high altitude, e.g., 22 km, where they enter the atmosphere. The low ambient air density, ~ 5% of that at sea level, greatly reduces air drag and heating, and enables spacecraft to reach LEO (Low Earth Orbit) without damage, and with only a small ΔV insertion burn. The launch tube is levitated by the magnetic repulsion between its attached set of superconducting current cables and a second set on the ground. The strong magnetic levitation force substantially exceeds the weight of the tube and cables. For example, a StarTram system with the exit of the launch tube at an altitude of 22 km above sea level (18 km above local ground level) the levitation force is 4 tonnes per meter of tube compared to a weight of 2 tonnes per meter. The resultant net lift force, as well as horizontal forces due to winds, are offset by a network of vertical and angled tensile tethers that reach to, and are anchored at, the ground. The StarTram design is based on existing materials, superconductors, and cryogenics, and appears technically and economically feasible. It incorporates large safety margins and multiple redundancy for reliability and the avoidance of single point failures. An artist's conception of the StarTram vehicle, exiting the levitated launch tube, is shown in Figure 1.

The "point design" considered in this description is for a manned vehicle corresponding to the following launch conditions: 1) launch height = 22 km, 2) launch angle = 5 degrees, and 3) launch velocity = 8 km/sec. These are nominal values that demonstrate the capabilities of the StarTram concept. Other combinations of launch height, launch angle and launch velocity may lead to a more optimal designs. The lengths of the acceleration tunnel and the levitated launch tube in this description are determined by the g-forces that humans can tolerate (~2.5 g). If the vehicle were used only for cargo, with higher g-load tolerance, the tunnel and levitation tube could be considerably shortened.

The cost to launch payloads into space is ~ \$10,000 per kilogram in LEO (Low Earth Orbit). The cost for GEO (Geosynchronous Earth Orbit)) and planetary exploration is much greater. Paradoxically, the energy cost to reach space is very small for objects directly accelerated to orbital velocities. The energy to place a kilogram in LEO then costs only 50 cents at 5 cents per kilowatt hour, a factor of ~ 10,000 smaller than the present cost with rockets.

This high cost results from the inherent limitations of rockets - their payload fraction is only about 1%, and they are complex and very expensive for both expendable and reusable versions, such as the shuttle. The development of improved reusable single stage to orbit (SSTO) spacecraft, or high Mach air breathing space planes, could cut launch costs somewhat, but they still will be high - \$1000/kg or more.

In 1996, Powell and Danby [1] and [2] proposed using superconducting (SC) magnets to magnetically levitate (Maglev) and propel high speed passenger vehicles. SC magnets on the vehicle induce opposing currents in ambient temperature aluminum guideway loops, stably levitating the vehicle with a large clearance (~ 20 cm). A small AC current (~ 10^3 A) carried in separate guideway loops propels the vehicle, which is phase locked in the AC current wave [Linear Synchronous Motor (LSM)]. The vehicle speed equals the product of frequency and pole pitch, regardless of drag force variations.

Japanese Maglev vehicles have operated at ~ 156 m/sec (350 mph), and the first 42 km section of a 500 km commercial route between Tokyo and Osaka is under construction. Low pressure tunnels for vehicle speeds of 1 to 2 km/s have been proposed in the past, because Maglev vehicles operating in the atmosphere are limited by air drag. Even greater speeds, including orbital values, appear possible in evacuated tunnels. A Maglev vehicle accelerating at 2.5 g would reach 8 km/sec in a 1200 km evacuated tunnel. The high magnetic lift to drag ratio (~ 10^4) and high LSM motor efficiency, would let the Maglev spacecraft reach orbital speeds with almost 100 percent efficiency.

At such speeds the spacecraft would disintegrate if launched from the Earth's surface, because of atmospheric forces, deceleration, and heating. If launched at high altitude where air density is very low, however, the Maglev spacecraft could reach orbit without damage. Figure 2 shows the predicted deceleration and nose heating as a function of launch altitude and velocity. For 8 km/s and 22 km altitude (~ 18 km above the ground at selected sites), the initial deceleration (< 2 g) and nose heating (< 5 kW/cm^2) values appear acceptable, and decreases to negligible levels a few seconds after atmospheric entry.

Magnetically assisted launch of spacecraft from the Earth's surface has been previously investigated. The Maglifter study [3] found that modest initial velocities (~ 300 m/s) significantly increases payload. Here, we examine a new concept, StarTram, that enables orbital launch velocities and high payload fractions. StarTram uses superconducting (SC) cables to magnetically levitate an evacuated launch tube to an altitude$\geq$ 22 km.

StarTram is technically and economically feasible. One site could launch a million tons per year to LEO, 1000 times the present rate, at a unit cost of \$30 per kilogram - 1/300th of the present cost. StarTram requires surprisingly little energy. To deliver a million tons per year to LEO, 2000 MW(e) would be needed - less than 0.5% of US electrical capacity. StarTram would enable humanity to expand into space - space tourism and habitats would become practical, solar power satellites a major world energy source, and colonization of the solar system a reality.

2. DESCRIPTION OF LAUNCH SYSTEM

The StarTram design described here uses existing materials, superconductors (SC), and cryogenics. Large safety margins are applied to structural stresses and SC current density. Single point failure is prevented by the use of multiply redundant independent SC cables, structures, and tethers. Components can be repaired or replaced if necessary. The system can withstand all conceivable environmental conditions. The magnetic force (N/m) on a levitated SC cable is

$$(F_m)_L = f_{GL}\left(\frac{\mu_O}{2\pi}\right)\left(\frac{I_G}{I_L}\right)\frac{I_L^2}{H_O} \tag{1}$$

with the oppositely directed ground (I_G) and levitated (I_L) cable currents in amps, and the height (H_O) of the levitated cable above the ground in meters. The factor (f_{GL}) reflects the geometric effects of finite length and positioning. For infinite parallel cables positioned with aligned magnetic and gravitational force vectors, $f_{GL} = 1$. For finite length, multi-cable systems, f_{GL} is ~ 0.8 to 0.9. Figure 3 shows the magnetic levitation force [curve ①] as a function of I_L for $f_{GL} = 1$ and $H_O = 18$ kilometers. The ground cable to levitation cable current ratio (I_G/I_L) is constant (= 20), and the magnetic lift force increases as $(I_L)^2$. For a given lift a high I_G/I_L ratio enables a small I_L, reducing levitated cable weight. A high I_G/I_L ratio also minimizes the effects of Earth's magnetic field. The total amount of superconductor for the ground and levitated cables increases with I_G/I_L, but modestly, a factor of 2.3 for $I_G/I_L = 20$, as compared to the amount for $I_G/I_L = 1$. However, the increase in total cost is a much smaller factor, since the levitated cable costs more ($ per kA·m) than the ground cable. The optimum I_G/I_L ratio appears to be in the range of 10 to 30, but detailed studies are needed for a precise value.

The net upwards force (N/m) is the magnetic force minus the weight of the cable and support structure ($M_p g$), launch tube ($M_{LT} g$) and anchoring tethers ($M_T g$),

$$(F_m)_L^{**} = (F_m)_L - (M_p + M_{LT} + M_T)\, g \tag{2}$$

Tether weight depends on the magnitude of $(Fm)_L^{**}$, tether density ρ (kg/m³), operating stress S_O (N/m)², height H_O (m) and angle relative to the surface. Figure 3 illustrates the effects of cable weight [curve ②], launch tube weight [curve ③], and tether weight [curve ④] at a levitation height of 18 kilometers. Launch tube weight is independent of I_L; SC cable and structure weight scales as (I_L) and tether weight scales as $(f_L)^2$, where f_L is the fraction of the magnetic lift restrained by tethers. Launch tube weight depends on the ambient atmospheric pressure, increasing at lower altitudes, but the greater magnetic lift force more than compensates. Tether weight is minimized by lightweight materials having high tensile strength (~ 3 GPA) and moduli (~ 200 GPa) such as Kevlar and oriented polyethylene (Spectra). Net lift force [curve ④] is positive when $I_L > (I_L)_O$; at $I_L = 12$ megamp, the net lift force is 1 metric ton per meter, about 25% of the total magnetic lift force. The net lift fraction increases with I_L.

Figure 4 shows the geometry of the StarTram acceleration tunnel and launch tube. The spacecraft (illustrated in Figure 5) starts at point 1, accelerates (a_{12}) to launch velocity (V_2) at point 2, coasts upward in the launch tube to point 4, and then enters the atmosphere. The ground level acceleration tunnel is at elevation, h_{12}, above sea level, with length S_{12} [For $a_{12} = 25$ m/sec² (2g) and $V_2 = 8000$ m/s, S_{12} is 1200 km].

$$S_{12} = V_2^2/2a_{12} \tag{3}$$

Constraints on launch altitude and angle affect the launch tube trajectory. Altitude should be ≥ 22 km and the launch angle ~ 5 degrees relative to the horizon. Steeper angles need excessive ΔV burn for orbit insertion, while shallower angles cause excessive atmospheric heating. At 5 degrees and 8 km/s launch velocity, the ΔV insertion burn for a 500 km orbit is only 0.34 km/s (Figure 6). At 10 km/s launch velocity, GEO orbit requires a ΔV burn of only 1.5 km/s (Figure 7). Various launch trajectories have been examined. A tangent trajectory (i.e., a straight line tangent to point 2) is too long, ~ 500 km. A trajectory with constant upwards curvature reaches 22 km in only 260 km (centripetal acceleration of 2.5g), but the launch angle, 8.3 degrees, is too steep. The ΔV burn for LEO is ~ 1 km/sec, which significantly reduces payload. Altitude and angle requirements with acceptable launch tube length can be achieved with a variable curvature trajectory (Figure 4). Segment 1 of the trajectory curves upward with centripetal acceleration a_{23} (R_{23} = Radius of curvature).

$$a_{23} = V_2^2/R_{23} \tag{4}$$

While segment 2 curves downward with centripetal

$$(F_m)_L = f_{GL}\left(\frac{\mu_O}{2\pi}\right)\left(\frac{I_G}{I_L}\right)\left(\frac{I_L^2}{H_O}\right) x$$

$$x\left[\frac{H_o^2}{H_o^2 + \Delta W^2} - \frac{H_o^2}{H_o^2 + (W_o + 2\Delta W)^2}\right] \tag{12}$$

where W_O is the width of the ground dipole loop, $W_O + 2\Delta W$ is the width of the levitated dipole loop, ($\Delta W > 0$), and H_O the levitation height. The first term in brackets is the upwards magnetic force from the ground cables directly underneath. The second term is the downwards force from the ground cables on the opposite side of the loop. Typically, this is ≤ 10% of the upwards force. Each side of the levitated loop also experiences a horizontal magnetic force (N/m)

$$(F_m)_H = f_{GL}\left(\frac{\mu_O}{2\pi}\right)\left(\frac{I_L^2}{H_O}\right)\{① - ② - ③\}$$

$$① = \left(\frac{I_G}{I_L}\right)\left[\frac{(W_O + \Delta W)H_o}{H_o^2 + (W_O + \Delta W)^2}\right]$$

$$② = \left(\frac{I_G}{I_L}\right)\left[\frac{\Delta W H_O}{H_o^2 + \Delta W^2}\right]$$

$$③ = \frac{H_O}{H_O + 2\Delta W} \tag{13}$$

The first term, ①, is the <u>inwards</u> force towards the dipole center caused by the ground cables on the opposite side of the loop; ② is the <u>outwards</u> force caused by ground cables underneath; and ③, a much smaller term, is the <u>outwards</u> force from the levitated cable on the other side of the loop. The <u>net</u> horizontal magnetic force on the levitated cable can be inwards, outwards, or zero, depending on the values of W_O/H_O and $\Delta W/H_O$. Neglecting the small ③ term in equation (13), net horizontal force is zero when

$$\frac{\Delta W}{W_O + \Delta W} = \frac{H_o^2 + \Delta W^2}{H_o^2 + (W_O + \Delta W)^2} \tag{14}$$

Solving for $\Delta W/H_O$,

$$\frac{\Delta W}{H_O} = \frac{1}{2}\frac{W_O}{H_O}\left[\sqrt{1 + 4\left(\frac{H_O}{W_O}\right)^2} - 1\right] \tag{15}$$

For $W_O/H_O = 3$, $\Delta W/H_O = 0.304$. Accordingly, at $H_O = 18$ km, ground dipole loop width is 54 km and levitated loop width is 65 km.

The precise ΔW for which the net magnetic force is zero depends on the actual loop details, including how rapidly dipole width varies with length, and finite length effects. For this study, the net horizontal force is assumed to be zero, though in the actual system it may be desirable to have a non-zero net force.

4. RESTRAINING TETHER SYSTEM

Various tether configurations to anchor the levitated cables and launch tube have been examined. Figure 10 shows a configuration where the tension force, F_c, in the vertical tether (tether C) offsets most of the net magnetic lift force, with the rest offset by the tension forces, F_A and F_B, in the angled tethers (A and B) at each side. Prestressing the angled tethers increases the lateral stiffness, reducing horizontal displacements from wind forces.

The net magnetic lift force (N/m of tube) equals the total magnetic lift force minus the weight of the platform and launch tube.

$$(F_m)_L^\star = (Fm)_L - (M_P + M_{LT})\, g \tag{16 a}$$

The net lift force (N/m) is balanced by tension forces from the 3 tethers

$$(F_m)_L^\star = F_C + \eta_O\left[F_A(x = 0) + F_B(x = 0)\right] \tag{16 b}$$

multiplication by the factor η_O gives the vertical components of F_A and F_B at the platform. The net magnetic lift force (N/m) on the system of platform, launch tube, and tethers is

$$\begin{aligned}(Fm)_L^{**} &= (Fm)_L^{*} - (M_A + M_B + M_C)\, g \\ &= (\gamma - 1)\, (F_m)_L\end{aligned} \tag{16 c}$$

For continued lift capability in the event that some superconducting cables degrade or fail, the net lift factor, γ, should be > 1, with a desirable value in the range of ~ 1.2 to 1.3. The relative vertical forces carried by the angled and vertical tethers is an important factor for design. Angled tethers are heavier than vertical ones, which favors having most of the vertical force carried by the vertical tether. However, to maximize lateral stiffness, having most of the vertical force in the angled tethers is favored. The force (N/m of tube) carried by the vertical tether C can be expressed as a fraction, λ, of the net magnetic lift force.

$$F_C = \lambda\, (Fm)_L^{*} \tag{17}$$

The remainder of the lift force, $(1 - \lambda)\ (Fm)_L^{*}$ is carried by the angled tethers A and B. The weight of tether C (N/m of tube) is given by

$$\begin{aligned}M_C\, g &= A_C\, \rho_C\, H_O\, g \\ &= \frac{F_c}{S_O\,(C)}\, \rho_C\, H_O\, g\end{aligned} \tag{18}$$

For minimum weight, the tether material should have low density, ρ_C, and high tensile operating stress, $S_O(C)$. A high tensile modulus is also very desirable to minimize extensibility under load. Possible tether materials include Kevlar 49 and oriented polyethylenes such as Spectra and Dynmeea. Oriented polyethylenes have low density (910 kg per m^3), high ultimate strength (~ 3 GPa) and high tensile modulus (~ 200 GPa). For this design, the tether stress is assumed to be a small fraction, only 20%, of ultimate strength, corresponding to an operating stress of 0.6 GPa (90,000 psi).

The behavior of the two angled tethers is determined from the catenary equations. The horizontal force components (N/m of tube) are constant along the tethers, and equal and opposite

$$(F_A)_H = (F_B)_H = \frac{(1 - \lambda)\,(Fm)_L^{*}}{2\, \sinh\, [\psi + \beta]} \tag{19 a}$$

The tether tension forces (N/m of tube) vary as x (= lateral distance from platform)

$$\begin{aligned}&F_A\,(x) = F_B\,(x) \\ &= (F_A)_H\, \cosh \left[\psi + \beta \left(1 - \frac{2x}{L_1}\right)\right]\end{aligned} \tag{19 b}$$

The tethers reach their ground anchors at $x = L_1 = H_O \cot \theta$. Their tension force (N/m of tube) is maximum at the platform (x = 0).

$$\begin{aligned}&F_A\,(x = 0) = F_B\,(x = 0) \\ &= (F_A)_H\, \cos h\, [\psi + \beta]\end{aligned} \tag{19 c}$$

The parameters β and ψ are given by

$$\begin{aligned}\beta &= \frac{q\, L_1}{2\,(F_A)_H} \\ \psi &= \sinh^{-1}\left(\tan\theta\, \frac{\beta}{\sinh\beta}\right)\end{aligned} \tag{19 d}$$

where the weight per unit length of tether, q (N/m per meter of tube)

$$q = \frac{F_A\,(x = 0)\, \rho_A\, g}{S_O\,(A)} \tag{19 e}$$

For this study, the angled tethers are assumed to have the same density, ρ, and maximum operating stress, S_O, as the vertical tether.

Equations (19a) through (19e) are solved simultaneously to yield $(F_A)_H$, F_A, β, ψ, and q. The remaining tether quantities are then calculated. The weight of the angled tether (N/m of tube) is given by the difference between the vertical forces at the two ends of the tether [i.e., at the platform (x = 0) and at the surface anchor point ($x = L_1$)]

$$M_A\ g = M_B\ g = \int_{X=0}^{X=L_1} q\,ds \qquad (20)$$
$$(F_A)_H\ \{ sinh\ [\psi + \beta] - sinh\ [\psi - \beta$$

The lineal density of stretched tethers is assumed to equal that of unstretched tethers. This slightly over-estimates the weight of the tether, by ~ 0.3%. The sag ratio, f, at the mid-span of the angled tethers is

$$f = \frac{1}{2\beta} \{cosh\ [\psi + \beta] - cosh\ \psi \} - \frac{1}{2}\ tan\ \theta \qquad (21)$$

where the distance from the midpoint of the tether to the straight chord above [chord is drawn from the platform to the surface anchor] is given by d = f L_1.

The horizontal restoring force of the tether network is given by, assuming a horizontal displacement δx = u to the right (Figure 10B),

$$\Delta F = K_{AB}\ u = \left[F_A' \left(x = L_1 + u\right)\right]_H' - \left[F_B' \left(x = L_1 - u\right)\right]_H \qquad (22)$$

where K_{AB} is the stiffness constant, F_A' and F_B' are the perturbed tension forces in the tethers, with their horizontal components designated by the subscript H. F_A' and F_B' are obtained from the solution of equations (19a) through (19e) for the perturbed state, under the condition that the weight of the tethers in the perturbed state is the same as that in the unperturbed state. The values of β and ψ also change in the perturbed state, and become different for the A and B tethers. The value of K_{AB} is virtually constant for horizontal displacements of interest. The network displacement response to transverse wind forces is thus essentially linear.

Equations (16) through (22) fully describe the properties of the tether network, given the set of input parameter $[(Fm)_L, M_P, M_{LT}, \lambda,_c\rho,_o S\ (C), \theta, {}_oH\ ]$. Parametric studies have been carried out, but because of the very large parametric space involved, an optimum design has not yet been determined. The representative design shown in Table 2 appears very practical, but it can probably be improved with additional study.

High winds can horizontally displace the platform and launch tube. The wind force primarily acts on the launch tube, since it has the largest projected area, A_{LT} (m^2). For a horizontal wind of velocity V_W (m/sec) perpendicular to the launch tube, the wind force is (N/m of tube)

$$F_W = \frac{1}{2}\ \rho_{AIR}\ C_D\ A_{LT}\ V_W^2 \qquad (23)$$

At a speed of 50 m/sec (110 mph), the wind force is 110 N/m, based on $\rho_{AIR} = 0.0645$ kg/m^3 (22 km altitude), drag coefficient $C_D = 0.2$ and $A_{LT} = 7m^2$ per meter of tube (Figure 9C). For the tether network in Table 2, this would produce a displacement of 8 m. Such displacements pose no problem for the tethers, since the changes in tensile stress are small. However, wind caused displacements may exceed that allowable for the launch tube if they occur over a short section. A 50 km long section of tube readily accommodates large horizontal deviations (e.g., ± 100 meters) since there is sufficient time for magnetic force guidance corrections to adjust the path of the 8 km/s spacecraft . However, for shorter sections, e.g., a few kilometers in length, wind forces should not make the track deviate by more than ~ 1 meter from its planned alignment. Deviations smaller than ±1 meter can be handled by the clearance between the spacecraft and the launch tube guidance loops, whose position can be adjusted in real time if desired.

Wind velocities of 50 m/sec are rare at 22 km altitude. Strganac [4] gives wind speeds as a function of altitude and season at 69 locations in the Northern Hemisphere. His data indicates that high latitude locations (i.e., ≥ 70° N) generally have similar wind patterns. Averaging 4 of these locations gives mean wind speeds at 22 km altitude that range from a low of ~ 6 m/s during the summer season (June, July, August) to ~ 12 m/s in the spring (March, April, May) and fall (September, October, November) seasons, going up to ~ 22 m/s in the winter season (December, January, February). Wind speeds at the 95th percentile (i.e., 95% of winds have speeds below the gusted value) are 13 m/s in the spring and fall, and 48 m/s in the winter. These wind patterns apply to a StarTram site located in Greenland. Other sites, such as the south polar plateau (85°S) and the Australian outback (25°S), would have lower wind speeds. Since winds will usually strike the StarTram track obliquely and not at 90°, the actual wind force will be substantially less than given by equation (23). The above wind statistics indicate that a StarTram site could operate over 95% of the year with allowable displacements using a passive tether network. With an active control system to limit tether movement, the site could operate 100% of the year. Figure 10A shows a simple approach to actively limit displacement. If the wind force is to the right, pulling down on control tether A counteracts it, preventing horizontal displacement of the platform. If the wind is to the left, control tether B is pulled down. The magnitude P of the control force (N/m of tube) is determined for a catenary of mid span sag ratio f with point loading at x = αL_1

$$P = \left[\frac{8f}{3\alpha(1-\alpha)}\right] F_W \qquad \textbf{(24)}$$

For typical values of $\alpha \sim 0.8$ and $f \sim 0.09$, P is ~ 1.5 F_W, or about 160 Newtons per meter of tube for a wind speed of 50 m/sec (110 mph). The control tethers are only about 3 km in length.

A second approach is to have small currents in the tethers interact with the magnetic field of the SC ground cables. The resultant forces can be upwards or downwards, depending on the direction of the control currents. The control force is ~ 100 Newtons per amp, when integrated over the length of the tether. With small, lightweight (about 1% of tether weight) aluminum conductors, the tether could quickly respond to all wind forces, including the most extreme. This control approach requires that the tracks of the A and B tethers be oriented to have a directional component that lies parallel to the launch tube track.

The StarTram tether network is more complex than the idealized configuration in Figure 10, which shows only the primary tethers spaced at intervals of 1 to 2 kilometers along the tube. In practice, the primary tethers would transition to a web of small secondary tethers that attach to the platform and launch tube at ~ 50 meter intervals. The transition points are located ~ 1 km below the launch tube. The secondary tethers overlap, so that if a primary tether failed, the structure would continue to be anchored by the secondary tethers still connected to other primary tethers. This arrangement distributes wind loads more uniformly, and minimizes horizontal displacements of the launch tube for locations between the primary tethers. Additional stiffening is provided by strong longitudinal tension forces carried either in the platform/launch tube structure itself, or in separate cables attached to the structure. A modest weight of Kevlar or polyethylene tension cable, e.g., 5% of the platform/launch tube weight, would carry a tension force of on the order of 5×10^7 newtons, which would prevent local wind gusts from causing excessive displacements.

As the spacecraft moves along the curved launch tube, the brief impulse (~ 10^{-2} sec) of centripetal force ($F_S = M_S a_S / L_S$) causes a slight vertical displacement of the tube - upwards or downwards, depending on the direction of curvature.

$$(\delta y)_{LT} = \frac{1}{2}\left(\frac{M_S a_S}{L_S}\right)(M_{LT} + M_P)^{-1}\left(\frac{2 L_S}{V_S}\right)^2 m \qquad \textbf{(25)}$$

For a spacecraft mass (M_S) of 200 MT, velocity (V_S) of 8000 m/s, and length (L_S) of 30 m, centripetal acceleration (a_S) of 25 m/sec^2, and $M_{LT} = M_P = 1$ MT/m, the value of $(\delta y)_{LT}$ is only 2 millimeters. The corresponding mechanical energy imported to the tube is ~ 400 J/m, resulting in small vertical oscillations of the tethers and launch tube. These are rapidly dissipated by active and passive dampers in the tether network. The oscillations only occur after the spacecraft has passed, because their propagation velocity along the track is much smaller than the velocity of the spacecraft.

The launch tube/tether system has a very low horizontal oscillation frequency, ~ 0.01 Hz; moreover, it responds very sluggishly to wind forces. At 22 km altitude, for example, a 50 m/s (110 mph) wind gust takes over 6 seconds to move the launch tube by 1 meter. This sluggish response lets the tether system time average varying wind forces, and makes it easier to control launch tube position. However, since there will be a delay of ~ 30 seconds between the time control forces applied at ground level can affect a platform at 22 km, an anticipatory control approach appears necessary. Knowledge of the strength, direction, and duration of incoming winds, gained by laser doppler radar or other methods, will help determine were and when control forces should be applied.

Time varying wind forces can potentially induce oscillations in the tether network. However, their magnitude should be very small, because of the system's low natural frequency and its strong damping capability, with active control of the tethers and/or passive damping by magnetic or hydraulic "dash pots."

The StarTram tether system is designed to be ultra reliable, redundant, and fail-safe. Tether operating stress is low, ~ 20% of ultimate strength. The platform and launch tube are tied to the many over-lapping, independent, and redundant secondary tethers, which in turn are attached to primary tethers. Similar multi-strand fail-safe space tethers have been proposed. If individual load bearing strands in the primary tethers fail, their loads transfer to neighboring strands through secondary strands. Such tethers can continue to operate, even if many local failures occur. Finally, adjacent primary tethers will take over the load even if a primary tether were to completely fail.

5. SUPERCONDUCTING CABLE PLATFORM AND LAUNCH TUBE SYSTEMS

The StarTram levitated cables are held inside a thin, wide (1 m x 12 m) rigid platform structure made of lightweight, high strength graphite epoxy composite (Figure 9B). The platform is connected to the launch tube underneath by graphite epoxy struts, forming an integrated, rigid structure. The distance of separation is on the order of 30 meters, so as to reduce the fringe field strength in the launch tube to less than 1000 gauss.

The attractive magnetic forces between the cables in the platform are much stronger, by a factor of ~ 100, than the magnetic levitation force caused by the ground cables. The strength of this attractive force depends on the position of the cable in the platform and the distance between them. For the StarTram design described here, the center cable in the array of 7 cables, for example, has zero net magnetic force, while the 2 outer cables experience the largest forces, a net force of 9.9×10^5 N/m directed towards the center of the platform. This is approximately 160 times greater than their levitation force, based on a cable separation of 2 meters. These attractive forces are carried in compression by graphite-epoxy honeycomb reinforcement structures placed between the cables, with the amount of structural material determined by local loading. Additional reinforcement struts are incorporated above, below and between the cables, resulting in a rigid, strong platform. Maximum structural stress in the graphite epoxy composite is 2×10^8 N/m^2 (30,000 psi), which is far below its ultimate strength. The total weight of the platform structure, including cables and connecting struts to the launch tube, is estimated at 10,000 N/m of launch tube (1 MT/m).

The launch tube is a cylindrical shell of 7 meters inside diameter. Internal supports and normal temperature aluminum loops levitate and guide the high velocity Maglev spacecraft along the evacuated launch tube. The 15 centimeter thick wall of the launch tube is made of graphite-epoxy honeycomb, with an equivalent solid fraction of 10%. The external collapsing pressure of the launch tube is estimated to be 2.6×10^5 N/m^2 , based on standard engineering formulas. This is a factor of 60 greater than the ambient pressure of 4×10^3 N/m^2 at 22 km altitude. Such a large safety margin appears more than sufficient. At low altitudes, where the ambient pressure approaches 10^5 N/m^2, a substantially thicker wall, e.g., 45 cm, would be used. Since collapsing pressure scales as the cube of wall thickness, the safety margin at low altitude is comparable to that at high altitude.

The probability of air leaks into the evacuated interior of the launch tube is negligible if the tube wall honeycomb is made of multiple independent and redundant closed cells. These are connected to form an integrated structural unit. If a crack occurs in the wall of one cell, external air cannot flow into the tube's interior, since the adjacent cells retain their integrity. For air to enter, all of the adjacent cells at one location in the tube wall would have to fail. If cracks and failures are randomly distributed, the probability of this is infinitesimally small. The StarTram launch tube wall has 6 layers of independent cells in the honeycomb, with the surface area of each cell less than 1 m^2. The chance of a through leak in the tube wall over a period of 30 years is much smaller than 10^{-9}.

The end of the evacuated launch tube has to prevent entry of the external atmosphere at 22 km altitude, yet allow exit of the spacecraft. Various end "window" options have been examined, including retractable diaphragms, thin plastic film burst diaphragms (e.g., ~ 50 microns thickness), MHD pumps, and gas dynamic ejectors (e.g., steam or air). The mechanical and burst diaphragm options have potential problems involving premature opening or timing, and are vulnerable to single point failure. At this point the gas dynamic option appears to be the leading candidate for the end window.

6. SUPERCONDUCTING CABLE DESIGN

The StarTram design described here is based on existing liquid helium cooled (T = 4 K), multi-filament NbTi superconductor. Liquid nitrogen cooled (T = 75 K) superconductors may render NbTi and helium obsolete by the time StarTram is built. Critical current densities of ~ 10^6 A/cm^2 at 4 Tesla and 75 K in $Yba_2Cu_3O_{7-\delta}$ films deposited on flexible nickel substrates have been achieved. Commercial versions of such high temperature superconductors would make StarTram simpler and cheaper.

The largest superconducting project to date was the superconducting Super Collider (SSC). The SSC was to be 87 km in circumference, comprised of two collider rings with 3972 long (15 m) dipole magnets and 196 short (13m) dipole magnets in each ring, along with thousands of additional quadruple and corrector magnets. The total amount of NbTi superconductor was ~ 1000 metric tons; total refrigeration loads were ~ KW at 4 K (equivalent, including liquefaction), ~ 100 KW at 20 K; and ~ 650 KW at 80 K.

Although StarTram would be physically larger than the SSC, its cryogenic engineering would be much simpler. The StarTram NbTi superconductor would operate at lower fields and further from critical current limits than the SSC conductor, and its field and current would be constant, not periodically ramped. Moreover, unlike the SSC, accurate placement of conductors and precise control of field magnitude and direction is not required. Finally, StarTram does not have SSC's many thousands of magnet current leads, with their attendant mechanical and heat leak problems.

The StarTram NbTi conductor strands are assumed to be similar to the SSC inner conductor. Conductor strands contained 7450 NbTi filameters (6 μ diameter), with a Cu/SC ratio of 1.3/1. The critical current density was 1.64 x 10^5 A/cm^2 at 7 Tesla, and 2.70x10 ^{5}A/cm ^{2} at 5 Tesla. Manufacturing reproducibility was excellent, and critical current was not significantly degraded when fabricated into multi-strand conductor. The fabricated SSC multiple (30) strand conductor had a critical current of 10.9 kA at 7T. Individual strands were produced in lengths $\geq$ 3 kilometers.

A surprisingly small amount of superconductor is required for the levitated StarTram cables. Each of the 7 cables on the levitated platform carries 2.07 megamps; at a design current density of 2 x 10^5 A/cm^2, each cable then requires only about 10 cm^2 of NbTi superconductor to carry its supercurrent. Adding in 13 cm^2 of copper stabilizer (Cu/SC ratio of 1.3/1) the total conductor volume per cable is only 23 cm^2, with a corresponding weight of 20 kilograms per meter.

Although the amount and weight of the superconductor in a StarTram levitated cable is small, there are a number of requirements that strongly impact on the cable design, and affect its size, weight and operating parameters.

The **first** requirement that must be satisfied is that the diameter of the conductor region must be large enough that the operational current density is less than the critical current density at the corresponding value of the surface magnetic field.

Consider a single cable carrying a current I_L/N amps (I_L is the total current in the array of N cables (e.g., N=7) on the platform). The maximum azimuthal magnetic field $(B_\theta)_{MAX}$ at the surface of a cylinder of radius r_C (meters) on which the superconductor is positioned as a current sheet is [$(B_\theta)_{MAX}$ in Tesla]

$$\left(B_\theta\right)_{\max} = \frac{\mu_o}{2\pi}\left(\frac{I_L}{N}\right)\left(\frac{1}{r_C}\right) \qquad \textbf{(26)}$$

The value of r_C must be large enough that the magnitude of $(B_\theta)_{MAX}$ is compatible with the allowable critical current density J_C (amps/cm^2). For NbTi superconductor in the operating range considered for StarTram, J_C tends to scale as the inverse of $(B_\theta)_{MAX}$, i.e.

$$J_C = K\left(B_\theta\right)^{-1} \qquad \textbf{(27)}$$

For the SSC conductor the critical current density at B = 5.6 Tesla is 2.42 x 10^5 Amp/cm^2.

Based on the radius of r_C = 0.15 meter, and an array of 7 cables on the platform $(B_\theta)_{MAX}$ is 2.67 Tesla. The critical current density for the SSC type superconductor would then be 5 x 10^5 amps/cm^2, for $(B_\theta)^{-1}$ scaling. The operating J_{JC} of 2 x10^5 A/cm^2 is thus only about 40% that of the critical current density. This provides a very large safety margin during normal operation.

If a section of one of the cables were to transition to the normal state, its current would be diverted into the other cables. Under these conditions, the drop in total current in the array, and the local increase in magnetic field in the sections of the other co-cables that paralleled the section that had transitioned to the normal state would be quite small. There would be an accompanying drop in the critical current density, but the safety margin would essentially remain constant.

The probability of having enough adjacent sections in the 7 parallel cables transitioning to the normal state that system failure could occur is negligible.

If the 7 cables on the platform are <u>not</u> cross connected, then transition to the normal state at any point in a given cable will cause the entire cable to go normal. Most of the current that had been carried by the transitioned cable will inductively transfer to the remaining superconducting cables on the platform. This will then cause the surface field and the current density to increase in the remaining cables, reducing the safety margin between the operating and critical current densities.

At some point, if a large enough fraction of the N cables transition to the normal state, the operating current density and the surface magnetic field in the remaining cables will sufficiently increase that their critical current density limit is reached, and all of the cables would then go normal, causing loss of levitation.

This worst case was analyzed, and it was used as the basis for the choice of such design parameters as operating current density, conductor radius, and the number of cables, N, to ensure an adequate safety margin.

For the design choices of $J_{SC} = 2 \times 10^5$ Amp/cm², $r_C = 0.15$ meter, and N= 7, three of the seven cables on the platform would completely transition to the normal state, and levitation capability would still be maintained. In this situation, J_{SC} would increase to 2.12×10^5 Amp/cm², and $(B_\theta)_{MAX}$ would reach 4.16 Tesla. The corresponding critical current density, J_C, at this field would be 3.25 Amp/cm² which would be slightly greater than the 3.12×10^5 Amp/cm² value for J_{SC}. [The actual safety margin would be greater however, since the average field on the superconductor is only about 50% of the maximum. Since the filaments in the actual menolithe conductor are effectively in parallel, these filaments operating at $B_\theta < (B_\theta)_{MAX}$ would still be well below their individual critical current limit.]

By basing the choice of design parameters on a very unlikely worst case scenario, and then using a cross connection approach between cables that greatly enhances system redundancy, it is believed that a very robust levitated cable system can be achieved - one that should be virtually incapable of losing levitation capability.

The **second** requirement that must be satisfied is that the magnetic forces on the superconducting winding must be transferred to a support structure which holds the winding firmly in place while still enabling good cooling.

Figure 11 illustrates the mechanical support structure for the conductor winding inside each of the StarTram levitated cables [the separate support structure that holds the 7 cables in place against their interactive magnetic forces has been described previously].

Each of the levitated cables has 40 individual conductors (each carries 50 kiloamps, for a total cable current of 2.07 megamps). The 40 conductors are helically would on a 30 centimeter diameter cylindrical tube. Each conductor consists of a high purity matrix in which are imbedded the superconducting NbTi/Cu strands.

The helical winding has a relatively long pitch with the pitch length considerably larger than the diameter. As a result the magnetic force on the long pitch helical winding closely approximates that for a winding in which the conductor direction is purely longitudinal. In this case, the radially inwards magnetic pressure Pm (Newtons/in²) is given by

$$Pm = \frac{\left(B_\theta\right)_{\max}^2}{2\mu_O} \qquad \textbf{(28)}$$

The cylindrical support tube is actually a close fitting double tube. The outer tube is made of aluminum, with a center core of high purity (99.999%) aluminum. The inner tube is made of graphite epoxy honeycomb.

The inner tube provides the mechanical support to withstand the radial inwards magnetic pressure, while the outer tube acts to widely disperse heat that may be released by momentary local conductor movements and/or flux jumps. This helps to ensure that the superconductor windings operate in an essentially uniform temperature environment, minimizing the chances of a transition to the normal conducting state. The cold high purity aluminum core has a very high thermal conductivity (~ 1000 W/cm K) which enables heat to be widely dispersed with a minimal temperature difference.

The support tubes are segmented, with overlapping sliding joints at their ends. This arrangement enables the tubes to readily compensate for the differential thermal contraction between the inner portion of the cable which is at 4 K, and the outer vacuum boundary which is at the ambient atmospheric temperature. Aluminum, for example, contracts by 0.4% when it is cooled from normal temperature (300 K) down to 4 K.

As the support tubes are cooled down, the sliding joints allow them to contract slightly, while their center positions remain longitudinally fixed relative to the outer pipe.

The tubes are designed so that they can withstand an inwards pressure that is 10 times greater than the magnetic pressure in the worst case scenario, that is, where 3 of the adjacent 7 sections levitated superconducting cables fail, and all of the current flows in the 4 remaining cables. This safety factor of 10 appears more than adequate. The corresponding weight of the graphite epoxy and aluminum tubes are 7 and 10 kilograms per meter of cable, respectively. The total weight of the support tubes is thus 17 kg per meter of cable, slightly less than the 20 kg per meter weight of the superconductor. [there is also an additional weight of 20 kg per meter required by the high purity matrix in which the NbTi/Cu superconductor strands are imbedded.]

The **third** requirement that must be satisfied is that the conductor be adequately cooled, and that any energy released by conductor motion and/or flux jumps be transported away from the conductor so that will remain in the superconducting state.

The StarTram conductor design is very conservative with regard to energy release and cooling, because: 1) the diameter of the individual NbTi filaments in the superconducting strands are very small (~ 6 microns), which minimizes the probability of flux jumping, and the amount of energy release should it occur; 2) the superconducting strands are imbedded in a high purity (99.999%) high electric conductivity aluminum matrix that effectively shield them from rapidly changing magnetic fields, preventing the possibility of a triggered sequence of flux jumps; 3) the conductors are rigid and mechanically well supported, minimizing the possibility and amount of energy release from movements; and 4) the conductors are designed to be cryostable - that is, if all of the NbTi stands in the conductor transitioned to the normal state and their current switched to the high purity aluminum matrix, the heat flux resulting from I^2R heating to the helium coolant is low enough that the conductor can be cooled back to the temperature at which the NbTi would regain superconductivity.

The upper surfaces of the conductors are directly exposed to the liquid helium coolant, allowing the I^2R and heat to be transferred from the conductors to the helium. The magnetic pressure on the conductors is very strong, i.e., on the order of 50 atmospheres) radially downwards towards the support tube, holding them firmly in place. In addition, there is an open graphite-epoxy grid on trop of the conductor winding, rigidly positioned between the winding and the enclosing helium coolant pipe.

The **fourth** requirement that must be satisfied is to have good thermal insulation between the liquid helium cooled region with its conductors and the outer tube of the cable, which is at the atmospheric ambient temperature. For altitudes greater than ~ 10 kilometers, the ambient atmospheric temperature is constant at 216 K, well below the average ambient surface temperature of ~ 300 K at many locations.

However, even though the average ambient temperature on the outer wall is lower than normal, heat leakage into the 4 K region must be minimized, in order to keep the amount and cost of refrigeration reasonable.

Heat leakage is minimized by using multi-layer vacuum insulation between the outer tube wall of the cable, and the inner 4 K region. The multi-layer insulation has a very low thermal conductivity, typically on the order of 0.5×10^{-6} W/cm K. In addition, an intermediate temperature thermal shield is used. This intercepts a substantial fraction of the thermal leakage and removes it at a temperature of ~77 K, the normal boiling point of liquid nitrogen. The electric energy input required to reject a unit amount of heat from a 77 K region is much less than the same unit of heat rejected from 4 K. The Carnot efficiency power for a refrigeration cycle operating between 77 K and 216 K is ~2 watts (e), per watt (th) at 77 K, compared to Carnot efficiency of ~50 watts (e) between 4 K and 216 K. (The actual refrigeration power will be on the order of four times the Carnot efficiency power, due to various irreversible losses in the refrigeration cycle.)

Using the intermediate thermal shield, the actual insulation heat leak between 77 K and 4 K can be reduced to ~0.02 watts (th)/m^2, a very small quantity, corresponding to only a few watts per kilometer of levitated cable. The corresponding electrical input power to the 4 K refrigerator will be on the order of 4 kW(e) per kilometer of cable, a negligible amount. Refrigeration for the complete 7 cable array would then have a total electric power requirement of approximately 30 kW(e) per kilometer, or about 10 MW(e) for the entire ~300 km long levitated cable/launch tube system.

7. SUMMARY AND CONCLUSIONS

A revolutionary new concept, termed StarTram, is described for launching passengers and payloads into orbit at very low cost. Reusable StarTram spacecraft are magnetically levitated and accelerated at modest levels (i.e., 2.5 g) to orbital speeds (~8 km/sec) inside a ground based vacuum tunnel. After reaching launch speed, the StarTram spacecraft enters an upward curving, magnetically levitated vacuum launch tube, in which it travels upwards to an altitude of 22 kilometers above sea level. At the exit point of the launch tube, the vehicle transitions into the low density atmosphere (~5 % of sea level density) through a fast opening airlock. At an altitude of 22 km, the heating rates and deceletation levels on the spacecraft are sufficiently reduced that atmospheric entry is practical.

The launch tube is levotated by the magnetic repulsive force between the currents carried in a set of superconducting cables attached to the tube, and the oppositely directed currents carried in a second set of superconducting cables located at ground level beneath. The vertical and lateral position of the levitated cable/launch tube system is maintained by a network of high strength, lightweight tensile restraining tethers (e.g., Spectra or Kevlar material) that are anchored to the ground. The tether network maintains correct launch tube position even if high winds act on the system

The StarTram point design described uses currently available materials and well developed commercial superconducting components. The NbTi superconductors operate at current densities that are well below present limits, as are the stresses in the tethers and structural materials. The StarTram design is highly redundant and reliable, with no possibility of single point or common mode failures. If an individual superconducting cable tether, or structural element were to fail, other components would take over the load, with essentially no degredation or impact on overall system performance. To significantly affect system performance, a very large fraction, e.g., 50 % or more, of the multiply redundasnt individual components would have to fail. This appears extremely unlikely.

Superconducting maglev technology similar to that proposed for levitating and accelerating StartTram spacecraft has been demonstrated in Japan. Full scale commercial type Maglev vehicles have operated in the atmosphere at speeds of up to 350 mph, both as individual 100 passenger cars, and in coupled tram sets consisting of 5 cars.

StarTram launch costs, including amortization of the launch system capital cost, O&M costs, and energy costs would be less than $30 per kilogram of payload, a factor of 300 lower than present launch costs. The total launch capacity of a StarTram system would be extremely large - up to a million tonnes per year or more.

While building StarTram would be a very large scale project, requiring a great deal of engineering R&D, there does not appear to be any breakthroughs needed in materials and superconducting technology to build a practical, cost-effective system. Moreover, the anticipated future developments in the high temperature superconductors, when they become available, would appear to significantly simlify superconducting requirements and reduce overall cost.

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[3] John C. Mankins, "The MagLifter: An Advanced Concept Using Electromagnetic Propulsion in Reducing the Cost of Space Launch," (AIAA 94-2726), *38th Joint Propulsion Conference and Exhibit*, Indianapolis, IN, June 24-29, 1994.

[4] T. W. Strganac, "Wind Study for High Altitude Platform Design," NASA Reference Publication 1044, 1979.

Table 1: StarTram System Parameters

Spacecraft	**Nominal Value**
Launch Velocity	8 km/s
Launch Altitude (Above Sea Level)	22 km
Gross Weight	200 MT
Empty Weight	100 MT
Payload to LEO	70 MT
Overall Dimensions	5m x 5m x 40 m
Launch Kinetic Energy	1.8 Gw Hr
Atm Deceleration At Launch	17 m/sec^2 (1.7 g)
ΔV Less Thru Atm	0.05 km/s
ΔV Burn to LEO	0.35 km/s

Acceleration Tunnel	**Nominal Value**
Length	1280 km
Ground Elevation (Above Sea Level)	3 km
Longitudinal Acceleration	25 m/sec^2 (2.5 g)
Velocity at End	8.02 km/s
Time in Tunnel	5.3 minutes
Acceleration Driver (Avg.)	20 GW(e)

Launch Tube	**Nominal Value**
Total Length	281 km
Length of Levitated Section	220 km
Ground Elevation (Above Sea Level)	3 km @ Start; 4 km @ End
Trajectory Shape	Recurve
Launch Angle	5 Degrees
Centripetal Acceleration	25 m/sec^2 (2.5 g)
Time in Tube	0.58 minutes

Table 2: StarTram Platform and Tether Parameters

Platform and Launch Tube	**Nominal Value**
Levitation Geometry	Tilted Linear Dipole Loop
Maximum Altitude	22 km Above Sea Level
Maximum Levitation Height, H_O	18 km Above Surface
Loop Width (Variable)	3.6 x Local Levitation Height
Weight of Platform/m of Track, Mpg	1 MT/m
Weight of Launch Tube/m of Track, $M_{LT}g$	1 MT/m @ 22 km 2 MT/m @ 10 km
Gross Magnetic Lift/m of Track, $(Fm)_L$	4 MT/m @ 22 km 6 MT/m @ 10 km
Net Magnetic Life/m of Track, $(Fm)_L^{**}$	1.2 MT/m @ 22 km 2.5 MT/m @ 10 km
Levitation Current, I_L	14 Megamps

Tethers	**Nominal Value**
Number and Type	2 Angled Plus Vertical
Tether Angle	45 Degrees
Material	Onernod Polyethylene
Operating Tensile Stress	$6x10^8$ N/m^2
Ultimate Tensile Strength	$3x10^9$ N/m^2
% Load Factor in Vertical Tether, λ	70%
Weight of Angled Tethers/m of Track	0.32 MT/m @ 22 km
Weight of Vertical Tether/m of Track	0.42 MT/m @ 22 km
Sag Ratio of Angled Tethers, Midspan	0.0905
Platform Horizontal Motion From Cross Wind	
Without Active Control of Tethers	8 m @ 50 m/sec (110 mph)
With Active Control of Tethers	$\leq$ 1 m @ 50 m/sec (110 mph)

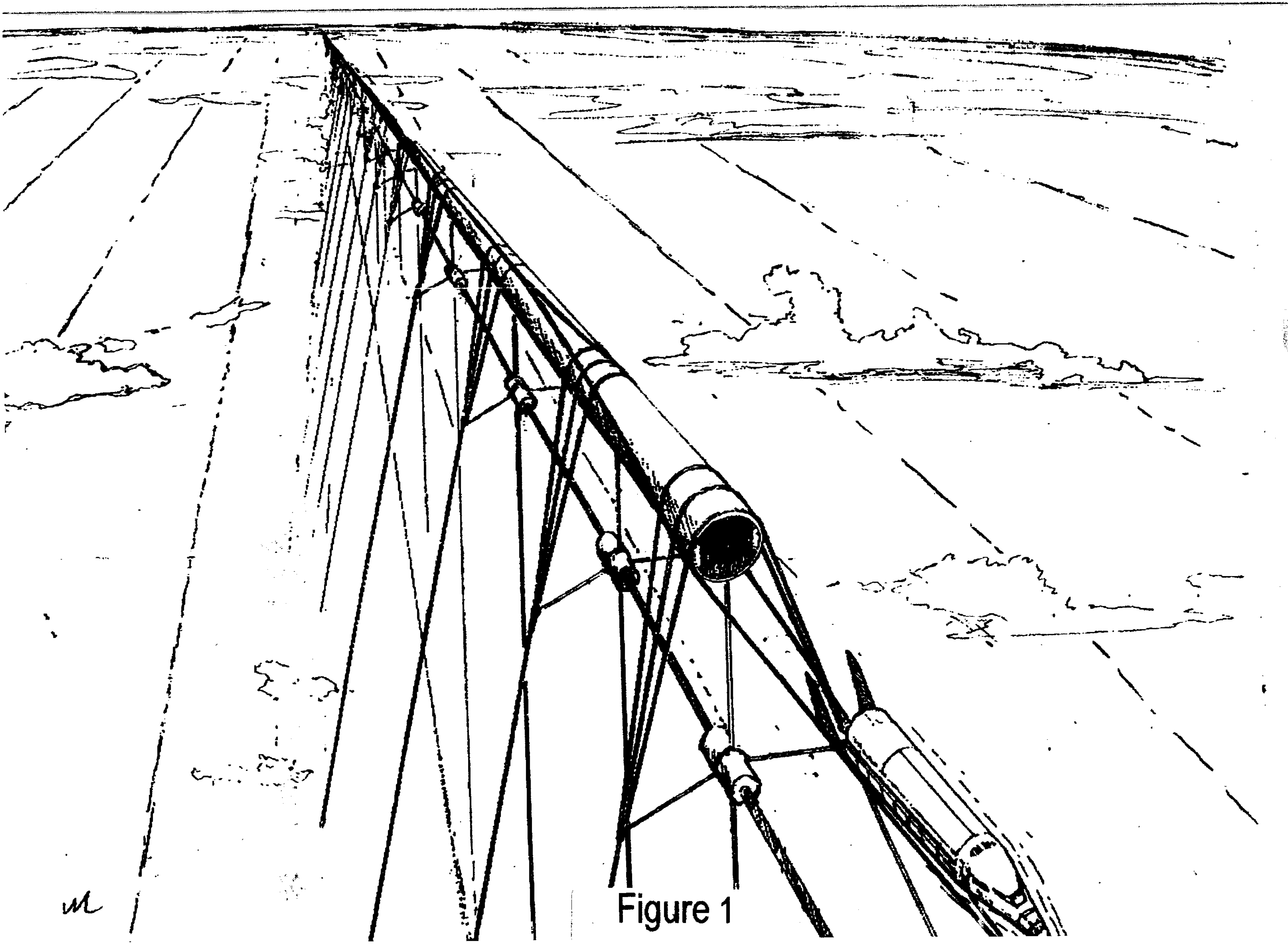


Figure 1

Effect Of Launch Altitude On Spacecraft Deceleration And Heating

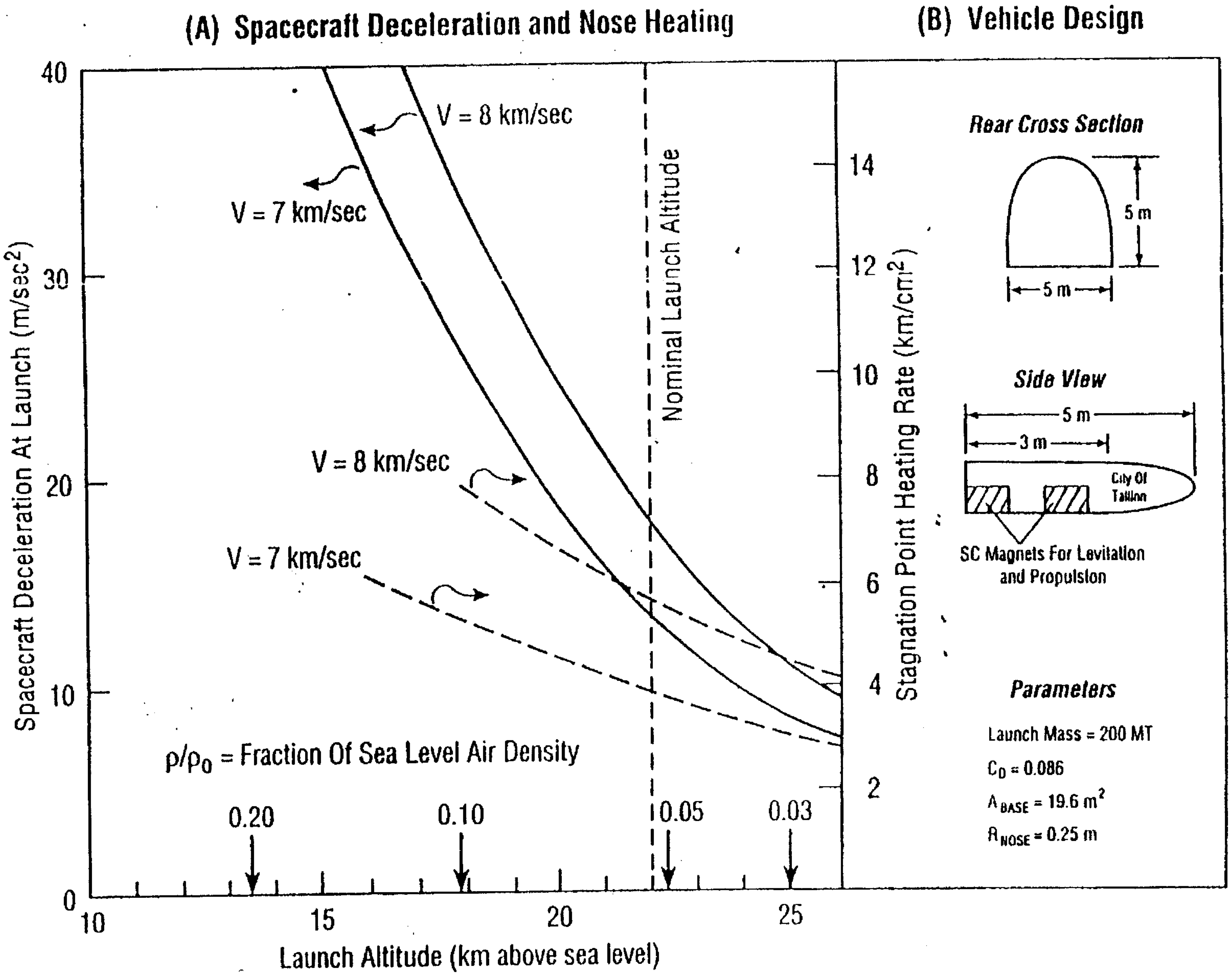


Figure 2

Force On Levitated Cable vs Current In Cable

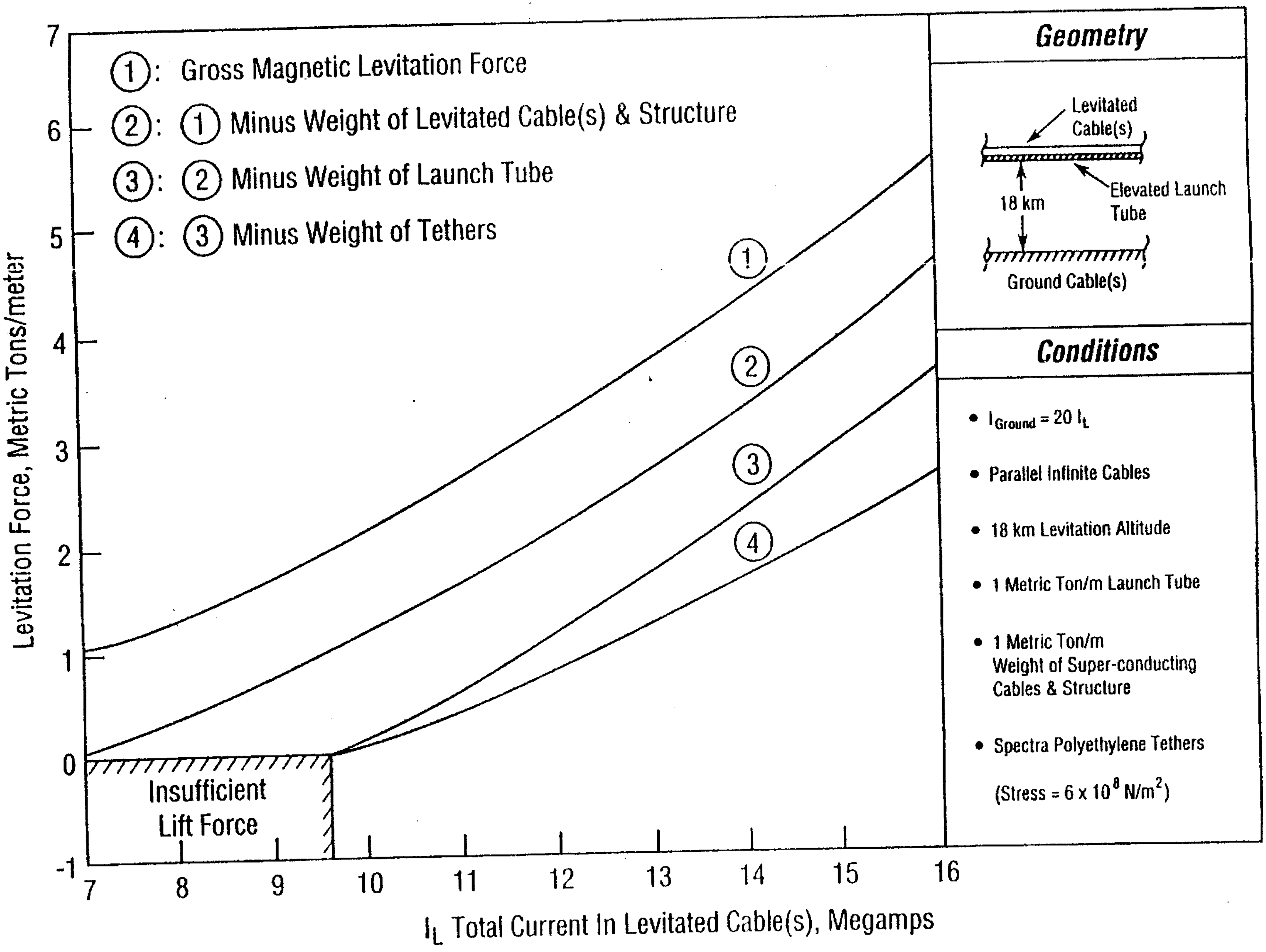
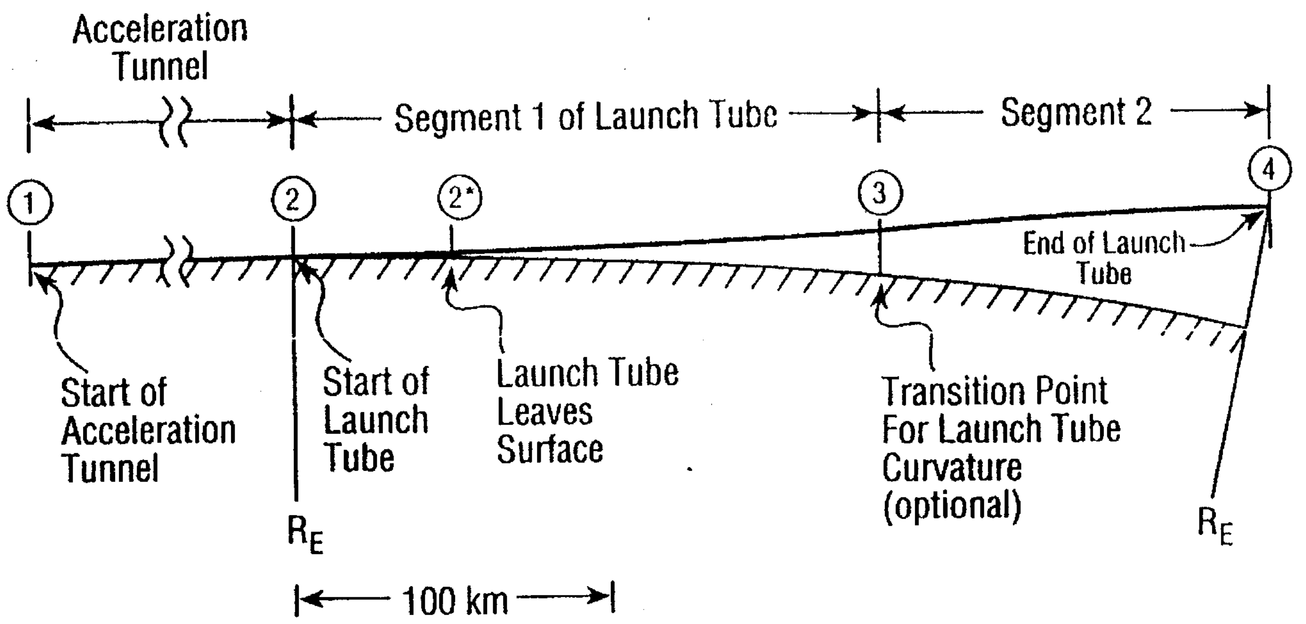


Figure 3

Trajectory Of Generic StraTram Launch Tube



Illustrative Altitude Profile
(Recurve Trajectory)

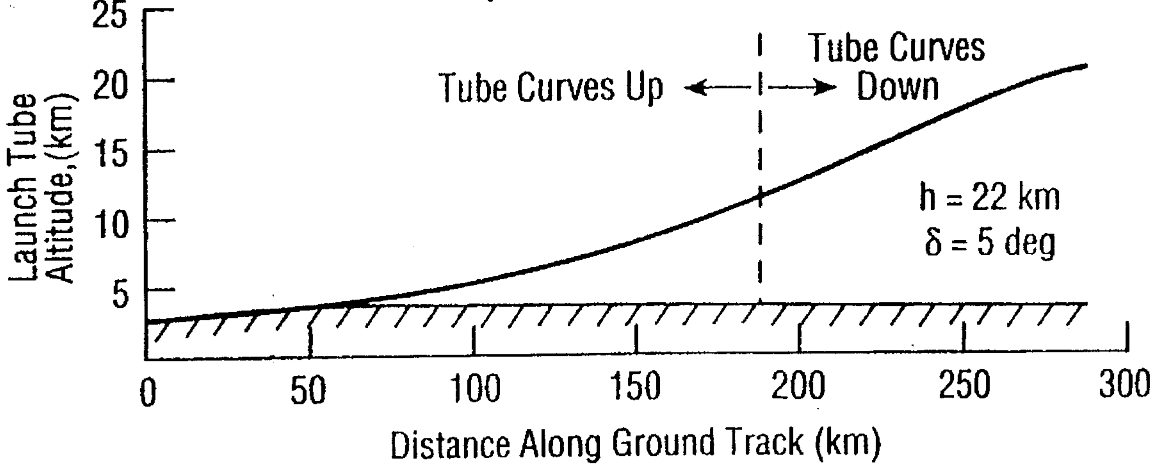


Figure 4

Vehicle In Acceleration Tunnel
(Wings Retracted)

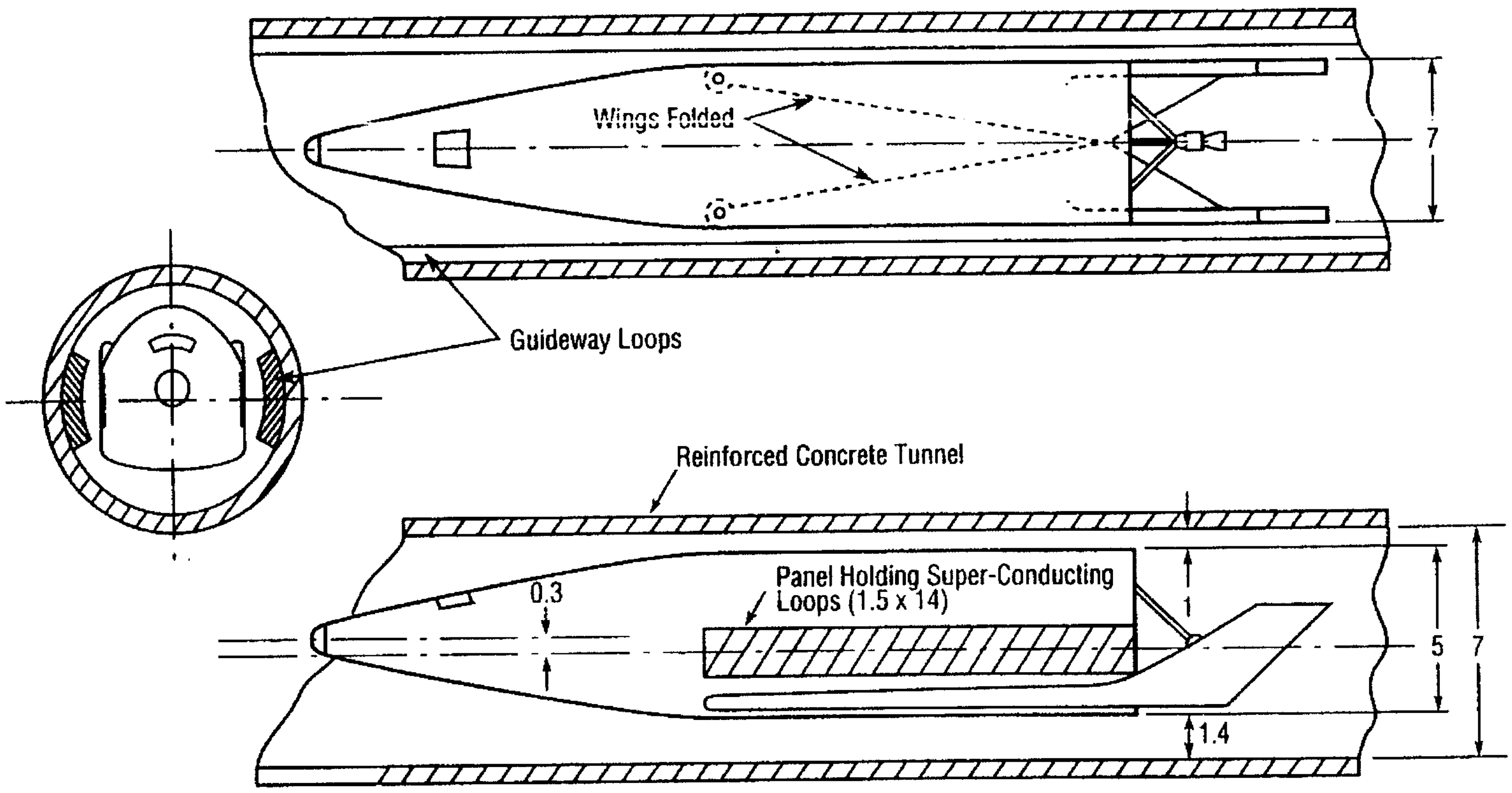


Figure 5

Ascent Trajectory to LEO

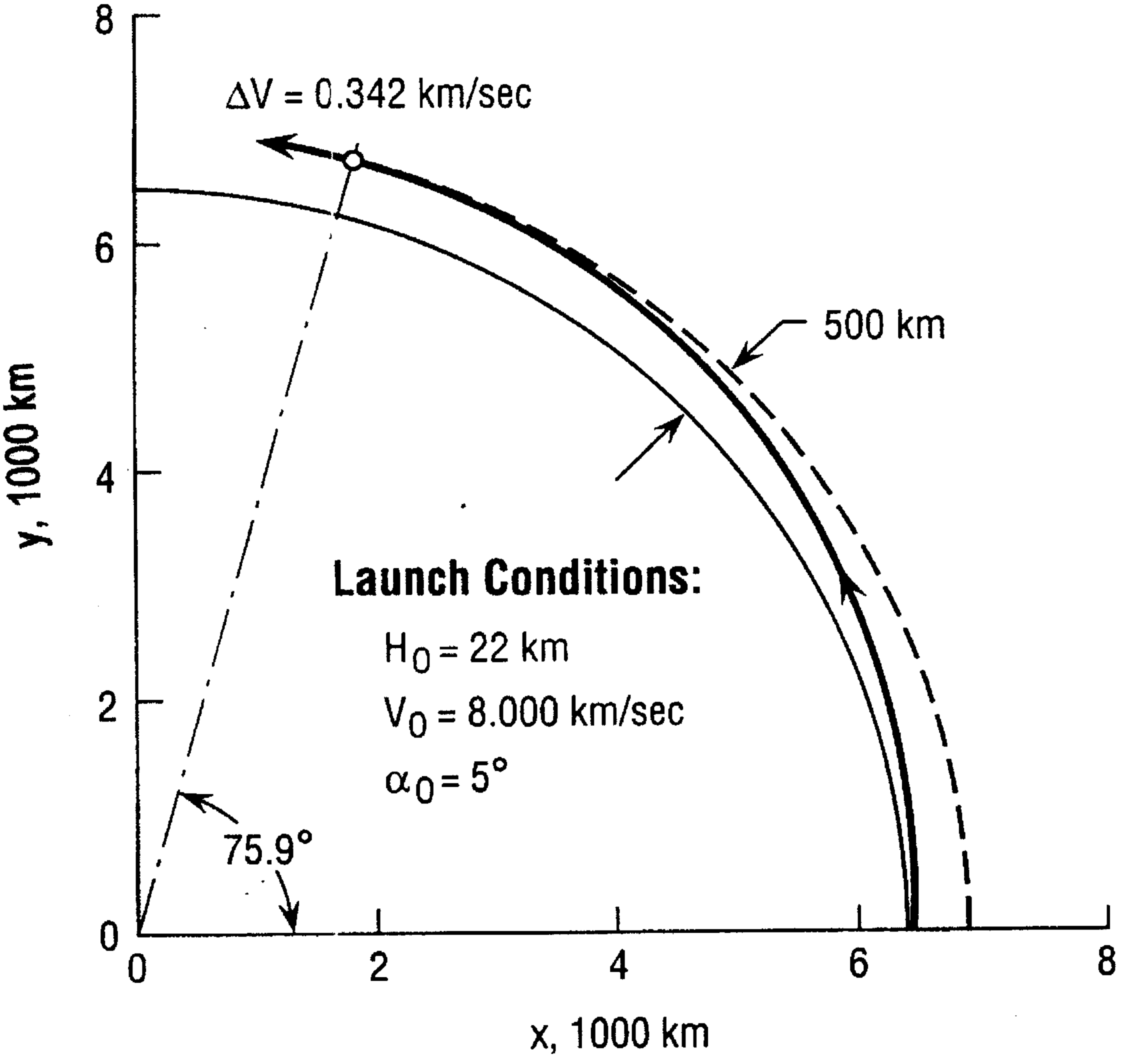


Figure 6

Ascent Trajectory to GEO

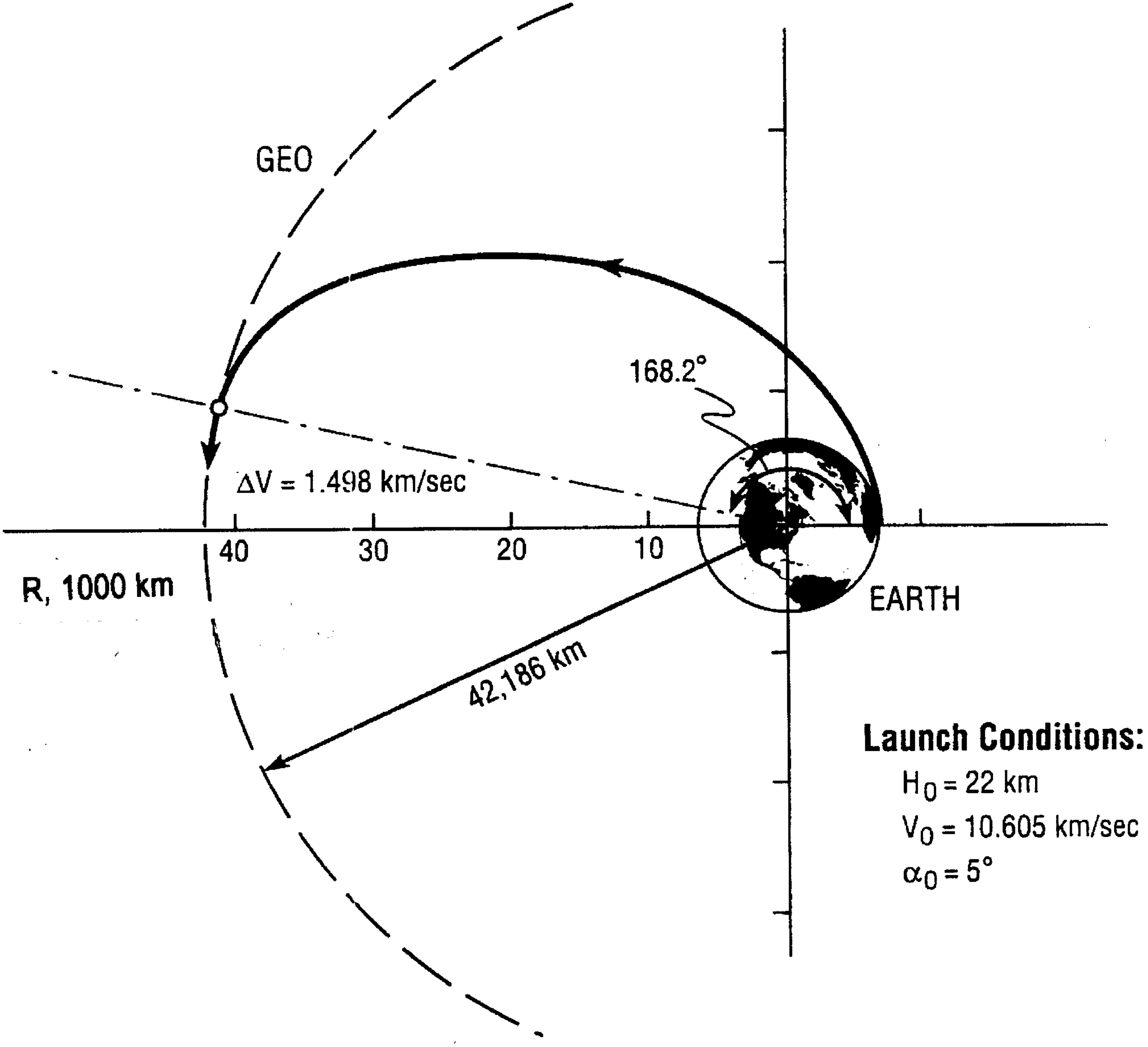
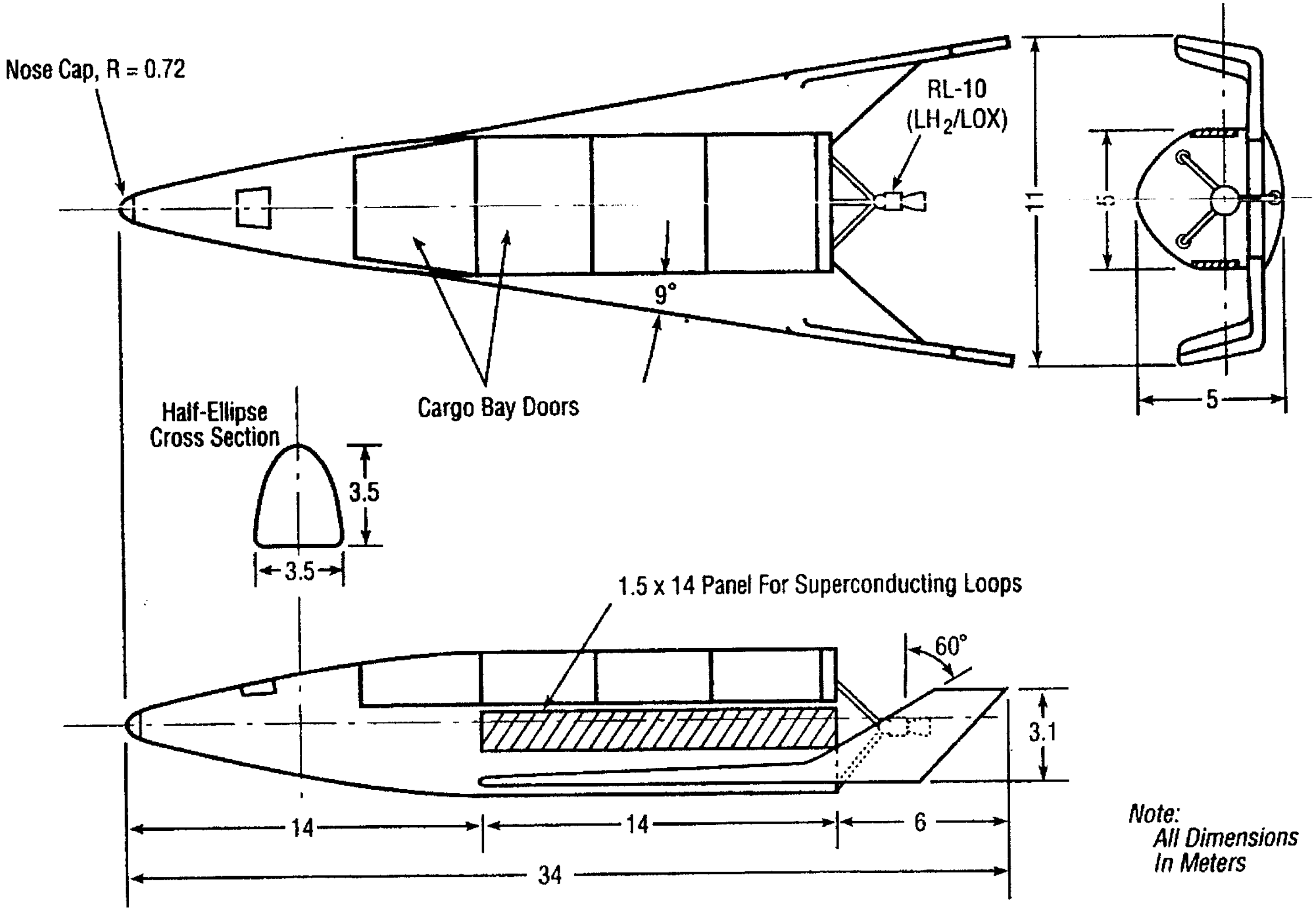


Figure 7

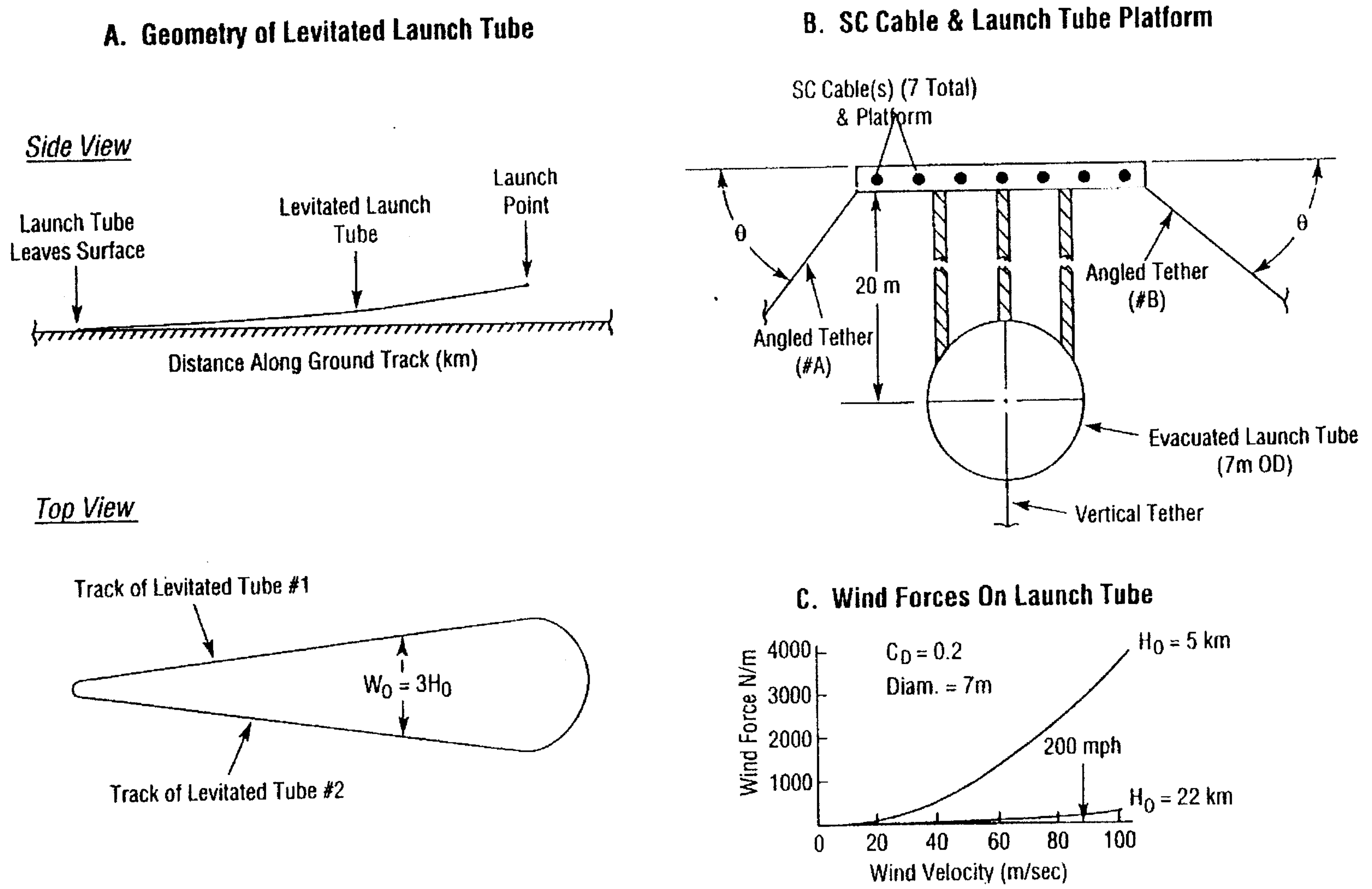
Vehicle In Reentry/Flying Configuration
(Wings Deployed)



Note:
All Dimensions
In Meters

Figure 8

StarTram Levitated Cable and Launch Tube



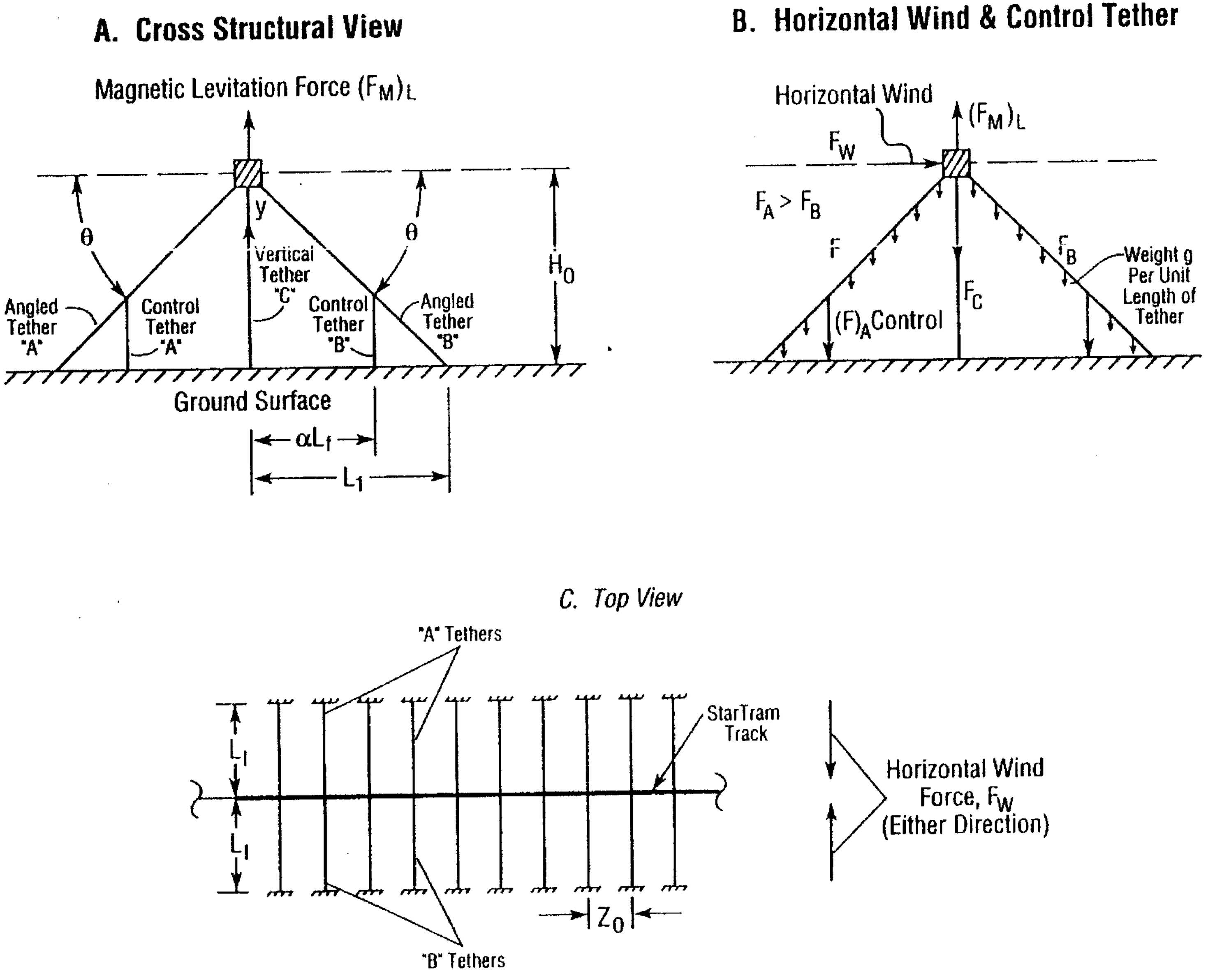
A. Geometry of Levitated Launch Tube

B. SC Cable & Launch Tube Platform

C. Wind Forces On Launch Tube

Figure 9

StarTram Tether Geometry (Idealized)



A. Cross Structural View

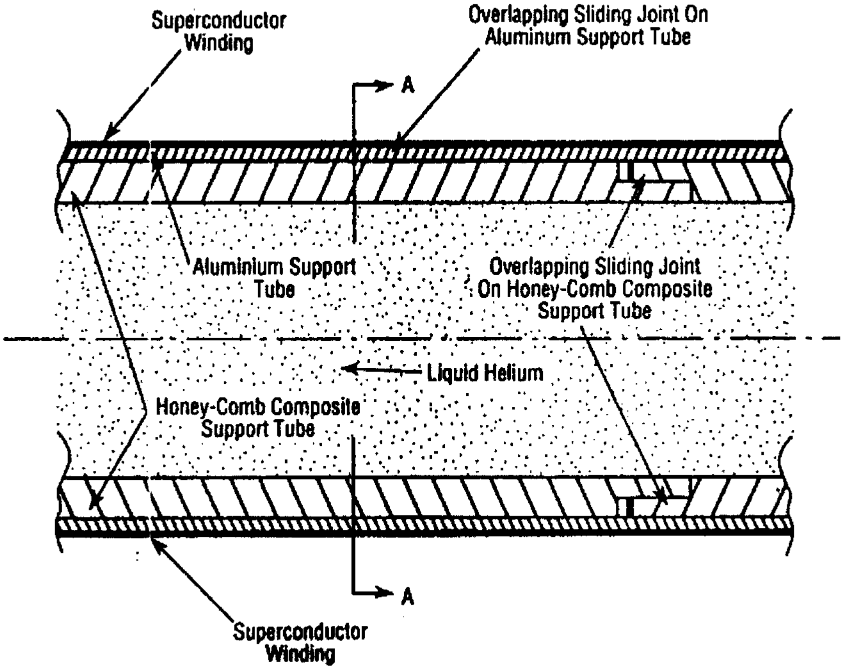
B. Horizontal Wind & Control Tether

C. Top View

Figure 10

Superconductor Winding and Support Tube For Levitated Cable

A. Longitudinal Cross Section



B. Superconductor Winding Pattern (Not To Scale)

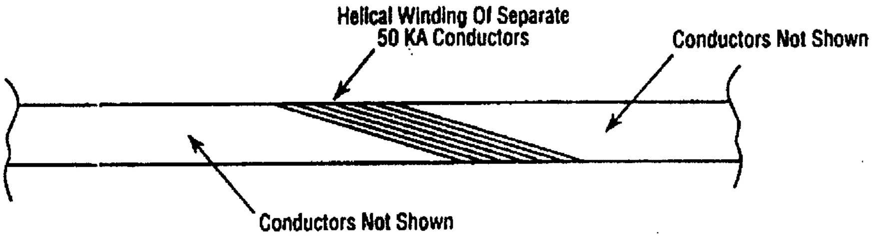


Figure 11