Fisher Space Systems

Space Track Launch System
Tower

by
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1. Introduction

The Space Track Launch System (STLS) is a two stage launch system. The first stage is a tall tower with rotating ribbons (Fisher, J.F., 2007). The tower (figure 1) is from 50-150 km in height. At the top of the tower, there is a rotating truss which supports four ribbons (two ribbons from each end of the truss) made of high strength fiber composites. Counterweights (CW) (Fisher, J.F., 2010) are attached to the end of each ribbon.

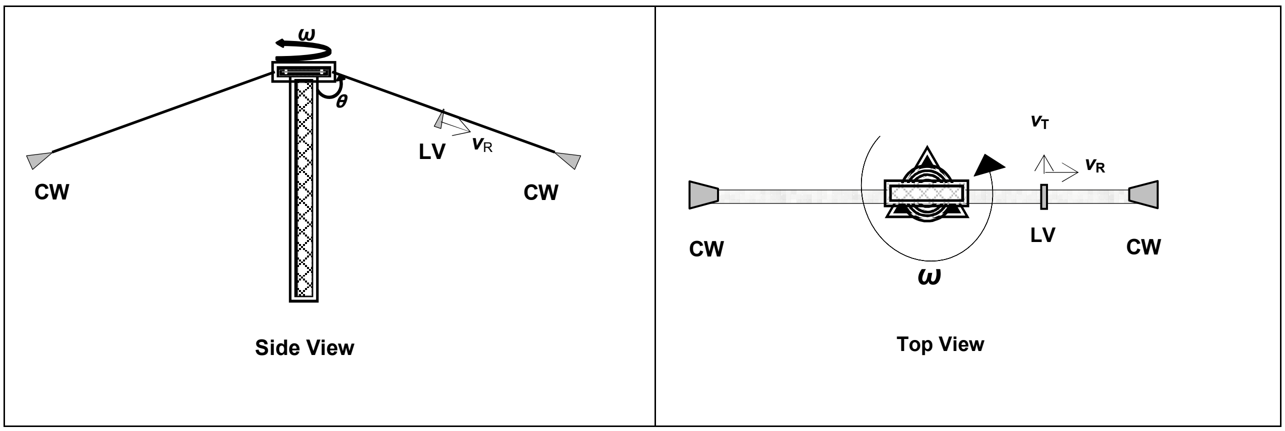

Figure 1. Space Track Launch System

The second stage is a liquid fueled launch vehicle (LV) designed to launch from the STLS (Fisher, J.F., 2009). The launch vehicle attaches to an ejector which is attached to an overcarriage (Fisher, J.F., 2010). The overcarriage has four tapered wheels which rest on top of the ribbon. The overcarriage and launch vehicle travel down the ribbon and are accelerated by the centrifugal force resulting from the distance from the axis of rotation and by the contact force (Coriolis force) provided by the rotating ribbon. At a predetermined point along the ribbon, the ejector fires and the launch vehicle detaches from the overcarriage and ribbon. The liquid propellant rocket engines ignite and the second stage proceeds into orbit. The overcarriage returns to the launch site to be refurbished and reused.

The system is unique for several reasons. First, the first stage is all electric and can be used four to five times per week. The electric motors restore rotational kinetic energy to the ribbons in approximately 24 hours. Second, there are two sets of ribbons which allow one set to remain operational while the other is undergoing inspection and repair. Third, for launch altitudes greater than 70 km, the second stage launch vehicle can take advantage of the gravity assist provided by the Earth resulting in significant propellant mass savings. Fourth, the ejector attachments mate to a standard overcarriage but the ejector itself is unique to the second stage launch vehicle. As such, a variety of second stage launch vehicles can be used. Finally, the overcarriage returns to the launch site, making the STLS a completely reusable launch system. This paper presents an initial design for the tower beginning with the load at the top of the tower.

2. Tower Load

The load (figure 2) at the top of the tower at startup will consist of the mass of the counterweights, the ribbons, the ribbon support structure, the tower truss, the cable support columns, the turntable and gear assembly, the motors, the research station, the elevators, the guy wires, and a tower interface ring. During operation, the tower load will increase due to the mass of the 2nd stage launch vehicle. The basic tower design is a second generation system. The first generation system will be approximately 50-100 km high and the load at the top will probably be lower than the final load for a 100-150 km high tower. But, to ensure scalability and to help determine the direction for technology development, the load at the top of the 2nd generation systems will be assessed. The mass analysis begins with the ribbon support structure.

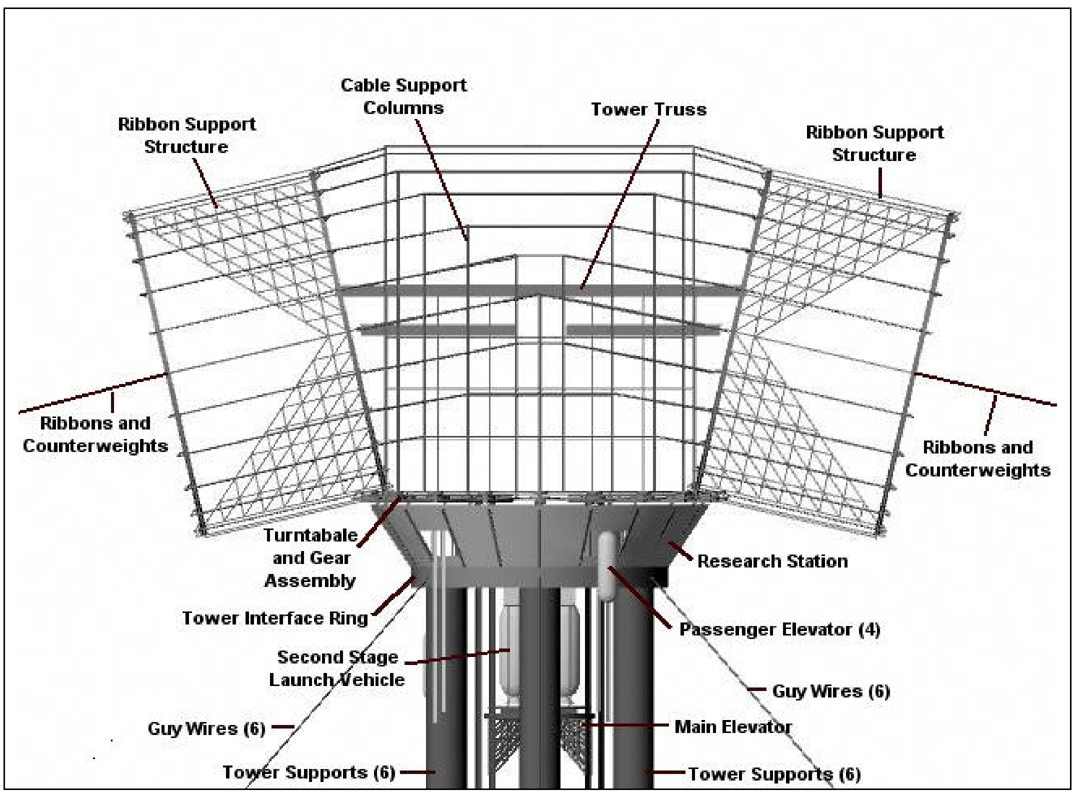

Figure 2. Tower Load

2.a. Ribbon Support Structure

As shown in figure 2 above, there are two ribbon support structures. Each structure supports two ribbons and 80 counterweights (Fisher, J.F., 2010). To estimate the mass, the physical properties of a new composite material known as M5® (M5®, 2006) will be used. M5® has a modulus of elasticity of 330 GPa, a tensile strength of 10 GPa, a compression strength of 2 GPa, and a density of 1700 kg/m^3. The mass for a single structure will first be determined and then doubled for the total load on the turntable.

The mass for a 400 km long carbon nanotube ribbon with 200 tons of counterweights rotating at an angle of 77^o from the vertical is approximately 3.9 x 10^5 kg. Together, the counterweights and ribbons exert a force of 1.7 x 10^7 N on the ribbon support structure. The ribbon support structure is approximately 32 m in diameter and consist of six 'wings' attached to the ribbon support ring and frame. There are two ribbons. Therefore, each ribbon exerts a force of 8.3 x 10^6 N on three wings. As shown in figure 3 below, each ribbon is wrapped around a rectangular beam which is 1.5 m wide and 0.1 m thick.

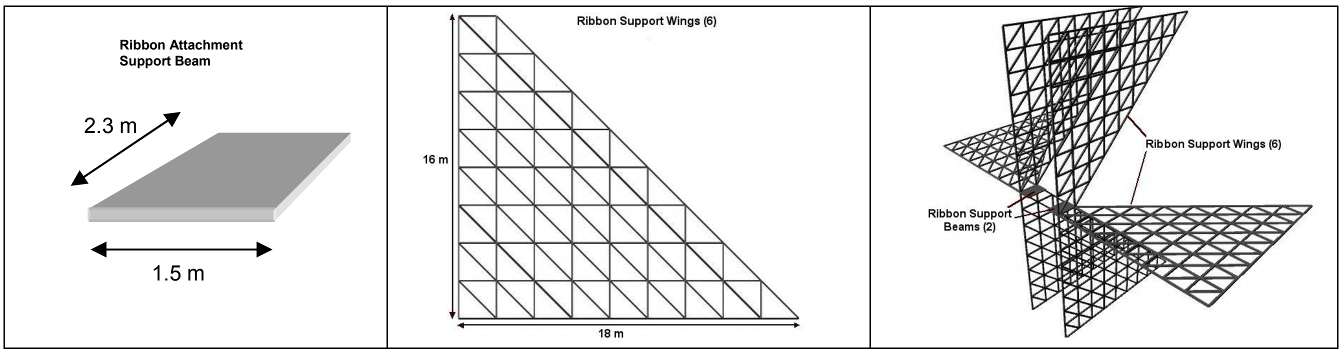

Figure 3. Ribbon Support Structure

The beam is modeled as a cantilever with uniform load (Shigley, L. and Mitchell, L., 1983, p.805). The maximum deflection is given by,

$$y_{\max} = -\frac{wl^4}{8EI} \qquad (1)$$

where w is the load per unit length equal to 8.3 x 10^6 N/m, l is the length to be determined, E is the modulus of elasticity for M5® equal to 3.3 x 10^{11} N/m^2, and I is the area moment of inertia. For a rectangular cross section, the area moment of inertia, I, is given as,

$$I = \frac{bh^3}{12} \qquad (2)$$

where b is the thickness equal to 0.1 m and h is the length to be determined.

Solving equation 1 above for the area moment of inertia, using a maximum deflection of 1 mm and a safety factor of 6, gives the area moment of inertia, I, as 9.5 x 10^{-2} m^4 which in turn gives the length as approximately 2.3 m. Therefore, the volume of the beam is approximately 0.34 m^3 giving it a mass of 574.0 kg.

As shown in figure 3, the rectangular beam is attached to the tip of three wing shaped trusses. Each wing tip supports a lateral load of 2.8×10^6 N. This load is transferred uniformly to the base of the wing by the columns, beams, and struts of the wing shaped truss. The base of the wing is connected to two ribbon support rings and a frame. Using the compression strength of M5® with a safety factor of six gives the mass of a 2 m beam or column of 28.2 kg. There are 44, 2 m beams and 44, 2 m columns for a total mass of 2,481.6 kg. There are 44, 2.8 m struts for a total mass of 1,754.8 kg. The total mass of one wing is 4,236.4 kg. There are three wings for a total mass of 12,709.1 kg. The wing tips are attached to the ribbon support beam which has a mass of 574.0 kg giving a total estimated mass of 13,284 kg for one ribbon support structure. There are two ribbons and therefore, two support structures for a total mass of 26,568 kg. The masses are summarized in table I below.

Subsystem	**Mass**
Beams & Columns	2.5×10^3 kg
Wing Struts	1.8×10^3 kg
Subtotal	4.3×10^3 kg
X 3	1.3×10^4 kg
Ribbon Beam	5.7×10^2 kg
Subtotal	1.4×10^4 kg
X 2	2.7×10^4 kg

Table I. Ribbon Support Structure

2.b. Ribbon Support Ring and Frame

The ribbon support structure is attached to two 32 m diameter rings. This diameter was chosen to accommodate a variety of second stage launch vehicles (Fisher, J.F., 2009). The ribbon support ring and frame are shown in figure 4 below.

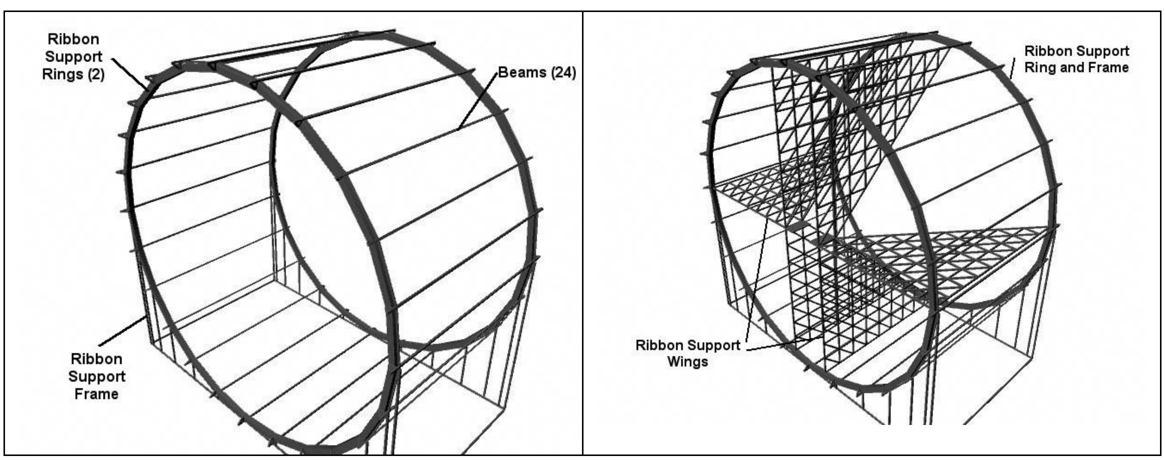

Figure 4. Ribbon Support Ring and Frame

The rings are supported by 24 beams. Each beam has silicon carbide bearings which allow the whole assembly to rotate. The assembly must rotate from 0 to 90 degrees in an effort to keep the gravitational and Coriolis acceleration forces perpendicular to the ribbon and to be in position to restore rotational kinetic energy after launch. Each bearing supports a load of 3.5 x 10^5 N. The properties of silicon carbide are such that the mass of the bearings are insignificant compared to the rest of the structure. The bearings are spaced approximately 4.2 m apart on the ribbon support ring. The 4.2 m section of ring is modeled as a rectangular beam with simple support and uniform load (Shigley, L. and Mitchell, L., 1983, p. 807).

The maximum deflection is given by,

$$y_{\max} = -\frac{5wl^4}{384EI} \qquad (3)$$

where the load per unit length, w, is 8.3 x 10^4 N/m, the distance between supports, l, is 4.2 m, and the modulus of elasticity, E, is 5.5 x 10^{10} N/m^2 (safety factor of 6). With a maximum deflection of 1 mm, the area moment of inertia is 6.1 x 10^{-3} m^4. From equation 2 above and with a width, b, of 0.5 m, the height, h, is approximately 0.5 m. This gives the volume of one ring as 26.9 m^3 and therefore, a mass of 4.6 x 10^4 kg, or for two rings, 9.2 x 10^4 kg.

The rings are supported by 24 beams. Each beam supports a load of 6.9 x 10^5 N. A torsion stress analysis shows that an area of approximately 3.6 x 10^{-3} m^2 per beam is sufficient to handle this load. Each beam is 18 m long which result in a mass of approximately 110.2 kg. There are 24 beams for a total mass of 2,643.8 kg.

The rings and beams are supported by a frame. The frame is made of the same size area as the beam but of differing length. The columns are 16.6 m, 12.4 m, 8.4 m, 5.0 m, 2.3 m, and 0.7 m in length. There are 4 columns of each length. The beams that make up the frame are 33.1 m and 18 m in length. The total mass of the frame is approximately 1,734.6 kg. The total mass of the ribbon support ring and frame is approximately 9.6 x 10^4 kg and is summarized in table II below.

Subsystem	**Mass**
Ribbon Support Rings	9.2 x 10^4 kg
Ring Support Beams	2.6 x 10^3 kg
Ring Support Frame	1.7 x 10^3 kg
Total	9.6 x 10^4 kg

Table II. Ribbon Support Ring and Frame

2.c. Ribbon Support Truss

As shown in figure 5 below, the ribbon support truss is similar to a standard box beam truss design. The ribbon support truss attaches to the ribbon support ring and frame at 5 attachment points located at the base of the frame. The ribbon support ring is attached to its counterpart via high tension CNT cables attached to the ring support beams. The mass of the cables is insignificant when compared to the rest of the structure and therefore, will not be considered in the mass analysis. The ribbon support ring and frame is titled 13^o from the truss to support the ribbon at the required angle for launch.

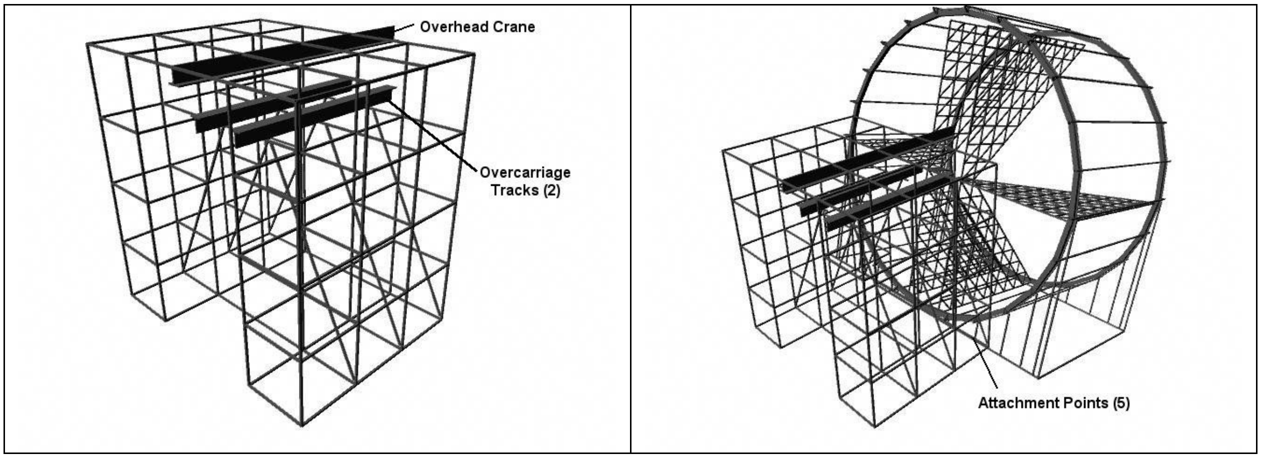

Figure 5. Ribbon Support Truss

The ribbon support truss is made of 120, 5 m beams, 64, 5 m columns, 6, 17.3 m struts, 2, 15 m overcarriage tracks, 2, 15 m overcarriage beams, 1, 20 m overhead crane track, and 1, 20 m overhead crane beam. The beams, columns, and struts each have a cross sectional area of 3.6×10^{-3} m^2. The total mass is therefore, 6.3×10^3 kg. The tracks and track beams each have a cross sectional area of 0.1 m^2. The total mass is 1.7×10^4 kg. The total mass of the ribbon support truss is approximately 2.3×10^4 kg and is summarized in table III below.

Subsystem	Mass (kg)
Beams, Columns, & Struts	6.3×10^3 kg
Tracks & Track Beams	1.7×10^4 kg
Total	2.3×10^4 kg

Table III. Ribbon Support Truss

2.d. Cable Support Columns

To distribute the load around the turntable, the ribbon support rings are connected together via high tension cables which are held in place by towers connected to the turntable (figure 6). There are 24 towers evenly spaced around the turntable. First, consider the 10 towers at the ends of the ribbon support truss, 5 towers at each end. The bottom of the ring support frame is connected directly with the tower truss and turntable at 5 points on its base. The top 5 points of the ring are connected to the top 5 points of the opposite ring via cables. The cables are held in place by the 10 towers which are connected to the turntable.

The load on the center tower is 1/24th of the load from one ribbon support ring or approximately 6.9×10^5 N. To make way for the 2nd stage launch vehicle, this load is divided by two support struts each 13.9 m long connected to the top of the ribbon

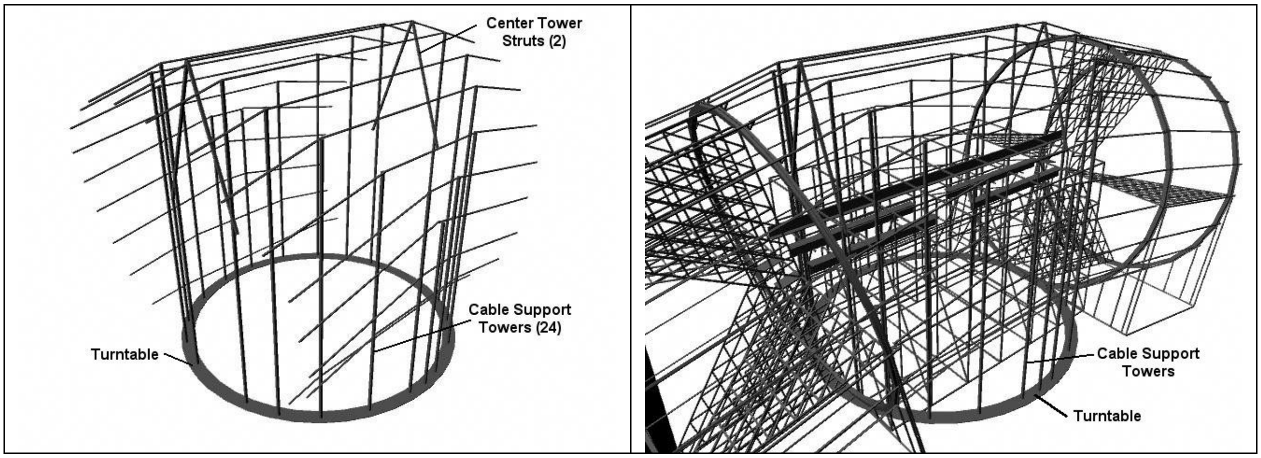

Figure 6. Cable Supports and Turntable

support truss. Each strut, therefore, has a load of 3.4 x 10^5 N. The critical load is 2.1 x 10^6 N for a safety factor of six. The strut will be modeled as an Euler column. The critical load for an Euler column is given by (Shigley, L. and Mitchell, L., 1983, p. 145),

$$P_{cr} = \frac{\pi^2 EI}{l^2} \quad (4)$$

where P_{cr} is the critical load equal to 2.1 x 10^6 N, E is the modulus of elasticity for M5® equal to 3.3 x 10^{11} N/m^2, I is the area moment of inertia to be determined, and l is the length of the column equal to 13.9 m. Solving equation 4 for the area moment of inertia gives I equal to 1.3 x 10^{-4} m^5. The area moment of inertia for a rectangular strut is given by equation 2 above. For a hollow rectangular beam, b_o = h_o = 0.25 m and b_i = h_i = 0.22 m giving a wall thickness of 1.5 mm and a cross sectional area of 0.014 m^2. Further analysis shows that this is indeed an Euler column. The mass of one strut is 333.2 kg and for all four struts the mass is 1,332.7 kg.

The remaining eight towers attached to top of the ribbon support truss are of different lengths. Four of the towers are 32.8 m and four are 31.1 m in length. The critical load for each tower is 2.1 x 10^6 N. From equation 4 above, the area moment of inertia, I, is 6.9 x 10^{-4} m^4 for the tallest tower. For a hollow rectangular column, b_o = h_o = 0.32 and b_i = h_i = 0.22 m with a wall thickness of 5.0 mm. Analysis shows that this is an Euler column. Therefore, the mass of the 32.8 m column is 3,011.0 kg. There are four of these columns for a total mass of 12,044.0 kg. Using the same area for the 31.1 m column gives its mass at 2,855.0 kg and with four towers, 11,420.0 kg.

The remaining 14 towers are attached to the turntable. Each tower supports twice the load with an upper cable and a lower cable. Using a safety factor of 6, the critical load is 8.4 x 10^6 N for each tower. The tallest of these last 14 towers is 28.9 m. Using equation 4 above, the area moment of inertia is 2.2 x 10^{-3} m^4. This gives b_o = h_o = 0.5 m and b_i = h_i = 0.45 m. The area is 4.8 x 10^{-2} m^2. There are four towers 28.9 m high, four towers 25.4 m high, four towers 21.4 m high, and two towers 16.9 m high. Using the same area for all towers gives a mass of 9,337.4 kg, 8,208.4 kg, 6,896.3 kg, and 2,731.0 kg respectively. The total mass for all towers is 51,970 kg and is summarized in table IV below.

Subsystem	Mass
4 Struts @ 13.9 m	1.3×10^3 kg
4 Col @ 32.8 m	1.2×10^4 kg
4 Col @ 31.1 m	1.1×10^4 kg
4 Col @ 28.9 m	9.3×10^3 kg
4 Col @ 25.4 m	8.2×10^3 kg
4 Col @ 21.4 m	6.9×10^3 kg
2 Col @ 16.9 m	2.7×10^3 kg
Total	5.1×10^4 kg

Table IV. Cable Support Columns

2.e. Turntable and Gears

The turntable consists of an upper rotating table and a lower support table. The upper rotating table is held into position by the gear assembly. There are 20 identical gear sets that make up the gear assembly. The total load on the upper rotating table is 1.2×10^7 N and is summarized in table V below.

Subsystem	Mass (kg)
Ribbon Support Structure	2.7×10^4 kg
Ring and Frame	9.6×10^4 kg
Ribbon Support Truss	2.3×10^4 kg
Ribbon Mass	1.9×10^5 kg
Counterweight	2.0×10^5 kg
Sub Total	5.4×10^5 kg
x 2	1.1×10^6 kg
2nd Stage Launch Vehicle	1.0×10^5 kg
Cable Support Columns	5.1×10^4 kg
Mass Total	1.2×10^6 kg
Load = Mass x 9.81	1.2×10^7 N

Table V. Load on Upper Table

2.e.1 Turntable

As shown in figure 6 above, to accommodate the ribbon support structure, the ring and frame, the truss, and the cable support columns, the upper table has an inner diameter of 30 m and an outer diameter of 33 m. Assuming a uniform load distribution with bearings centered on the table at a radius of 15.75 m, the load per unit length, w, is approximately 1.2×10^5 N/m. The table is modeled as a simple support with uniform load distribution with 40 bearings spaced 2.5 m apart. Using equations 2 and 3 above with a safety factor of 6, the table dimensions are outer radius 16.5 m, inner radius 15.0

m, thickness 0.2 m. This gives the upper rotating table a mass of 50,470 kg. The gear assembly supports the lower table at 20 locations. Therefore, it has the same inner and outer radius but a thickness of 0.53 m giving it a mass of 133,745 kg.

2.e.2 Gears

The upper rotating table is held into position by the gear assembly. The gear assembly is shown in figure 7 below. There are 20 identical gear sets that make up the gear assembly. The gear assembly is driven by a power divider ring that is in turn driven by four 6,700 hp high temperature superconducting motors (American Superconductor, 2010). Each motor has a mass of 25 metric tons.

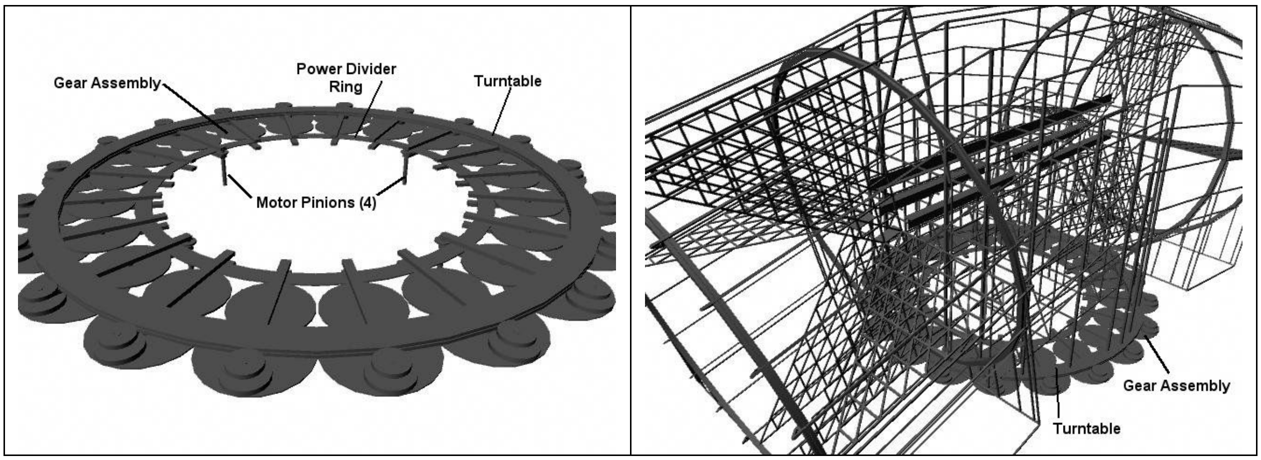

Figure 7. Turntable and Gear Assembly

The HTS motors produce their maximum torque at 230 rpm. The power divider ring is required to shift from the shaft speed produced by the HTS motor down to the rotation rate of the turntable (approximately 0.1 rpm). If not for the power divider ring, the face width of the gears would be to wide resulting in massive gears. The power transferred from the HTS motors to the power divider ring is approximately 26,800 hp. The power transferred from the ring to each 1st stage gear is approximately 1,340 hp. The mass of the gears is determined using the procedures outline in the referenced material (Shigley, L. and Mitchell, L., 1983, p. 606).

The diameters for the gears are determined using standard procedure when determining gear sizes from one rotation rate to another. In addition, the gears have to fit within the available space. Starting with the turntable and working back, the HTS motor pinion is determined to be 0.9 m in diameter. The load transferred to the power divider ring is approximately 4.8×10^5 N resulting in a face width of 10.0 cm. The HTS motor pinion withstands the heaviest load transfer of all the gears. Therefore, a torsional analysis was performed on the HTS motor pinion and found to be well within the parameters of the M5® material. Therefore, the mass of the HTS motor pinion is approximately 101.1 kg. Together, the HTS motor and pinion have a mass of 25,101 kg. There are four HTS motors and pinions resulting in a combined mass of 100,404 kg.

To match up with the HTS motor pinion, the power divider ring also has a face width of 10 cm. The ring has an inner diameter of 21.0 m and an outer diameter of 23.0 m. This gives the power divider ring a mass of 11,750 kg.

The outer diameter surface of the power divider ring is matched to the 1st stage gear. Therefore, the 1st stage gear has a face width of 10 cm. The 1st stage gear has a diameter of 4.0 m and a mass of 2,136 kg. The 1st stage pinion is mounted to the first stage gear and has a face width of 5.0 cm and a diameter of 0.5 m. This gives the 1st stage pinion a mass of 17 kg. Together, the 1st stage gear and pinion have a mass of 2,153 kg.

The 1st stage pinion is matched to the 2nd stage gear. Therefore, its face width is also 5.0 cm. The diameter of the 2nd stage gear is 5.0 m giving it a mass of 1,669 kg. The face width of the 2nd stage pinion is also 5.0 cm but its diameter is 1.0 m giving it a mass of 67 kg. Together, the 2nd stage gear and pinion have a mass of 1,736 kg.

A transfer gear is required to transfer the power from under the lower support table to the upper rotating table. The transfer gear has a lower gear connected to an upper gear via a drive shaft. The diameter of the lower gear is 2.0 m with a face width of 5.0 cm and the diameter of the upper gear is 1.5 m with a face width of 20.0 cm. The 20.0 cm face width is required to match the face width of the upper table. The masses of the gears are 267 kg and 601 kg respectively for a total of 868 kg.

The gears are held into place with upper and lower gear supports. The lower gear support is modeled as a cantilever with an end load. The maximum deflection is given by (Shigley, L. and Mitchell, L., 1983, p.804),

$$y_{\max} = \frac{-Fl^3}{3EI} \qquad (5)$$

where F is the end force equal to 1.2 x 10^4 N, l is the distance from the support to the load equal to 5.0 m, E is the modulus of elasticity for M5® equal to 1.1 x 10^{11} N/m^2 (safety factor of 3), and I is the area moment of inertia for a rectangular beam. For a maximum deflection of 1.0 mm, the dimensions of the lower gear support are 0.5 m wide and 0.2 m thick. This gives the mass of the lower gear support as 1,421 kg. Using the same dimensions for the upper gear support gives the total mass for the two supports as 2,842 kg. The mass of the gear set is 7,599 kg. The total mass of the turntable, the 20 gear sets, the power divider ring, and the HTS pinion is 4.4 x 10^5 kg and is summarized in table VI below.

2.f. Turntable and Gear Assembly Support

The turntable and gears are supported by 20 braces attached to a load bearing ring. The ring serves as the interface between the rotating structure and the stationary towers (figure 8). Each brace supports a load of 8.1 x 10^5 N. The braces provide the structure for the research station.

Subsystem	Mass (kg)
Upper Rotating Table	5.1 x 10^4 kg
Lower Support Table	1.3 x 10^5 kg
HTS Motors & Pinions	1.0 x 10^5 kg
Power Divider Ring	1.2 x 10^4 kg
20 Gear Sets	1.5 x 10^5 kg
Total	4.4 x 10^5 kg

Table VI. Turntable and Gears

The brace consist of a 6 m horizontal beam, a 6 m vertical column, and an 8.5 m strut. The strut must support a load of 1.1 x 10^6 N. Modeled as an Euler column (equation 4) with the critical load of 6.6 x 10^6 N gives the area moment of inertia, I, as 1.5 x 10^{-4} m^4 and an area of 4.2 x 10^{-2} m^2 for a 20.0 cm square strut. Adding the mass of one beam, one column, and one strut gives the mass of one brace as 1,461 kg. The mass of 20 braces is 2.9 x 10^4 kg.

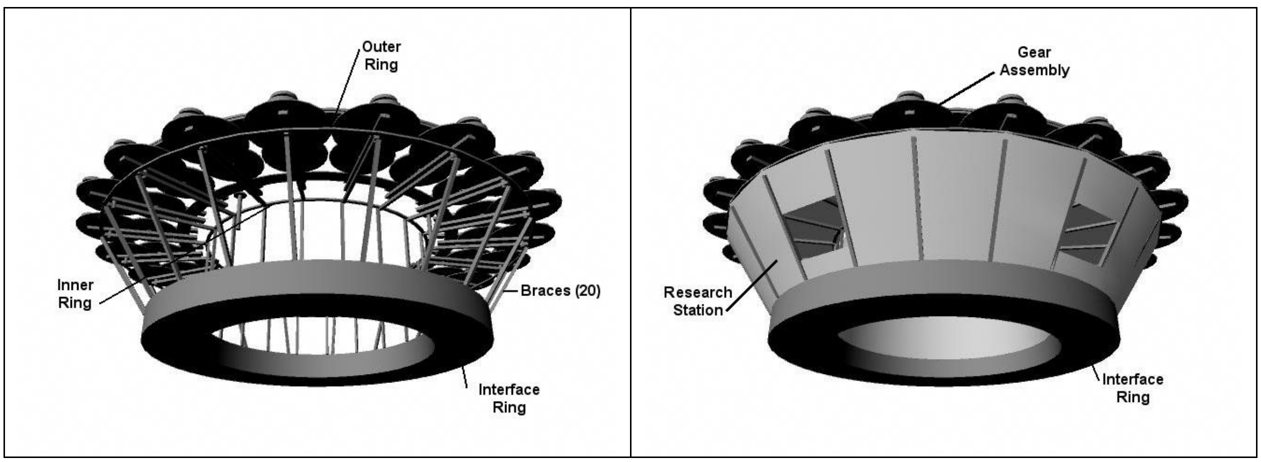

Figure 8. Turntable and Gear Assembly Support

There is an outer ring and an inner ring at the base of the gears to handle the lateral stresses. Both rings are of the same area dimension as the strut. The outer ring in 15.75 m in radius and has a mass of 7.1 x 10^3 kg. The inner ring has a radius of 9.75 m and a mass of 4.4 x 10^3 kg.

The research station is modeled as an inverted truncated cone with a base radius of 15.75 m, a height of 6 m, and a top radius of 9.75 m. The station is hollow through the center to allow passage of the 2nd stage elevator. With a wall thickness of 5 cm, the station has a mass of approximately 1.3 x 10^5 kg. The total mass of the turntable support and gear assembly is 1.7 x 10^5 kg and is summarized in table VII below.

Subsystem	Mass (kg)
20 Braces	2.9×10^4 kg
Outer Ring	7.1×10^3 kg
Inner Ring	4.4×10^3 kg
Research Station	1.3×10^5 kg
Total	1.7×10^5 kg

Table VII. Turntable and Gear Assembly Support

2.g. Elevators

There are five elevators, one main elevator that services the second stage launch vehicle and four passenger elevators. The main elevator (figure 9) carries the second stage launch vehicle to its launch position at the center of the rotating truss. It also serves as a heavy cargo elevator for the research station. The passenger elevators (figure 10) carry the flight crew and passengers to the research station to transfer to the 2nd stage launch vehicle. The passenger elevators also deliver light cargo and supplies to the research station. All five elevators hang from the top of the tower. Therefore, the elevators add significantly to the load of the tower.

2.g.1. Main Elevator

The overcarriage and second stage launch vehicle, when fueled, has a mass of 100 ton. The elevator consist of the second stage support structure which rest on a rotating table and is lifted into position by two scissor jacks. The jacks rest on a support base which in turn rest on three trusses. The trusses are attached to six carbon nanotube ribbons. Each ribbon has a 15 ton counterweight to counter balance the elevator with load and is driven by a ground based electric motor.

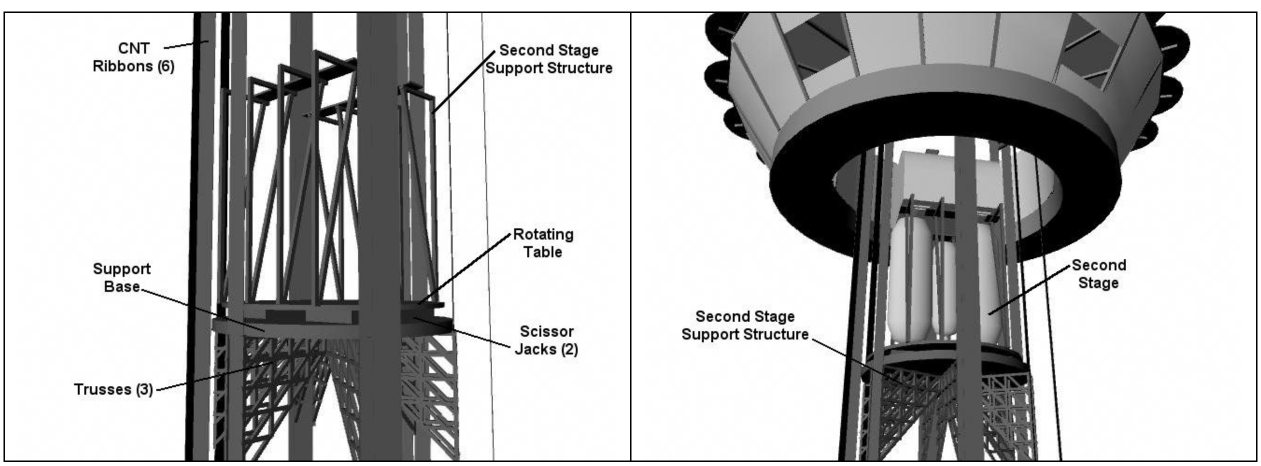

Figure 9. Main Elevator

The support structure consists of two 10 m tracks, one meter wide and 10 cm thick. The one meter wide tracks are attached to eight braces. Each brace consist of a 5.0 m beam, a 15.5 m strut, and a 15 m column. The mass of the eight braces and two tracks is approximately 5.1×10^3 kg.

The second stage support structure rest on a rotating table and is lifted into position by two scissor jacks. Scissor jacks with lifting capacities of 54 metric ton are commercially available (ECOA Industrial Products, Inc., 2004). Each jack has a shipping mass of approximately 9,435 kg making the total mass about 18,870 kg for the two jacks. Advances in design will most likely reduce this mass significantly, but for an initial mass estimate, 18,870 kg will suffice. The rotating table adds another 13,400 kg making the total mass 32,270 kg for the rotating table and scissor jack assembly.

The scissor jacks rest on a platform base. The platform is modeled as a cantilever with uniform load of 5.0×10^3 N/m. This gives the platform a thickness of approximately 5 cm. With a surface area of 64 m^2, the platform base has a mass of approximately 5.4×10^3 kg.

The platform base is supported by three trusses. Each of the three trusses supports an estimated load of 4.7×10^5 N. The truss is 10 m long and therefore, supports a uniform load of 4.7×10^4 N/m. Modeled as a simple support with uniform load with one meter separation between column supports, gives a 10 m long top beam an area of 8.5×10^{-3} m^2. Using the same area for all the support columns, beams, and struts gives the total mass of one truss as 4.6×10^3 kg. There are three trusses for a total mass of 1.4×10^4 kg.

The 2nd stage elevator is supported by six CNT ribbons. The total load for the six ribbons is approximately 2.4×10^6 N. This includes six 15 ton counterweights which are used to counter balance the 2nd stage launch vehicle. Therefore, each ribbon supports a load of 4.0×10^5 N. Maximum tension occurs with the elevator and 2nd stage launch vehicle at the bottom and the counterweights at the top. Using a CNT ribbon with a tensile strength of 25 GPa (safety factor of 6) gives a cross sectional area of 1.8×10^{-5} m^2 for the CNT ribbon. Each ribbon is approximately 300 km long (for a complete loop) and there are six ribbons for a total mass of 4.2×10^4 kg.

The 2nd stage elevator with counterweights is supported from the top of the tower. The total mass supported is approximately 1.9×10^5 kg and is summarized in table VIII below. This represents an additional load of 1.9×10^6 N at the top of the tower.

Subsystem	Mass (kg)
8 Braces & 2 Tracks	5.1×10^3 kg
Rotating Table & Jacks	3.2×10^4 kg
Platform Base	5.4×10^3 kg
Bridge Trusses	1.4×10^4 kg
Six CNT Ribbons	4.2×10^4 kg
Six Counterweights	9.0×10^4 kg
Total	1.9×10^5 kg

Table VIII. Main Elevator

2.g.2 Passenger Elevator

The primary purpose of the passenger elevator (figure 10) is to carry passengers and crew to the 2nd stage launch vehicle. The elevator also takes light cargo and researchers to the research station. The elevator serves as an escape vehicle in the event of a catastrophic failure of the tower. Therefore, it will be designed to separate from the elevator ribbon or station, thrust away from the tower, reenter the atmosphere, and land in a designed recovery area. In essence, the passenger elevator is a small reentry vehicle.

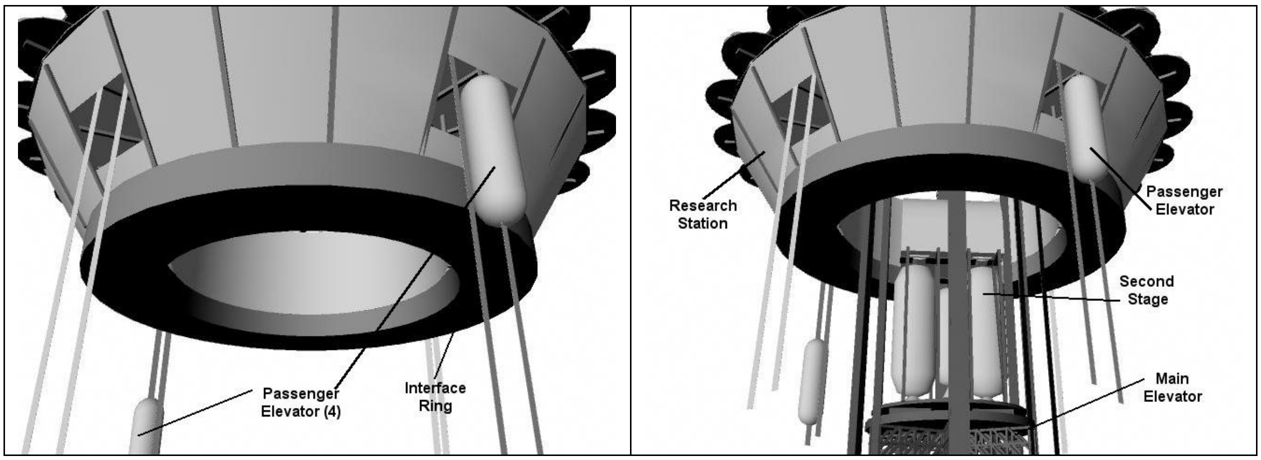

Figure 10. Passenger Elevator

The elevator can carry a maximum of 12 people. The mass estimating database compiled by Georgia Institute of Technology (Rohrschneider, R.R., 2002) is used to estimate the mass of the elevator. The database uses the English system of units to determine the weight of each component. Adding the weight of each component gives a total reentry weight for the elevator. The weight is then converted to the metric system for a total mass.

Several of the components are interrelated and depend on the reentry weight of the vehicle to estimate the component weight. In this case, an “educated guess” is made on the reentry weight and several iterations are done to approximate the total weight. The mass relationships are based on 1970s technology. To account for improvements in component technology, George Tech assigns a technology reduction factor (TRF). Table IX below summarizes the results of the third iteration for the total estimated weight of the passenger elevator. This results in an estimate weight of 11,688 lb or a mass of 5,302 kg.

A counterweight of similar mass is used to counterbalance the passenger elevator. The entire assembly is connected to a CNT ribbon and raised and lowered from the research station by ground based electric motors. The mass of the ribbon is approximately 1,756 kg making the total mass of one passenger elevator an estimated 12,360 kg. With the main elevator and four passenger elevators, the total mass hanging from the research station is approximately 2.4×10^5 kg.

Component	Reference	Initial Weight (lb)	TRF (%)	Final Weight (lb)
Fuselage	6	1,165.3	0	1,165.3
Crew Cabin	6	1,252.0	0	1,252.0
Thermal Protection	1	2,120.6	35	1,378.4
Reaction Control	3	159.3	0	159.3
Prime Power	6	352.0	0	352.0
Electrical Control & Distribution	3	705.5	18	578.5
Hydraulics	3	13.3	0	13.3
Surface Control	1	35.9	0	35.9
Avionics	1	2,281.8	50	1,140.9
Environmental Control & Life Sup	3	2,971.1	0	2,971.1
Personnel Equip	3	2,523.0	0	2,523.0
Propellants	1, 2, & 10	118.3	0	118.3
Total		13,698.1	14.67	11,688.0

Table IX. Estimated Weight of the Passenger Elevator

2.h. Interface Ring and Guy Wires

The rotating truss and the research station are connected to the inflatable towers by an interface ring. The interface ring has six inflatable tower supports but will be modeled with five supports. This allows for an increased safety factor and maintenance or replacement of a single tower. The interface ring is connected to six guy wires to support the tower and restrict its precession due to rotation of the tower truss, ribbons, and counterweights.

2.h.1. Guy Wires

The tower will want to precess due to an unbalanced lateral load at the top. This lateral load is caused by the difference in force due to the rotation of the Earth and its effect on the center of mass of the ribbons and counterweights. The maximum force occurs at the equator when the center of mass is in the same/opposite direction as the tangential velocity of a point on the Earth. For example, when looking down on the tower and the tower is rotating in a counterclockwise direction, the tangential velocity of the center of mass on the southern side is approximately +463 m/s and the tangential velocity of the center of mass on the northern side is approximately -463 m/s. This results in a maximum force of 8.8×10^6 N in the southern direction. The precession due to the force is held in check by a CNT guy wire. For a 150 km high tower with a guy wire at 45^o, the mass of the guy wire is approximately 1.4×10^5 kg and for six guy wires the total mass is approximately 8.2×10^5 kg. Unfortunately, due to the elasticity of the CNT cable, the tower will sway a maximum distance of approximately 10 km southward with a period of about 4.4 minutes. Strong stomachs are advised.

2.h.2 Interface Ring

Adding the mass of the guy wires gives the total load on the ring at approximately 2.9×10^7 N. The interface ring has a radius of approximately 9.75 m and is modeled as a simple support with uniform load (equation 3). The separation between supports is approximately 20.5 m. Assuming a uniform load distribution, each tower supports a load of 5.7×10^6 N. The supports are 20.5 m apart and therefore, represent a uniform load of 5.5×10^5 N/m. This gives an area moment of inertia of 22.8 m^4. With a square beam, the width is approximately 4.0 m. Using the M5® material, gives a mass of approximately 2.0×10^5 kg. The total load on the six towers is approximately 3.1×10^7 N and is summarized in table X below.

Subsystem	Mass (kg)
Counterweight	2.0×10^5 kg
Ribbon	1.9×10^5 kg
Ribbon Support Structure	2.7×10^4 kg
Ribbon Support Ring & Frame	9.6×10^4 kg
Ribbon Support Truss	2.3×10^4 kg
SubTotal	5.4×10^5 kg
X2	1.1×10^6 kg
Cable Support Columns	5.1×10^4 kg
Turntable & Gears	4.4×10^5 kg
Turntable & Gear Assembly Support	1.7×10^5 kg
Main & Passenger Elevators	2.4×10^5 kg
2nd Stage Launch Vehicle	1.0×10^5 kg
Guy Wires	8.2×10^5 kg
Interface Ring	2.0×10^5 kg
Total Mass	3.1×10^6 kg
Total Load	3.1×10^7 N

Table X. Tower Load

3. Support Tower

As mentioned in section 2 above, the total load on the six towers is approximately 3.1×10^7 N. Each tower will support 6.1×10^6 N or one fifth the load. This is to ensure maintainability and replacement, if necessary, of a single tower. Of course, during replacement of a tower, all personnel will be evacuated from the research station and all launch operations will cease until the tower is replaced, inspected, and cleared for operations.

The interface ring is 4.0 m wide. Therefore, the tower will have a radius of 2.0 m allowing it to mate directly to the interface ring. This gives the tower an area of 12.6 m^2 resulting in a load per square meter of 4.8×10^5 N/m^2. The research station, interface ring and six support towers are shown in figure 11 below.

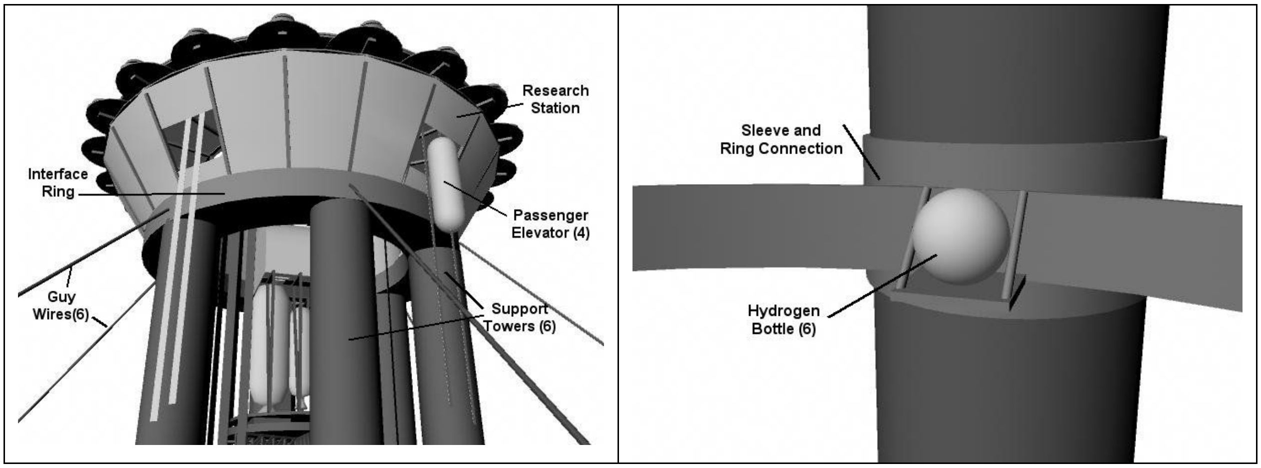

Figure 11. Support Towers

Several authors have theorized on the possibility of tall support towers (Smitherman Jr., D.V., 2000; Seth, R.K., Quine, B.M., and Zhu, Z.H., 2009; Bolonkin, A.A., 2006), both towers in compression and towers in tension. Although towers in compression could possibly be built to support loads on the order of 10^7 N, it is believed that towers in tension will offer the greatest cost and time of construction advantages. To allow the clearance for the personnel and launch vehicle elevators, the outer radius of each tower will be kept constant. As more towers are added the load and thus the internal pressure increases. Therefore, the thickness of the material must increase if the radius is to remain constant.

A carbon nanotube material with a safety factor of six is chosen for the fabric of the tower. Again, this is a second generation Space Track Launch System. It is assumed that the CNT material will have properties similar to that projected for the CNT fiber, i.e. a working tensile strength of 25 GPa (SF = 6) with a density of 1300 kg/m^3. The initial design of the tower is in 10 km increments. The U.S. Standard Atmosphere (NASA, 2000) is used for the atmospheric properties and the properties are averaged over the 10 km increment. The average value for the atmospheric properties used in the analysis is shown in table XI below. Each tower is identical in design; therefore, the analysis begins with the load per unit area on one tower.

The analysis for the support tower relies heavily on the work presented in “Feasibility of 20 km Free-Standing Inflatable Space Tower” by R.K.Seth, B.M. Quine, and Z.H. Zhu (Seth, R.K., Quine, B.M., and Zhu, Z.H., 2009). The resulting equations are reproduced below. These equations are based on the material properties and the properties of the internal gas at a predetermine R/t ratio and result in a maximum payload capacity (MPC).

$$W'_{MPC} = \left[\frac{\sigma}{R/t}\right] - \left[\left(\frac{2H\rho g}{R/t}\right) + H\rho'_g g\right] \quad \text{(ref., eq. 12, p.346)}$$

$$\rho_g^{'} = \frac{\mu\sigma}{R_g T\left(R/t\right)}$$ (ref., eq. 9, p.346)

The quantity $\sigma/R/t$ is the maximum internal pressure allowed by the material, σ is the working tensile strength of the material equal to 25 GPa, H is the length of the inflatable section equal to 10 km, ρ is the mass density of the material equal to 1300 kg/m^3, g is the acceleration due to gravity equal to 9.81 m/s^2, $\rho_g^{'}$ is the density of the gas used for the internal pressure, μ is the molecular mass (2.0 x 10^{-3} kg/mol for hydrogen, 4.0 x 10^{-3} kg/mol for helium), R_g is the gas constant equal to 8.314 J/K/mol, and T is the average temperature over the 10 km section of tower (table XI).

Altitude (km)	Temp (K)	Press (Pa)	Den (kg/m^3)
150 ≤ H ≤ 140	597	5.88 x 10^{-4}	2.96 x 10^{-9}
140 ≤ H ≤ 130	514	9.88 x 10^{-4}	6.02 x 10^{-9}
130 ≤ H ≤ 120	414	1.91 x 10^{-3}	1.53 x 10^{-8}
120 ≤ H ≤ 110	302	4.87 x 10^{-3}	5.96 x 10^{-8}
110 ≤ H ≤ 100	220	1.97 x 10^{-2}	3.29 x 10^{-7}
100 ≤ H ≤ 90	192	1.08 x 10^{-1}	1.99 x 10^{-6}
90 ≤ H ≤ 80	193	6.18 x 10^{-1}	1.09 x 10^{-5}
80 ≤ H ≤ 70	210	3.14 x 10^{0}	5.06 x 10^{-5}
70 ≤ H ≤ 60	234	1.36 x 10^{1}	1.96 x 10^{-4}
60 ≤ H ≤ 50	259	5.09 x 10^{1}	6.68 x 10^{-4}
50 ≤ H ≤ 40	261	1.83 x 10^{2}	2.51 x 10^{-3}
40 ≤ H ≤ 30	239	7.42 x 10^{2}	1.12 x 10^{-2}
30 ≤ H ≤ 20	222	3.36 x 10^{3}	5.37 x 10^{-2}
20 ≤ H ≤ 15	217	8.88 x 10^{3}	1.42 x 10^{-1}
15 ≤ H ≤ 10	220	1.93 x 10^{4}	3.04 x 10^{-1}
10 ≤ H ≤ 5	240	4.03 x 10^{4}	5.75 x 10^{-1}
5 ≤ H ≤ 0	272	7.77 x 10^{4}	9.81 x 10^{-1}

Table XI. Average Atmospheric Properties

For example, for the first section of tower between 140 km and 150 km using hydrogen gas and with an R/t ratio equal to 5.0 x 10^4, gives the maximum payload capacity equal to 4.8 x 10^5 N/m^2 which is equal to the required 4.8 x 10^5 N/m^2.

The first section of tower is connected to the second section of tower via a sleeve and ring arrangement (figure 11). The ring connects all six towers together resulting in a more stable configuration. Guy wires are attached at the intersection and a hydrogen gas bottle is mounted on the ring to replace hydrogen gas that dissipates from the support tower. Dissipation of hydrogen gas is estimated to be about 100 moles per day (Choi, S. and Sankar, B.V., 2008). The hydrogen bottle is sized to provide approximately a 170 day supply of hydrogen gas. The mass of the tower, the gas, the guy wires, the sleeve, ring, and hydrogen bottle are determined and added to the tower load for the next section of tower.

The buoyant force of air becomes significant at around 30 km and begins to have an impact on the tower load. The buoyant force is taken into consideration at altitudes below 30 km. By Archimedes's Principle, the buoyant force is the weight of the air displaced by the volume of the support tower and the average atmospheric density between the incremental altitudes (table XI).

At an altitude of 20 km, the incremental height is reduced to 5 km. This provides more guy wire support for wind loading. Helium gas is used as the working fluid to prevent the possibility of a hydrogen gas explosion. An excel spreadsheet was developed to handle the necessary calculations allowing the *R/t* factor to be adjusted to reach the desired results. The results are summarized in table XII below.

Altitude (km)	Load (N)	R/t factor	MPC (N/m^2)	Added Load (N)
150 ≤ H ≤ 140	6.00E+06	5.0×10^4	4.8×10^5	1.70E+06
140 ≤ H ≤ 130	7.70E+06	4.2×10^4	5.6×10^5	1.80E+06
130 ≤ H ≤ 120	9.50E+06	3.3×10^4	7.1×10^5	1.73E+06
120 ≤ H ≤ 110	1.12E+07	2.6×10^4	8.8×10^5	2.16E+06
110 ≤ H ≤ 100	1.34E+07	2.2×10^4	1.0×10^6	2.77E+06
100 ≤ H ≤ 90	1.61E+07	1.7×10^4	1.3×10^6	3.37E+06
90 ≤ H ≤ 80	1.95E+07	1.4×10^4	1.6×10^6	3.88E+06
80 ≤ H ≤ 70	2.34E+07	1.2×10^4	1.8×10^6	4.12E+06
70 ≤ H ≤ 60	2.75E+07	1.0×10^4	2.2×10^6	4.13E+06
60 ≤ H ≤ 50	3.16E+07	9.1×10^3	2.5×10^6	4.13E+06
50 ≤ H ≤ 40	3.58E+07	8.0×10^3	2.8×10^6	4.59E+06
40 ≤ H ≤ 30	4.04E+07	7.0×10^3	3.2×10^6	5.24E+06
30 ≤ H ≤ 20	4.56E+07	6.1×10^3	3.6×10^6	6.30E+06
20 ≤ H ≤ 15	5.19E+07	5.4×10^3	4.1×10^6	6.90E+06
15 ≤ H ≤ 10	5.88E+07	4.8×10^3	4.6×10^6	7.19E+06
10 ≤ H ≤ 5	6.60E+07	4.3×10^3	5.2×10^6	7.22E+06
5 ≤ H ≤ 0	7.32E+07	3.9×10^3	5.8×10^6	6.81E+06
Base Load	8.00E+07			

Table XII. Support Tower Load (per Tower)

A base load of 8.0×10^7 N over an area of 12.6 m^2 results in a load per unit area of 6.4×10^6 N/m^2 or about 921 psi. Concrete for this loading is readily available and relatively inexpensive. The span between the support columns is about 16.4 m allowing plenty of clearance for passage of the second stage launch vehicle onto the main elevator. There are six entry ways onto the main elevator (figure 12). Therefore, aerospace companies wishing to launch from the Space Track Launch System can have access from one of six different tracks that lead onto the elevator.

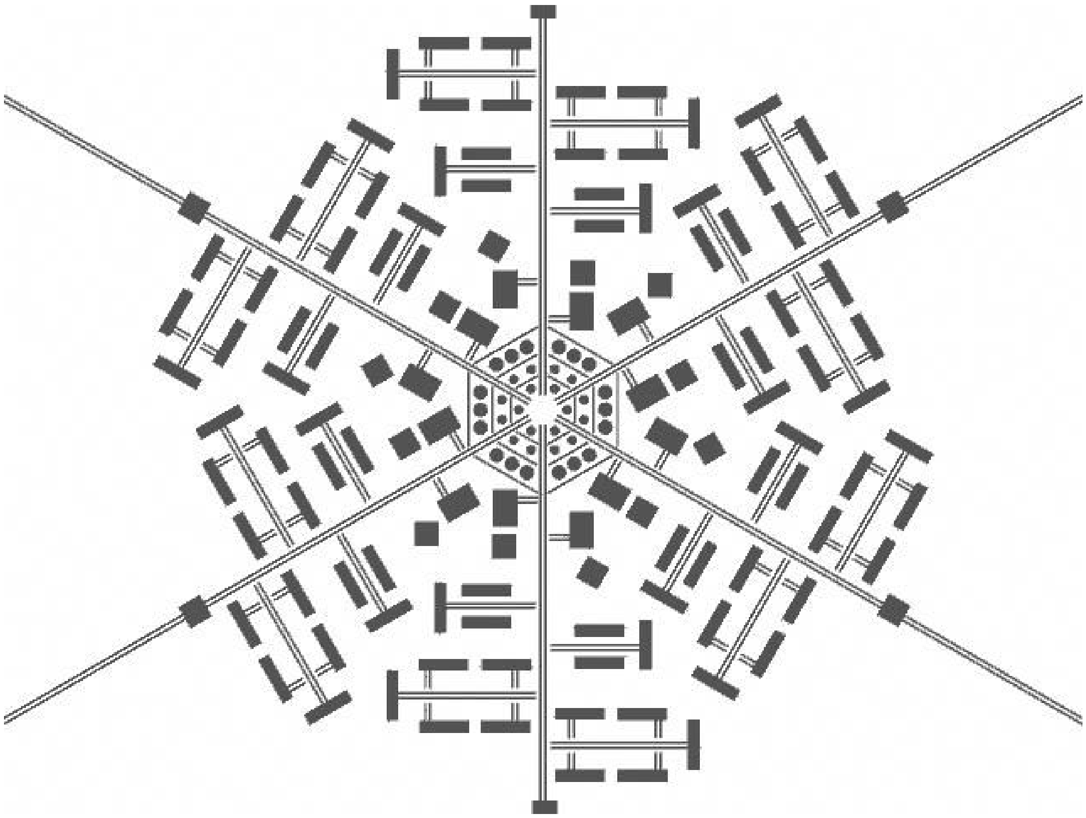

Figure 12. Base Station

4. Conclusion

This paper presents an initial design and mass estimate for the first stage of the second generation Space Track Launch System. The first stage is all electric and can be used four to five times per week. The electric motors restore rotational kinetic energy to the ribbons in approximately 24 hours. Each tower supports an initial load of 6.0×10^6 N. The tower material, fill gas, guy wires, and connecting sleeves result in a base load of 8.0×10^7 N per tower. There are six towers supporting the research station and rotating truss. The support towers are wide enough apart to allow access to the main elevator.

Aerospace companies can line up along the track for easy access to the launch system from six different access ports. With two sets of ribbons, two second stage launch vehicles can be launched for each recharge cycle resulting in eight to ten launches or approximately 24,000 to 30,000 kg of mass into low earth orbit per week. The overcarriage can accommodate a wide variety of launch vehicles making the Space Track Launch System an economical and universal launch system.

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