Fisher Space Systems, LLC

Space Track Launch System
Counterweight

by
Jerry F. Fisher

1. Introduction

The counterweight is a vital part of the Space Track Launch System (STLS). First, it provides stability and shifts the center of mass further down the ribbon. Second, the counterweight absorbs the shock produced by launch. Third, the counterweight returns to the tower at the end of its operational lifetime rolling up the ribbon as it returns.

The 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 below) is from 100-150 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. A counterweight (CW) is attached to the end of each ribbon.

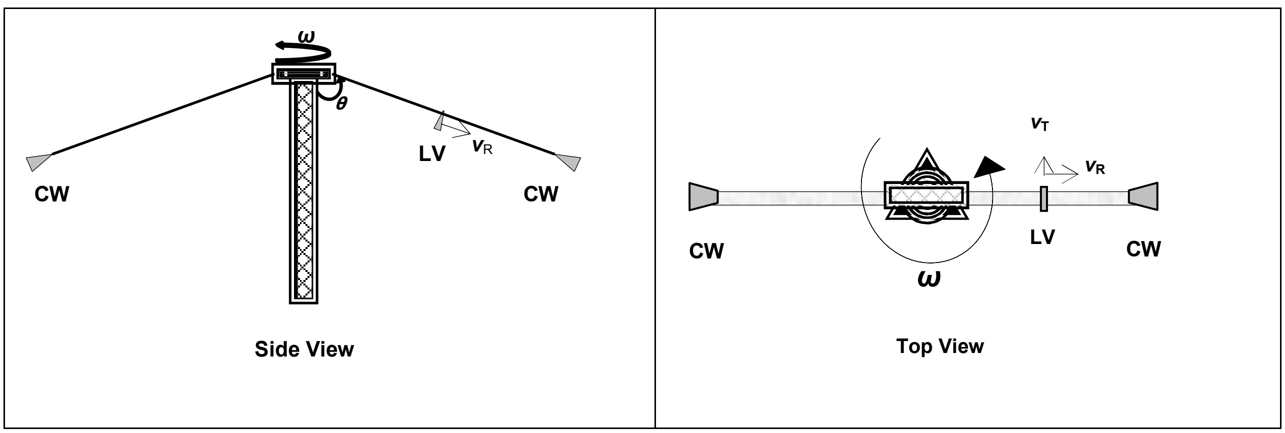

Figure 1. Space Track Launch System

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 two to three times per day. The electric motors restore rotational kinetic energy to the ribbons in approximately six hours. Second, there are two sets of ribbons which allow

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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 and mass estimate for the counterweight.

2. Counterweight

A 400 km long carbon nanotube ribbon with a 200 ton counterweight rotating at an angular velocity of 1.3×10^{-2} rad/sec at an angle of 77^{o} requires a ribbon mass of 458 ton (Fisher, J. F., 2007). A 200 ton counterweight would be impossible to deploy as a single unit. Therefore, the counterweight is divided into 80 counterweight units at an estimated mass of 2.5 ton each. As such, the ribbon mass is divided by 80, giving 5,724 kg per unit. The counterweight unit is shown in figure 2 below.

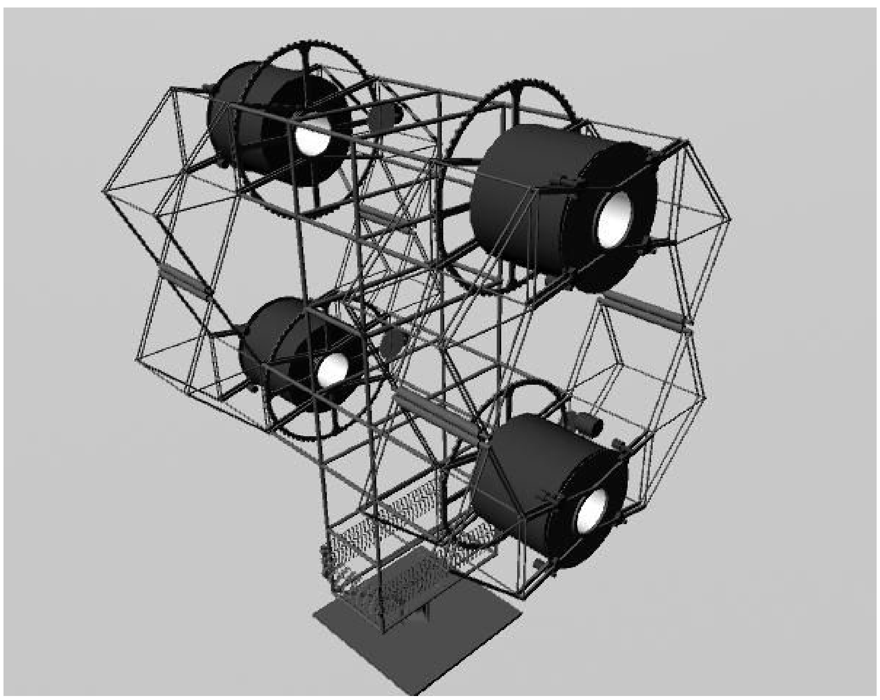

Figure 2. Counterweight Unit

Each counterweight unit has four ribbon spools connected by a vertical truss and, therefore, can be divided into four identical subunits for mass analysis. As shown in figure 3 below, each subunit consists of a ribbon spool, ribbon, spool gear, motor and motor gear, disc brake, and frame. First, the mass of the subunit will be determined and multiplied by four. Then the mass of the vertical truss, power dissipation, and prime power will be determined and added to the subunits mass resulting in the total mass of the counterweight unit. The mass analysis begins with the ribbon spool.

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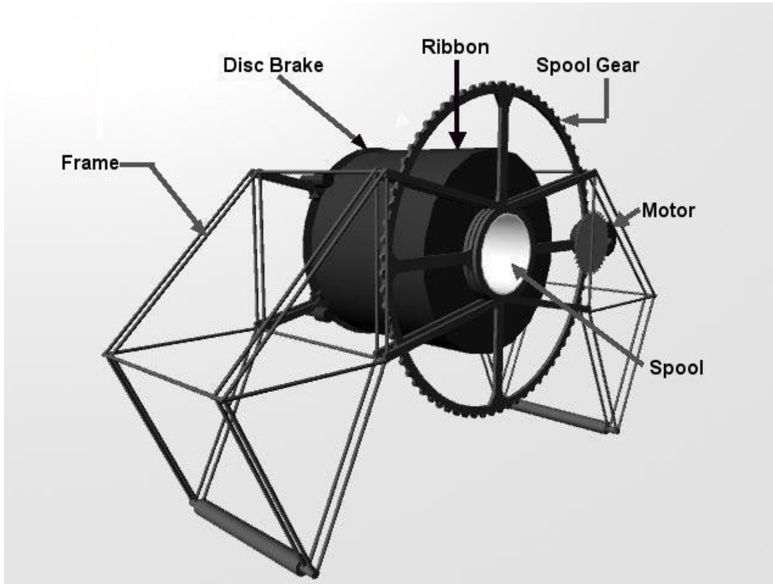

Figure 3. Counterweight Subunit

2.a. Ribbon Spool

The ribbon mass is 5,725 kg per counterweight unit. Each counterweight unit is further divided by four subunits. As such, each ribbon spool carries an estimated 1,431 kg ribbon. The carbon nanotube ribbon has a mass density of 1,300 kg/m^3. Therefore, the ribbon requires an estimated volume of 1.1 m^3.

The spool is made of Al/MWNT metal matrix composite (Choi, H., Shin, J., Min, B., Park, J., and Bae, D., 2009) with an outer diameter of 0.5 m. The outer diameter of the spool becomes the inner diameter of the ribbon. For a 1.0 m wide ribbon, the outer diameter of the ribbon is found by,

$$1.1m^3 = (1.0\,m)\pi\left[(r_o^2) - (0.25\,m)^2\right]$$

Therefore, the outer radius of the ribbon is approximately 0.6 m and the diameter is 1.3 m. After the ribbon is deployed, the load on the counterweight unit is,

$$F = m_{cw}\omega^2 l_r = \left(2.5x10^3\,kg\right)\left(0.013\,{}^{rad}\!/\!_{\sec}\right)\left(4.0x10^5\,m\right) = 1.7x10^5\,N$$

Assuming a uniform load distribution, each spool has a load of ¼ F or 4.2 x 10^4 N. The spool is a hollow cylinder with outer radius of 0.25 m and an inner radius of 0.24 m. The spool should be at least 1.0 cm thick to attach the ribbon support, spool gear, and disc brake. Is this thick enough to withstand the load?

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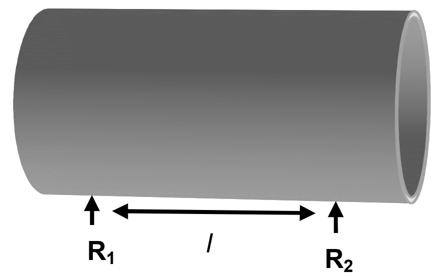

$$R_1 = R_2 = \frac{wl}{2}$$

$$y_{\max} = \frac{-5wl^4}{384EI}$$

$$I = \frac{\pi}{64}\left(d_o^4 - d_i^4\right)$$

Figure 4. Ribbon Spool

As shown in figure 4, the spool is modeled as a simple support with uniform load. R_1 and R_2 mark the location of the spool supports. The maximum deflection is given by (Shigley, L. and Mitchell, L., 1983, p.807),

$$y_{\max} = \frac{5wl^4}{384EI}$$

where w is 4.2 x 10^4 N/m, l is 1.0 m, E is ¼ (1.1 x 10^{11} N/m^2) equal to 2.8 x 10^{10} N/m^2 (safety factor of 4), and I is the moment of inertia. Inserting the variables gives the moment of inertia, I, as 4.6 x 10^{-4} m^4 and the maximum deflection as 4.3 x 10^{-5} m. Therefore, the spool is thick enough to withstand the load.

A shear stress occurs on the spool since the load exerts a force on the spool that is 0.25 m from the axis of rotation. A similar analysis (Shigley, L. and Mitchell, L., 1983, p. 61) will show that the shear stress is much less than the modulus of rigidity for the Al/MWNT composite and, therefore, is not an issue.

The ribbon on the spool is 1.0 m wide. The spool itself will have to be approximately 1.4 m long to accommodate the spool supports, spool gear, and disc brakes. Therefore, the mass of the spool is,

$$Mass = \rho Vol = \left(2650 \, {}^{kg}\!/_{m^3}\right)(1.4m)(\pi)\left[(0.25m)^2 - (0.24m)^2\right] = 57.1kg$$

2.b. Spool Gear & Pinion

As shown in figure 2 above, each counterweight unit has four spools, one for each ribbon. The counterweight unit is an active part of the STLS. It is designed to absorb the shock of launching a second stage vehicle and return to the tower at the end of its operational lifetime. Each spool is driven by a 20 kW motor. Assuming an 80% electrical to mechanical efficiency, approximately 15 kW of power is delivered to the spool gear.

From Mechanical Engineering Design (Shigley, L. and Mitchell, L., 1983, page 607), “When the gear and pinion are made of the same material, the pinion is always the weaker of the two …”. Therefore, the pinion gear face width will be determined first. The

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spool gear design will be based on the face width of the pinion gear. One method for determining the face width of a gear is given in Mechanical Engineering Design and reproduced in Appendix A. From Appendix A, the face width of the pinion gear is approximately 5.0 cm.

Now that the face width of the pinion is known, the mass of the spool pinion can be determined. The mass density for Al/MWNT is 2,650 kg/m^3. Therefore, the mass of the spool pinion is,

$$Mass = \rho Vol = \left(2{,}650\frac{kg}{m^3}\right)(0.05m)(\pi)(0.038m)^2 = 0.6\,kg$$

As shown in figure 5 below, the spool gear is mounted on one end of the spool. The inner diameter of the spool gear is 0.5 m and the outer diameter is 2.0 m. To match up with the spool pinion, the face width of the spool gear is 5.0 cm.

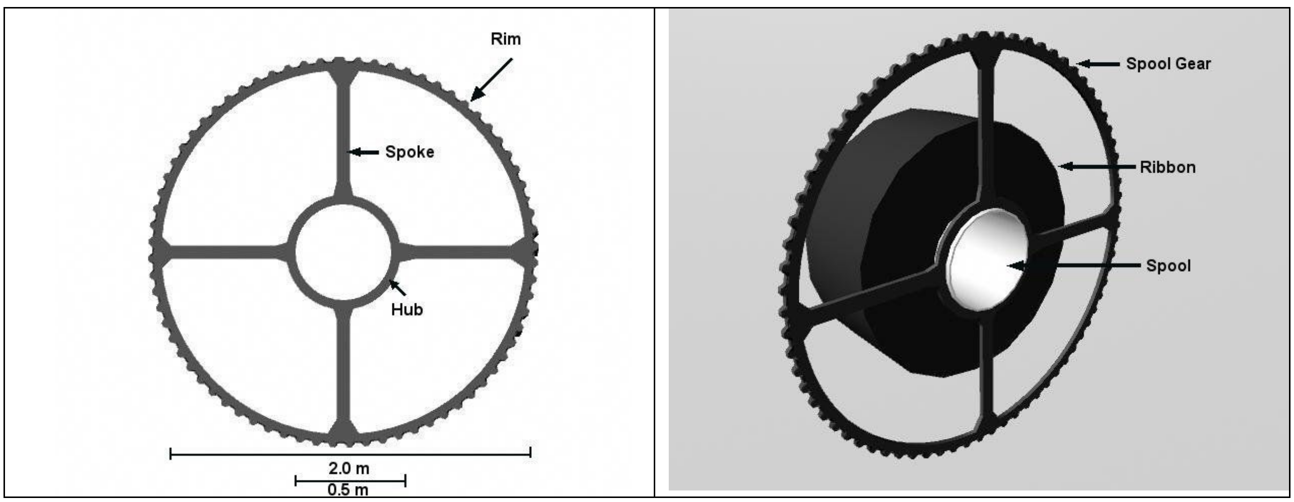

Figure 5. Spool Gear

To reduce the mass, a wagon wheel design was chosen for the spool gear. The mass is determined by first calculating the mass of the teeth, the rim, the spokes, and finally, the hub.

From Mechanical Engineering Design (Shigley, L. and Mitchell, L., 1983, p. 588), the minimum whole depth is given by,

$$h_t = \frac{2.25}{P} = \frac{2.25}{4} = 0.5625\,in = 1.43\,cm \approx 1.5\,cm$$

For an outer radius of 1.0 m and a width of 0.05 m, the mass of the teeth is approximately ½ the density of Al/MWNT times the volume or 6.2 kg.

The teeth are machined from an Al/MWNT rim which is 5.0 cm wide and has an outer radius of 0.985 m and an inner radius of 0.935 m. A shear stress analysis on the rim will show that the stress on the rim is much less than the modulus of rigidity for the Al/MWNT material. Therefore, the mass of the rim is given by,

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$$Mass = \rho Vol = \left(2{,}650\frac{kg}{m^3}\right)(0.05m)(\pi)\left[(0.985m)^2 - (0.935)^2\right] = 40.0\,kg$$

As shown in figure 5, four spokes attach the spool gear rim to its hub. The spoke is rectangular in design and is 0.635 m long and 0.05 m wide. The height of the spoke is determined by following the procedures outlined in Appendix B and is approximately 7.0 cm. Therefore, the mass of the spoke is given by,

$$Mass = \rho Vol = \left(2{,}650\frac{kg}{m^3}\right)(0.635m)(0.07m)(0.05m) = 5.9\,kg$$

There are four spokes for a total mass of 23.5 kg.

The mass of the hub which is 5.0 cm wide, 5.0 cm thick, and has an inner radius of 0.25 m is approximately 11.4 kg. The total mass for the spool gear and pinion are shown in table I below.

Spool Pinion	0.6 kg
Spool Teeth	6.2 kg
Spool Rim	40.0 kg
Spool Spoke	23.5 kg
Spool Hub	11.4 kg
Total	81.7 kg

Table I. Spool Gear Mass

2.c. Motor Gear & Pinion

As shown in figure 6 below, the spool pinion is mounted on the motor gear. Therefore, the motor gear has the same revolutions per minute, n_{mg}, as the spool pinion, n_p, or 356.5 rpm (Appendix A). The 20 kW motor produces a maximum torque at 2,000 rpm (EMS, 2010). Using a 3.0 inch diameter motor pinion, d_{mp}, and setting n_{mp} equal to 2,000 rpm, gives the motor gear diameter, d_{mg}, as,

$$n_{mg} = \frac{d_{mp}}{d_{mg}} n_{mp}$$

$$d_{mg} = \frac{(3.0)(2000)}{356.5} = 16.8\,in. = 42.8\,cm \approx 43\,cm$$

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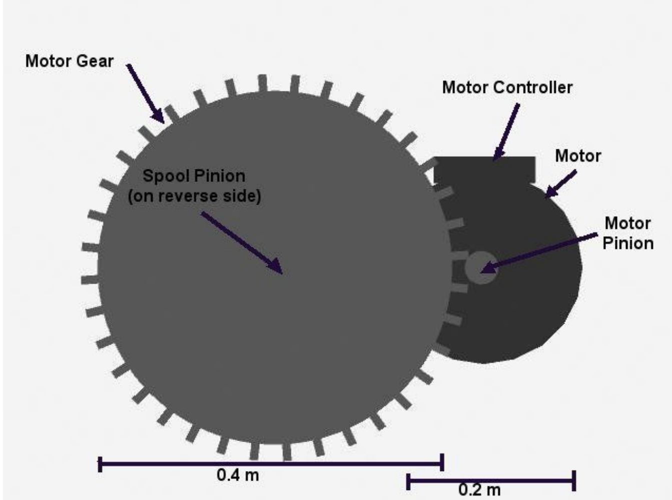

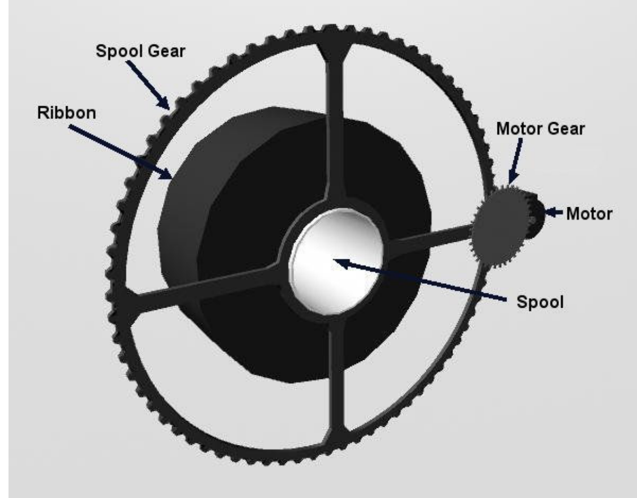

Figure 6. Motor Gear & Pinion

Again, the face width of the motor pinion must be determined first since the motor pinion and motor gear are made from the same material. Using the same procedures outlined in Appendix A for the spool pinion gives the face width of the motor pinion as 1.6 cm. Therefore, the mass of the motor pinion is,

$$M_{mp} = \left(2{,}650\frac{kg}{m^3}\right)(0.016\,m)(\pi)(0.04\,m)^2 = 0.2\,kg$$

and the mass of the motor gear as,

$$M_{mg} = \left(2{,}650\frac{kg}{m^3}\right)(0.016\,m)(\pi)(0.2\,m)^2 = 6.1\,kg$$

The motor weight with controller is 46 lb (300 A, 48 V, 25 hp, 89% eff.) or a mass of 20.9 kg (EMS, 2010). The total mass is shown in table II below.

Motor & Controller	20.9 kg
Motor Gear	6.1 kg
Motor Pinion	0.2 kg
Total	27.2 kg

Table II. Motor, Motor Gear, & Motor Pinion Mass

2.d. Disc Brakes

During ribbon deployment, the motor generators on the counterweight unit are used to maintain a constant spooling rate by adjusting the load resistance. As in motor generators for electric cars, the braking efficiency drops off considerably at low rpm.

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Therefore, electromagnetic (EM) disc brake calipers will be used to finish breaking and for holding the counterweight unit at the desired location. At launch, the counterweights are used to absorb some of the energy from launch. Sensors detect a sudden energy impulse in the ribbon and release the brakes. The motor generators slow the counterweight down and the EM brakes are applied.

The electromagnetic calipers are spring applied and normally closed. Typical EM disc brake calipers (KATEEL, 2010) have a braking force of approximately 1.6 kN and a holding force of approximately 4.0 kN. The holding force required is 4.2×10^4 N per ribbon spool. At a radius of 0.25 m, this force produces a torque of 1.1×10^4 N-m. Therefore, four EM calipers would be required at a radius of 0.7 m to provide a holding force of 4.2×10^4 N. Each EM caliper has a mass of approximately 20 kg giving a total mass of 80 kg for four calipers.

The disc is approximately 1.4 m in diameter with a disc thickness of 1.25 cm. As shown in figure 7 below, the disc is mounted at the opposite end of the spool and, therefore, has an inner radius of 0.25 m. This gives the disc a mass of approximately 39.2 kg.

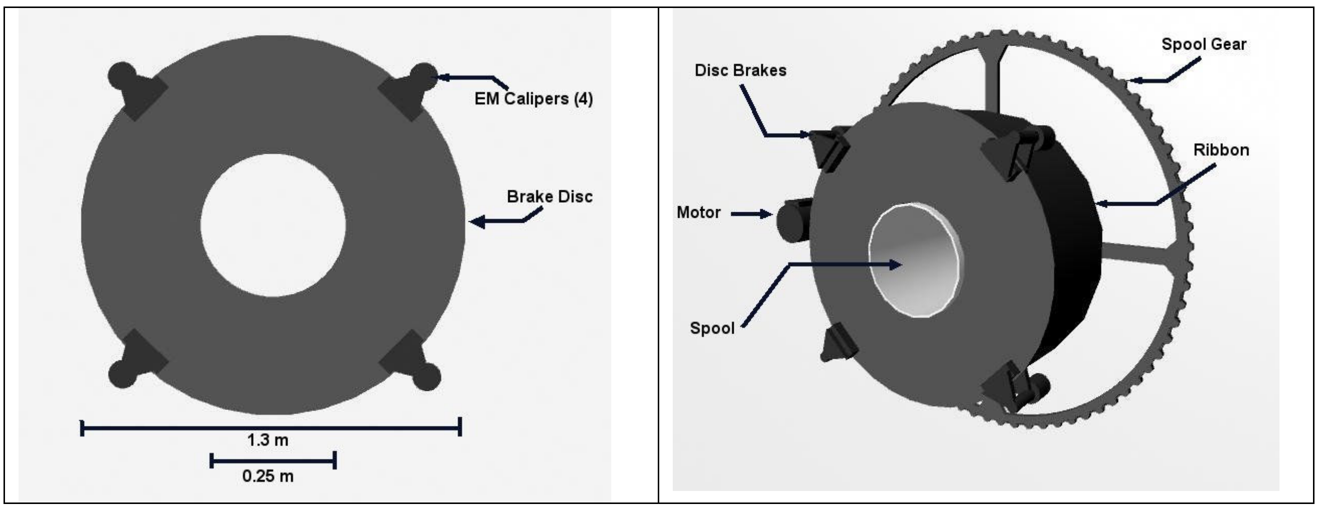

Figure 7. Disc Brakes

The total mass of the disc brakes with EM calipers is shown in table III below.

EM Calipers	80.0 kg
Disc	39.2 kg
Total	119.2 kg

Table III. Disc Brakes

2.e Ribbon Supports

As shown in figure 8 below, the ribbon spool is supported by 16 (8 on each side) cantilevers connected to the frame. Each cantilever is 1.0 m long and is modeled as simple support, moment load.

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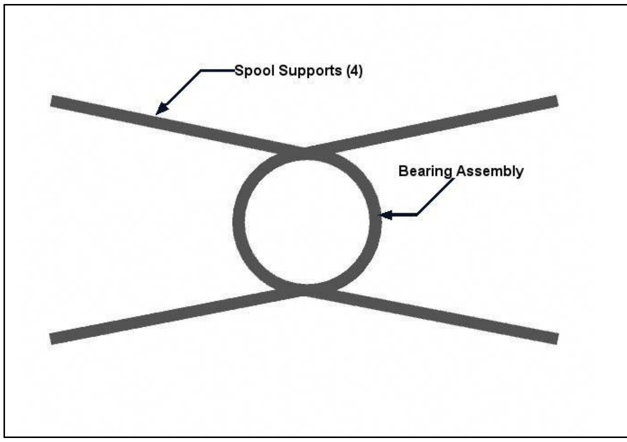

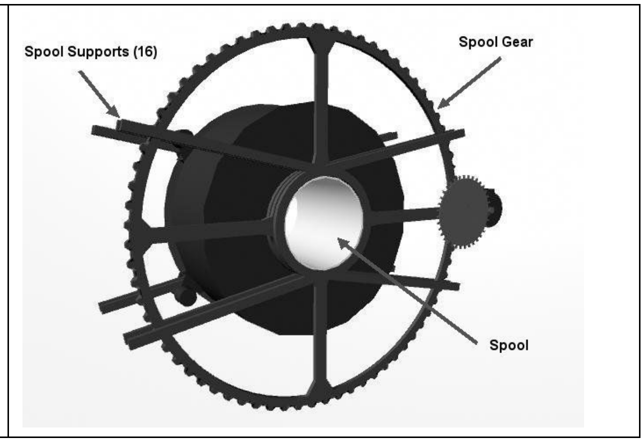

Figure 8. Ribbon Support

Following the procedures as outlined in Appendix B for the spoke gives the area moment of inertia, I, as 3.1 x 10^{-7} m^4 for a maximum deflection of 1.0 mm. From Mechanical Engineering Design (Shigley, L. and Mitchell, L., 1983, p. 813), the area moment of inertia for a rectangle is,

$$I = \frac{bh^3}{12}$$

For a base width, b, of 5.0 cm, the height, h, is 4.2 cm. This gives the mass of a single support beam as approximately 5.6 kg.

Four beams are connected to a bearing assembly which is attached to the spool. The bearing assembly will be modeled as a solid ring with an outer diameter of 60.0 cm, an inner diameter of 50.0 cm, and 5.0 cm wide. The mass of the bearing is approximately 11.5 kg. With four support beams per bearing assembly the mass is 33.9 kg. The total mass of 16 support beams and four bearings is 135.6 kg.

2.f Frame

The ribbon supports are attached to a frame. The frame is attached to two rollers, a forward roller and an aft roller. The rollers rest on top of a previously deployed ribbon. The frame is shown in figure 9 below.

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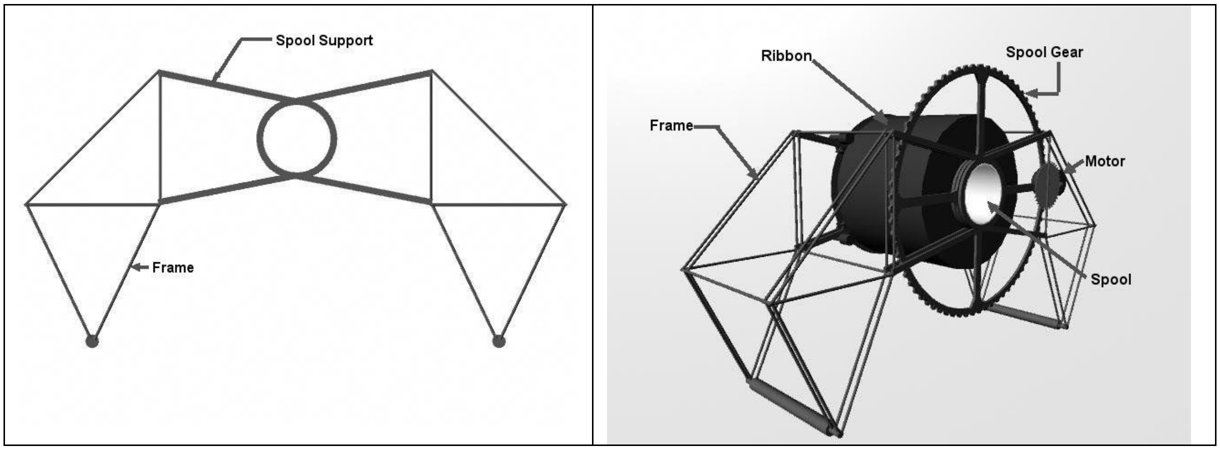

Figure 9. Frame

To find the mass of the frame, the mass of the rollers must first be determined then the mass of the roller struts, and finally, the mass of the beams and columns.

The load supported by the two rollers is found by summing the mass of the ribbon, the spool, the gears and motor assembly, the disc brake assembly, and the ribbon supports and then multiplying by 9.81 m/sec^2, the acceleration due to gravity. The top rollers support the bottom ribbon as well. This results in a load of approximately 3.6 x 10^4 N. With uniform load distribution, each roller supports 1.8 x 10^4 N.

Using a similar analysis as that presented in section 2.a above for the spool and choosing the outer diameter, d_o, of the roller as 12.0 cm, the inner diameter, d_i, of the roller is equal to 7.3 cm. The roller is made of Al/MWNT composite and, therefore, the mass is approximately 18.6 kg. With two rollers the mass is 37.2 kg.

Each roller supports a load of 1.8 x 10^4 N. There are 8 struts that support each roller. Therefore, assuming uniform load distribution, each strut supports a load of 2.3 x 10^3 N. The strut makes an angle of 26.6^o with the vertical. Therefore, the load on the strut is 2.5 x 10^3 N.

To be compatible with the ribbon supports, the outer diameter of the strut should be approximately 5.0 cm with an inner diameter of 4.8 cm, giving a thickness of 1.0 mm. Using Al/MWNT composite, this results in a load carrying capability of 2.3 x 10^4 N, more than enough to support a load of 2.5 x 10^3 N. The length of the strut is 1.1 m resulting in a mass of 0.5 kg. There are 16 struts supporting two rollers resulting in a mass of 7.3 kg.

There are 8 additional struts on the frame which are 1.4 m long. Using the same area gives a mass per strut of 0.6 kg for a total of 4.6 kg.

There are 16 beams and columns on the frame which are 1.0 m long for a mass of 0.4 kg, giving a total of 6.6 kg. The total mass of the frame is summarized in table IV below.

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Two Rollers	= 37.2 kg
16 Struts @ 1.1 m in length	= 7.3 kg
8 Struts @ 1.4 m in length	= 4.6 kg
8 Beams @ 1.0 m in length	= 3.3 kg
8 Columns @ 1.0 m in length	= 3.3 kg
Total Mass of Frame	= 55.7 kg

Table IV. Mass of Frame

As shown in figure 9 above, this completes the mass analysis of one of the counterweight subunits. There are four subunits connected to a vertical truss, two above the ribbon and two below the ribbon. The vertical truss supports the remaining subsystems which make the counterweight operational.

2.g Vertical Truss

The vertical truss connects the four subunits and supports the solar array, power conditioning, and resistive load to make the counterweight operational. The truss is made of Al/MWNT composite with the same diameter as that for the frame. As shown in figure 10 below, the vertical truss is made of 30 1 m beams, 28 1 m columns, 14 2 m beams, and 4 1 m struts.

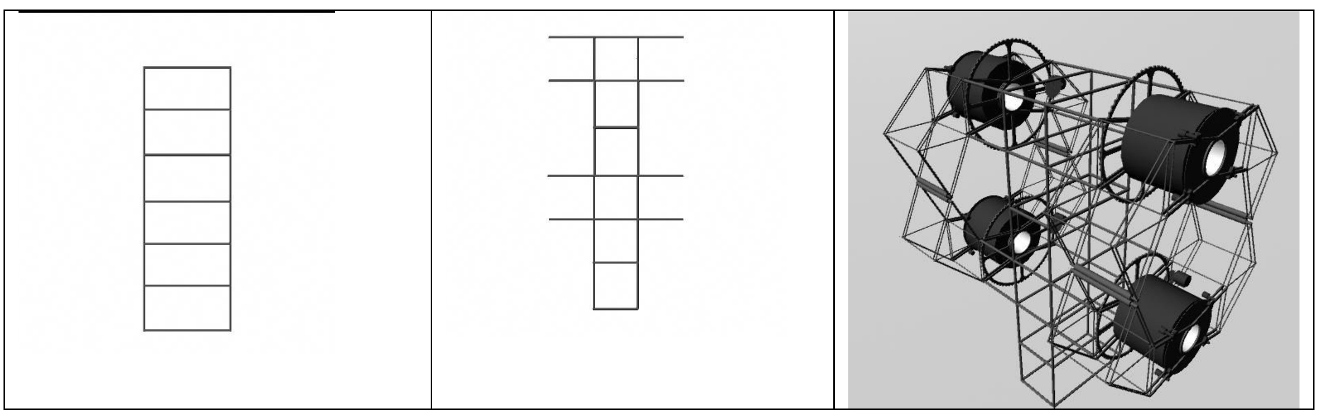

Figure 10. Vertical Truss

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The mass of the vertical truss is summarized in table V below.

30 1 m beams	38.4 kg
28 1 m columns	35.9 kg
14 2 m beams	35.9 kg
4 1 m struts	5.1 kg
Total	115.3 kg

Table V. Mass of Vertical Truss

2.h Power Dissipation

Four motor generators on the counterweight unit produce approximately 60 kW of power during deployment of the ribbons. This power is dissipated by a resistive load made of nichrome wires. The nichrome wires have a diameter of 3.3 mm, carry a current of 52 A, and operate at a temperature of 1000^{o} F. The length of the wire is given by,

$$l = \frac{RA}{\rho}$$

where the resistance, R, is 0.9 Ω; the area, A, is 8.3 x 10^{-6} m^2; and the resistivity, ρ, is 1.0 x 10^{-6} Ω-m. Inserting the variables gives the length of the wire at 7.7 m. The power dissipated per 7.7 m length of wire is approximately 2.5 kW. Therefore, to dissipate 60 kW of power would require 24 wires connected in parallel along a power bus.

Each wire is folded accordion style around three sides of the support strut to handle the estimated total current of 300 A from each motor. The mass of the 24 wire assembly is approximately 12.8 kg.

The wires are connected in parallel along the positive terminal of a copper power bus and terminate at the negative terminal of a copper power bus. Copper cables conduct the current from each motor to the power buses. The total mass of the cables and power buses is approximately 28.8 kg, bringing the total mass, including the nichrome wires, to approximately 41.6 kg.

2.i Prime Power

During deployment, the motors produce power which must be dissipated via the nichrome wires. During launch, the counterweights are used to absorb most of the shock and then return to the pre-launch position. However, the most strenuous requirement occurs when the counterweights return to the tower rolling up the ribbon on the spool as they go. With 4, 20 kW motors and assuming 80% electrical to mechanical efficiency, the time required to return to the tower is approximately 418 hours. The total energy required is 33,440 kW-hr. This energy can not be provided by an on board storage system or conventional photovoltaic cells and stay below the weight limit of 2500 kg per counterweight. Therefore, the energy is beamed to each counterweight by solid state

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lasers and converted to electricity by Aluminum Gallium Arsenide photovoltaic cells (AlGaAs).

Lawrence Livermore National Laboratory has done lethality testing and modeling using a high-power solid-state laser (Abbott, R.P., et el, 2006). The laser is meant for tactical battlefield applications and can be scaled to approximately 150 kW. It is compatible with the AlGaAs photovoltaic cells and has a transmission efficiency of 90% through the lower atmosphere.

The AlGaAs photovoltaic cells respond to a wavelength of 0.84 microns and are based on the research done by F.X. D'Amato (D'Amato, F.X., 1992). The efficiency is 59% at a maximum intensity of 54 kW/m^2. To deliver 80 kW of power to the motors at 59% efficiency would require an intensity of 136 kW/m^2, which is slightly below the maximum intensity delivered to the test cells described in the paper. Accounting for any additional losses, a 4.0 m^2 area should be enough to deliver the required energy to the 4 motors. Normal GaAs solar panels have a mass density of 10.1 kg/m^2 (Delft_SEreport, 2005, p. 53). The AlGaAs cells weight may be slightly different. Assuming 15 kg/m^2, the mass is approximately 60 kg for the collector. As shown in figure 11 below, the AlGaAs cells will be mounted on a thin Al/MWNT support structure and be capable of motion in two dimensions.

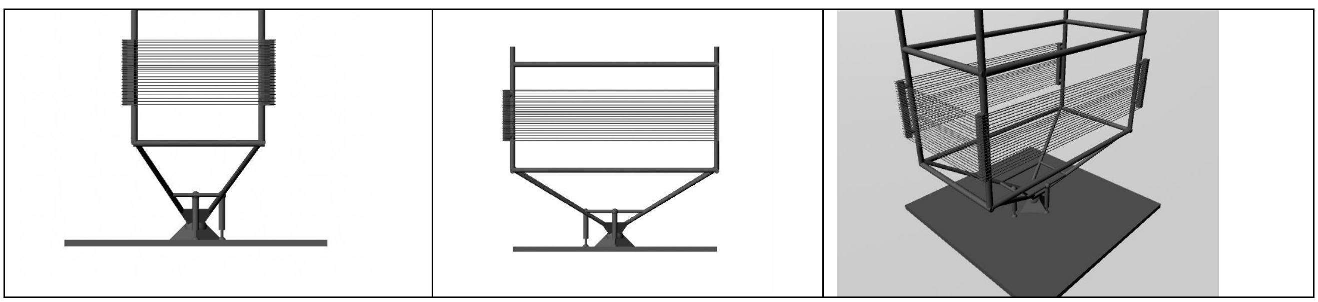

Figure 11. Prime Power

Pivoting of the photovoltaic cells is required to track the laser as the counterweight returns to the tower and also as it revolves around the tower. The Al/MWNT support, the pivot mount, and the solenoids add an estimated 15 kg to the structure. The whole prime power system is massed at approximately 75 kg.

Assuming 90% transmission efficiency, each counterweight unit requires a dedicated 150 kW ground based solid state laser. There are 160 counterweight units (80 on each side). Therefore, the amount of power required is approximately 24 MW. It takes approximately 418 hours of continuous power to bring all of the counterweight units back to the tower. This is an energy requirement of greater than 10 GW-hr. The system would require its own power station to provide the energy required for operation.

3. Summary and Conclusion

The counterweight is a vital part of the Space Track Launch System (STLS). First, it provides stability and shifts the center of mass further down the ribbon. Second, the counterweight absorbs the shock produced by launch. Third, the counterweight returns to the tower at the end of its operational lifetime rolling up the ribbon as it returns. To provide

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the necessary rotational kinetic energy for launch, a 200 ton counterweight is required. A 200 ton counterweight would be impossible to deploy as a single unit. Therefore, the counterweight is divided into 80 counterweight units at an estimated mass of 2.5 ton each. From the initial mass estimates in section 2 above, the total mass of the counterweight is shown in table VI below.

Ribbon Spool	57.1 kg
Spool Gear & Pinion	81.7 kg
Motor, Gear, & Pinion	27.2 kg
Disc Brakes	119.2 kg
Ribbon Supports	135.6 kg
Frame	55.7 kg
Sub-Total	476.5 kg
X4	1,906.0 kg
Vertical Truss	115.3 kg
Power Dissipation	41.6 kg
Prime Power	75.0 kg
Total	2,137.9 kg

Table VI. Counterweight Mass

The mass estimating calculations were based on a 2.5 ton counterweight unit. Therefore, there is an estimated 362 kg mass allowance for the final design of the STLS counterweight unit.

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Appendix A
Face width of a gear

The face width of the pinion gear is determined by following the procedures outlined in Mechanical Engineering Design (Shigley, L. and Mitchell, L., 1983, p. 606) and choosing N_p=12 and P=4 (chosen arbitrarily).

1. Pitch Diameter, $d_p = \frac{N}{P} = 3.0\,in.$
2. Pitch Line Velocity, $V = \frac{\pi d_p n_p}{12}$, where n_p is the revolution per minute of the pinion gear. The rpm of the pinion gear is given by,

$$n_p = \frac{d_g}{d_p} n_g$$

To find the rpm of the pinion gear, the rpm of the spool gear, n_g, and the diameter of the spool gear, d_g, are required. Assuming 15 kW of power delivered by the motor gives,

$$\mathrm{T}_g \omega_g = \mathrm{T}_p \omega_p = 1.5\,x 10^4 W$$

The torque on the spool gear, T_g, is given by the load on the spool, 4.2 x 10^4 N, and the distance from the axis of rotation, 0.25 m and is equal to 1.1 x 10^4 N-m. This gives the angular velocity of the spool gear, ω_g, equal to 1.4 rad/sec and, therefore, n_g as 13.6 rpm. The diameter of the spool gear, d_g, is 78.7 in. (2.0 m) which gives the pinion gear rpm as,

$$n_p = \frac{78.4}{3.0} 13.6 = 356.5\,rpm$$

Therefore, the pitch line velocity is,

$$V = \frac{\pi(3.0)(356.5)}{12} = 280.0 \frac{ft}{\min}$$

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3. Transmitted Load, $W_t = \dfrac{33x10^3 H}{V}$, where H = (1.5kW)(1.34) = 20.1 Hp. Therefore,

$$W_t = \frac{33x10^3(20.1)}{280.0} = 2.4x10^3\,lb$$

4. Velocity Factor, $k_v = \dfrac{1200}{1200+V} = 0.8$

5. Face Width, $F = \dfrac{W_t P}{k_v Y \sigma_p}$, where the form factor, Y = 0.27677 (Table 13-3, p.598).

The ultimate bending stress for AL/MWNT composite is 6.1x10^8 N/m^2. For a safety factor of 4, the permissible bending stress, σ_p = ¼ σ_u = ¼ (6.1x10^8 N/m^2) = 1.525 x 10^8 N/m^2 = 2.211x10^4 psi. This gives the face width of the pinion gear as,

$$F = \frac{\left(2.4x10^3\right)(4)}{(0.8)(0.27677)\left(2.2x10^4\right)} = 1.9\,in. = 4.9\,cm \approx 5.0\,cm$$

Appendix B

Spoke

As shown in figure B.1 below, the spoke will be modeled as a rectangular bar with a moment load. From Mechanical Engineering Design (Shigley, L. and Mitchell, L., 1983, p. 807), the deflection between point A and point B is given by,

$$Y_{AB} = \frac{M_B x}{6EIl}\left(x^2 + 3a^2 - 6al + 2l^2\right) \qquad (1)$$

and the deflection between point B and point C is given by,

$$Y_{BC} = \frac{M_B}{6EIl}\left[x^3 - 3lx^2 + x\left(2l^2 + 3a^2\right) - 3a^2 l\right]$$

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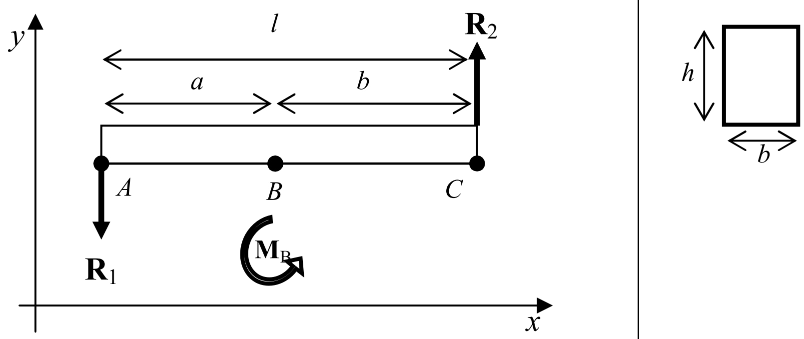

$$I = \frac{bh^3}{12}$$

$$R_1 = -R_2 = \frac{M_B}{l}$$

Figure B.1. Simple Supports-Moment Load

For uniform mass distribution and a uniform load, $a = b = ½\, l = 0.3175$ m. To find the maximum deflection of the spoke, the derivative of Y_{AB} is taken with respect to x and set equal to zero.

$$\frac{dY_{AB}}{dx} = \frac{d}{dx}\left[\frac{M_B}{6EIl}\left(x^3 + 3a^2x - 6alx + 2l^2x\right)\right] = 0$$

$$\frac{M_B}{6EIl}\left(3x^2 + 3a^2 - 6al + 2l^2\right) = 0$$

$$3x^2 + 3a^2 - 6al + 2l^2 = 0$$

$$x = \sqrt{-a^2 + 2al - \frac{2}{3}l^2}$$

Setting a equal to 0.3175 m and l equal 0.635 m gives the point of maximum deflection, x, equal to 0.183 m. Substituting the values for a, l, and x into equation 1 above gives the maximum deflection as,

$$y_{\max} = 0.00324\frac{M_B}{EI}$$

Allowing a maximum deflection of 1.0 mm and using the properties of Al/MWNT composite gives the moment of inertia, I as 1.2 x 10^{-6} m^4. This gives the height, h^3, as,

$$h^3 = \frac{12I}{b} = \frac{(12)\left(1.2x10^{-6}\,m\right)}{0.05m} = 3.0x10^{-4}\,m^3$$

and h equal to approximately 7.0 cm.

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