Fisher Space Systems, LLC

Space Track Launch System
Overcarriage

by
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1. Introduction

The overcarriage is a load bearing structure which rides on top of the ribbon and carries the second stage launch vehicle (LV) down the ribbon to the launch position. The overcarriage and launch vehicle for the Space Track Launch System (STLS) make up the second stage of a two stage system. The first stage is a tall tower with rotating ribbons (Fisher, J. F., 2007). The tower (Fig. 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. The truss is powered by electric motors. Each ribbon is attached to a counterweight (CW) to provide stability and shift the center of mass further down the ribbon.

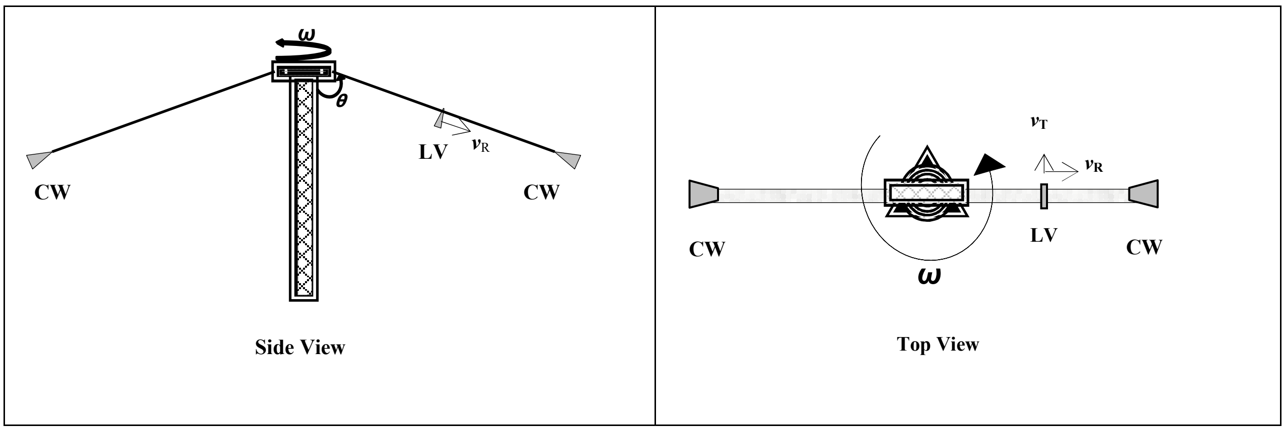


Figure 1. Space Track Launch System

The second stage is a liquid fueled vehicle designed to launch from the STLS (Fisher, J.F., 2009). The launch vehicle attaches to an ejector which is attached to the overcarriage. 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 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. 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 overcarriage.

2. Overcarriage

The overcarriage (Fig. 2) carries the launch vehicle down the ribbon to the launch point. The overcarriage rests on top of the ribbon with the second stage launch vehicle hanging below the ribbon. This puts the center of mass below the ribbon which results in a more stable system. The launch vehicle and overcarriage will experience a maximum load of over six times that produced by gravity and travels at a velocity of over 3 km/sec.

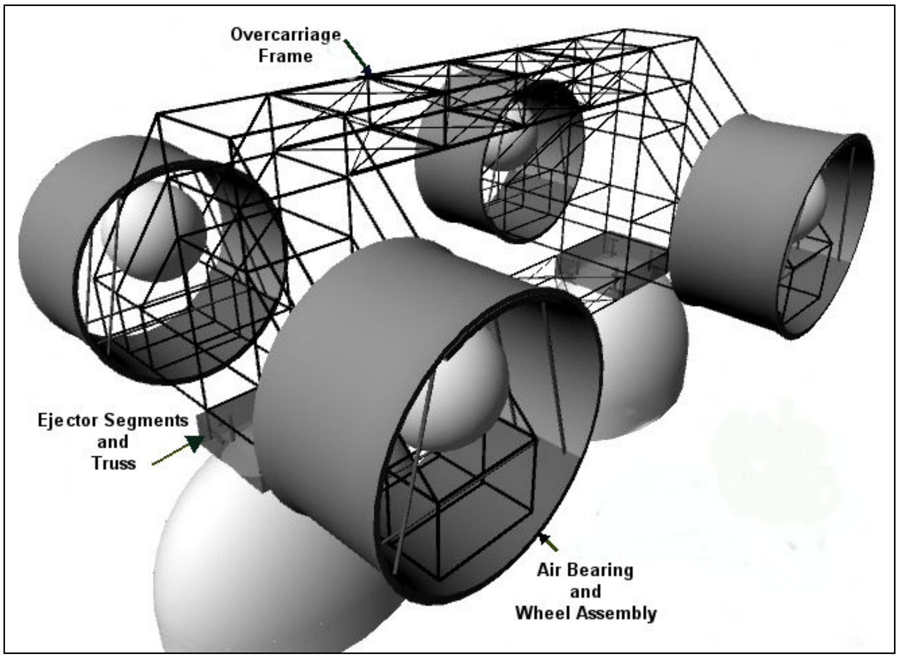


Figure 2. Overcarriage

The primary load bearing structure consists of four queen-post trusses. Two queen-post trusses are connected with cross beams resulting in a truss that is very similar to a bridge truss. Four vertical ties of the ‘bridge’ truss carry the load to the upper chords which transfer the load to the air bearings and wheels using inclined struts. The front and rear bridge trusses are attached to an ejector which attaches to the port and starboard propellant tanks of the launch vehicle via eight pre-stressed stainless steel bolts and eight frangible nuts. At launch, small explosives separate the frangible nuts, releasing the launch vehicle. The bolts retract into the nose cones of the port and starboard propellant tanks. Each bridge truss has two air bearings and two wheels. Assuming an 80 ton launch vehicle and a 20 ton overcarriage, each wheel must support up to 25 ton at rest and 150 ton during a 6g acceleration. The following sections discuss the initial design and mass estimate of the ejector segments and truss, overcarriage frame, and the air bearing and wheel assembly.

2.a. Ejector Segments and Truss

The ejector segments and truss (fig. 3) is a major load bearing component of the overcarriage. The ejector consists of two ejector segments attached to the port and starboard propellant tanks of the launch vehicle. Each segment has four pre-stressed stainless steel bolts and four frangible nuts. At launch, small explosives separate the frangible nuts, releasing the launch vehicle.

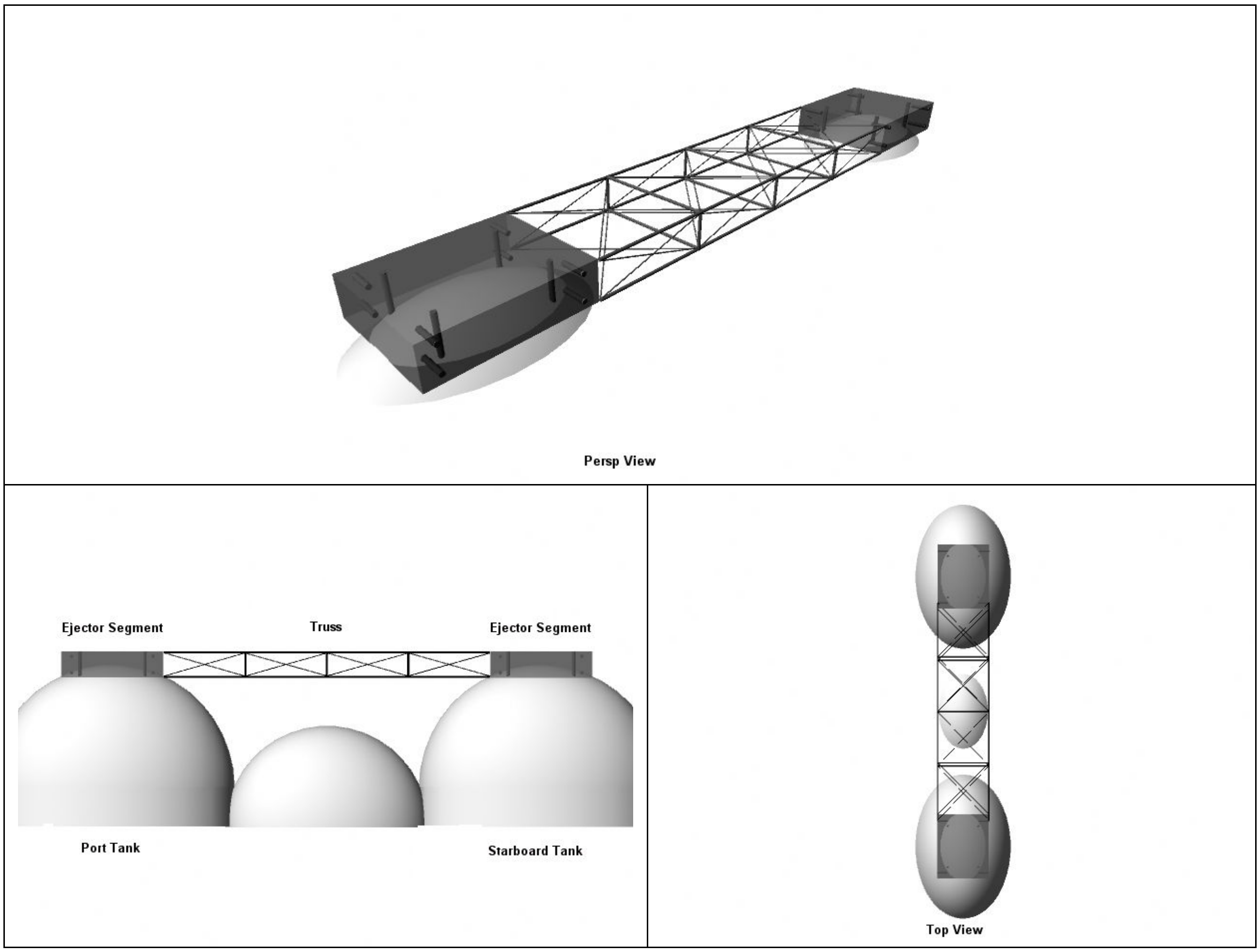


Figure 3. Ejector Segments and Truss

The bolts retract into the nose cone of the port and starboard propellant tanks. Each segment is made of a carbon/epoxy composite and supports ½ of the launch vehicle load under a 6g launch (assuming uniform load distribution).

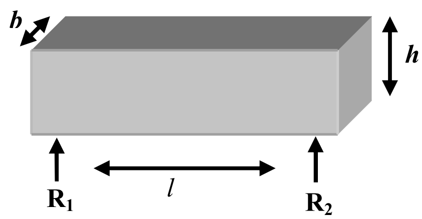
2.a.1 Ejector Segment Initial Design and Mass Estimate

For an 80 ton launch vehicle under a 6g load, each ejector segment supports a load of 2.4 x 10^6 N. The ejector segment is made of 60% Carbon Fiber and 40% Epoxy. This gives an ultimate strength, σ_u, equal to 1.47 x 10^9 N/m^2 and the modulus of elasticity, E, equal to 1.38 x 10^{11} N/m^2.

If the launch vehicle is supported only by frangible nuts with an outer diameter of 10 cm and an inner diameter 4 cm, then the contact surface area is equal to 6.6 x 10^{-3} m^2. There are four nuts per ejector segment. Therefore, the total contact surface area is 2.6 x 10^{-2} m^2. This gives a maximum load capability of 3.9 x 10^7 N which is ~ 10x launch vehicle load. Also, hardened stainless steel washers can be placed under the frangible nuts to spread the load over a larger surface area and to provide blast protection. Packing material is placed around the frangible nuts to contain the explosion debris. The packing material is replaced when refurbishing the overcarriage for the next launch.

The mass of the ejector segment is given by the density of the carbon/epoxy composite and the volume of the ejector segment. First, to determine the volume, the thickness of the ejector segment, h, must be estimated. The nose cone of the launch vehicle fits into the ejector segment. Therefore, as shown in figure 4, the ejector segment will be modeled as a solid rectangular segment with a uniform load distribution.

Also shown in figure 4 are the relevant equations (Shigley, J. and Mitchell, L., 1983) used to determine the area moment of inertia, I, and thus the thickness, h, of the ejector segment given a maximum deflection, y_{max}. If the distance, l, between two supports of the ejector segment is 1.0 m and the depth, b, is 0.5 m, what is the thickness, h?



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

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

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

Figure 4. Ejector Segment Model

Each ejector segment supports a maximum load of 2.4 x 10^6 N. There are 4 bolts. Assuming uniform load distribution, each bolt supports a load equal to 5.9 x 10^5 N. This gives the linear load, w, equal to 1.2 x 10^6 N/m. For carbon/epoxy, the modulus of elasticity, E, is approximately 1.14 x 10^{11} N/m^2 (60%Carbon Fiber/40%Epoxy).

Rearranging the equations and choosing the maximum deflection, y_{max}, equal to 0.1 mm gives,

$$I = \frac{-5wl^4}{384Ey_{max}}$$

$$I = \frac{-5(1.2x10^6)(1.0)^4}{384(1.14x10^{11}(1x10^{-4})} = 1.35x10^{-3}m^4$$

This gives,

$$h^3 = \frac{12I}{b} = \frac{12(1.35x10^{-3})}{0.5} = 3.25x10^{-2}m^3$$

Taking the cube root gives the thickness of the ejector, h, equal to 0.32 m.

The volume of the ejector segment is the volume of the rectangular solid minus the volume occupied by the nose cone of the launch vehicle. This volume is given by,

$$Vol = ldh - \frac{2}{3}\pi r^3 = (1.25m)(1.0m)(0.32m) - \frac{2}{3}\pi(0.4)^3 = 0.27m^3$$

The density of carbon/epoxy composite is 1,565 kg/m^3. This gives the mass of the ejector segment as 416 kg. There are two ejector segments giving a total mass of 832 kg.

2.a.2 Ejector Truss Design and Mass Estimate

The ejector truss (fig. 3) is a basic box beam design and is constructed with a new aluminum multi-walled carbon nanotube (Al/MWNT) composite metal matrix (Choi, H., Shin, J., Min, B., Park, J., and Bae, D., 2009). With a 4.5% by weight additive of MWNT, the Al/MWNT mechanical properties of aluminum are increased by a factor of 10. The ultimate strength, σ_u, is 610 MPa, the modulus is 1.10 x 10^{11} N/m^2, and the mass density, ρ, is 2,650 kg/m^3. The beams and columns making up the ejector truss are 4 cm diameter giving a cross sectional area of 1.26 x 10^{-3} m^2. The truss is made up of 22, 1.0 m long beams and 6, 0.32 m long columns, giving a total length of beams and columns of 23.92 m. This gives the mass of the ejector truss equal to 79.9 kg. The ejector truss is capable of resisting a lateral load of 9.82 x 10^5 N.

The total mass of the ejector is 912 kg and is summarized in table I below.

Two ejector segments	= 832.0 kg
Ejector truss	= 79.9 kg
Total for ejector	= 911.9 kg

Table I. Mass of Ejector Segments and Truss Assembly

2.b. Overcarriage Frame

The overcarriage frame (fig. 5) supports itself and the second stage launch vehicle under a 6g acceleration, a load of 5.9 x 10^6 N. The frame consists of four queen-post trusses.

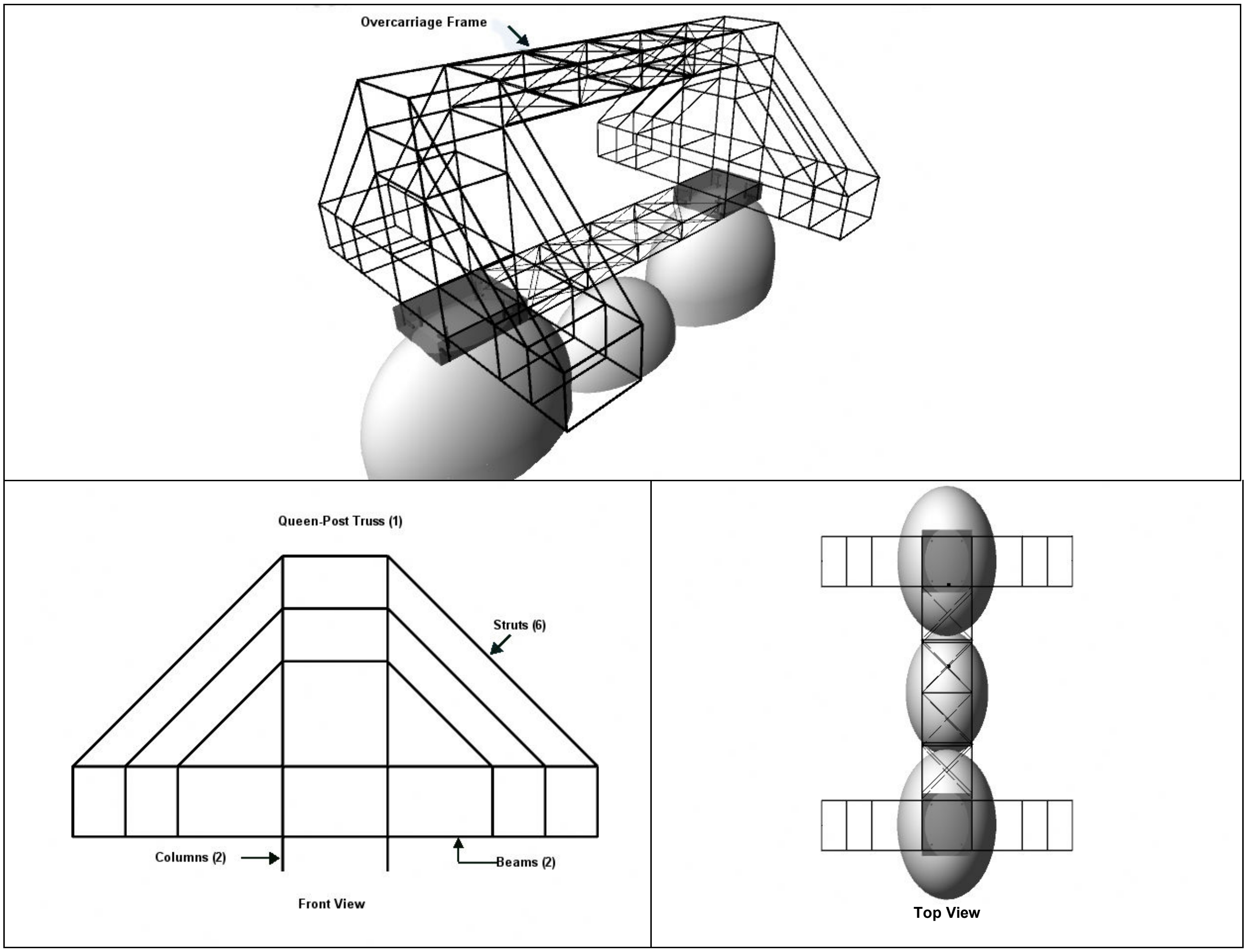


Figure 5. Overcarriage Frame

Each truss is connected by 1.0 m long beams forming a queen-post bridge approximately 1.0 m wide. Two bridges are connected by the ejector truss at the bottom and an additional box beam truss at the top. The overcarriage frame is constructed with the same Al/MWNT composite metal matrix material that is used for the ejector truss.

2.b.1 Queen-Post Truss

Each queen-post truss supports an estimated maximum load of ¼ of the combined overcarriage and launch vehicle load or 1.5 x 10^6 N. There are two columns in each truss. Therefore, each column supports a maximum load of 7.4 x 10^5 N, assuming a uniform load distribution. This gives a surface area for each column of,

$$A = \frac{Load}{\sigma_w} = \frac{7.4x10^5\,N}{2.0x10^8\,N/m^2} = 3.7x10^{-3}\,m^2$$

where the working tensile strength, σ_w , is 1/3 of the ultimate tensile strength, σ_u , equal to 2.0 x 10^8 N/m^2. This gives the radius of the column equal to 3.4 cm. Each column is approximately 3.0 m long. Therefore, the mass is,

$$Mass = \rho Vol = (2{,}650\,kg/m^3)(3.7x10^{-3}\,m^2)(3.0m) = 29.3kg$$

The mass of the two columns is 58.5 kg.

The two columns are attached to two 5.0 m beams. The beams are made of the same Al/MWNT material and have the same radius as the columns. Therefore, the mass of the two beams is 97.5 kg.

Each wing of the queen-post truss serves as a support for the air bearing and wheel. There is a maximum load of 7.4 x 10^5 N for each support. This load is assumed to be uniformly distributed over three columns. Therefore, each column supports a maximum load of 2.5 x 10^5 N. As a result, each column has a mass of 2.3 kg with a radius of 2.0 cm. There are six columns which result in a mass of 13.8 kg.

Each air bearing column is attached to the main load bearing column by an Al/MWNT strut. The struts make a 45^o angle with the horizontal. Therefore, each strut has a maximum load of 3.5 x 10^5 N giving the strut a radius of 2.4 cm and a cross sectional area of 1.7 x 10^{-3} m^2. There are two 2.8 m struts, two 2.1 m struts, and two 1.4 m struts. The mass of each strut is 13.0 kg, 9.8 kg, and 6.5 kg respectively, giving a total mass of 58.6 kg.

The total mass for the queen-post truss is shown in table II below.

Two main load bearing columns	= 58.5 kg
Two main load bearing beams	= 97.5 kg
Six air bearing columns	= 13.8 kg
Six air bearing to column struts	= 58.6 kg
Total for queen-post truss	= 228.6 kg

Table II. Mass of Queen-Post Truss

2.b.2 Queen-Post Bridge

Two queen-post trusses are connected together by 22, 1.0 m long beams forming a queen-post bridge. Each connecting beam has a radius of 2.0 cm and a mass of 3.3 kg, giving a total mass of 71.5 kg for the 22 beams. The total mass for the queen-post bridge is shown in table III below.

Two queen-post trusses	= 457.2 kg
22 connecting beams	= 71.5 kg
Total for queen-post bridge	= 528.7 kg

Table III. Mass of Queen-Post Bridge

2.b.3 Queen-Post Top Truss

There are two queen-post bridges connected by a box beam truss at the top and the ejector truss at the bottom. The top box beam truss is similar in construction to the ejector truss and has a mass of approximately 92.4 kg. The total mass of the overcarriage frame is shown in table IV below.

Two queen-post bridges	= 1,057.4 kg
Top box beam truss	= 92.4 kg
Total for overcarriage frame	= 1,149.8 kg

Table IV. Mass of Overcarriage Frame

2.c. Air Bearing and Wheel Assembly

The main air bearing (Fig. 6) attaches to the queen-post bridge axle. Each air bearing and wheel supports a maximum load of 1.5 x 10^{6} N. The load is transferred to

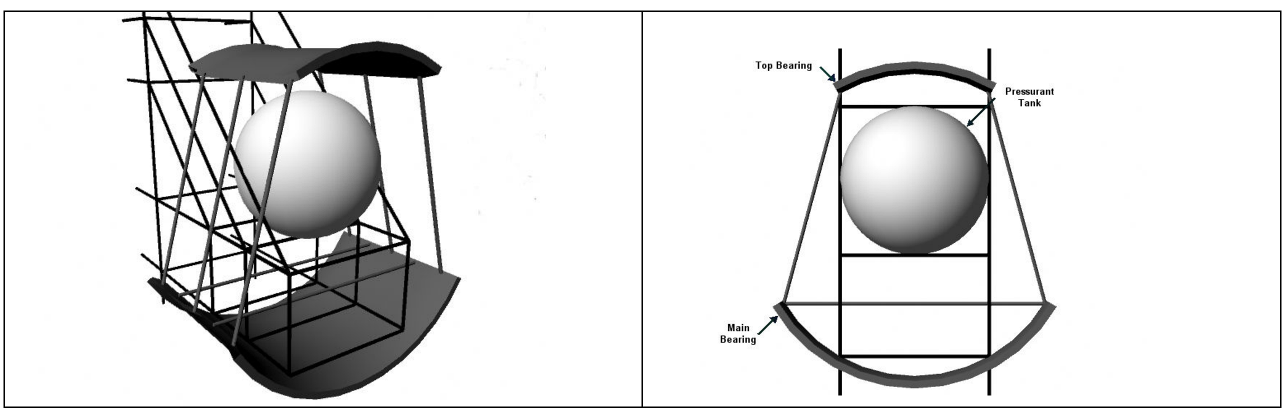


Figure 6. Overcarriage Air Bearing

the axle by 6, 0.68 m long columns. There are four air bearings, four wheels, and four pressurant tanks.

2.c.1 Pressure Requirements

The air bearing must produce a total lifting force of 1.5 x 10^6 N. The air bearing produces a uniform pressure distribution along its surface. The force, which equals the pressure times the area, provides both a vertical force component and a horizontal force component. The vertical force component is given by $F_u \cos\theta$. The horizontal force component is given by $F_u \sin\theta$. Taken over a large number of small areas, the vertical force sums to the total force required and is given by,

$$F_{Tot} = F_u\left[2\left(\sum_{n=0}^{N}\cos(nx) - 1\right)\right]$$

where

$$\sum_{n=0}^{N}\cos(nx) = \frac{\cos\left(\frac{Nx}{2}\right)\sin\left(\frac{(N+1)x}{2}\right)}{\sin\left(\frac{x}{2}\right)} \qquad \text{(Jeffrey, A., 2000)}$$

where N is the number of sections, x degrees wide. The sum is subtracted by 1 because $\cos(nx)$ when n = 0 can only be counted once. For example, if x = 0.5°, then N = 120 (nx goes from 0° to 60°) since the main air bearing spans an arc of 120°. Therefore,

$$\sum_{n=0}^{N}\cos(nx) = \frac{\cos\left(\frac{(120)(0.5)}{2}\right)\sin\left(\frac{(120+1)(0.5)}{2}\right)}{\sin\left(\frac{0.5}{2}\right)} = 99.99$$

and

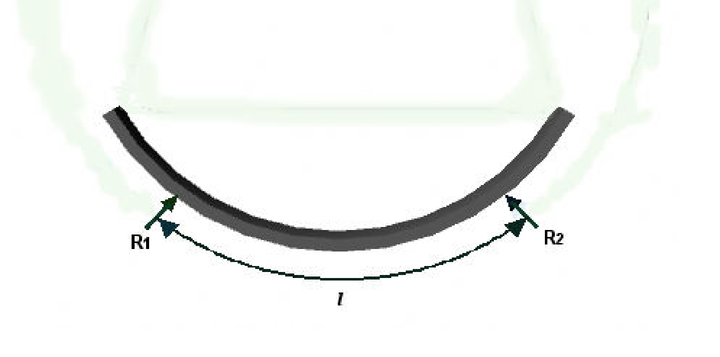
$$F_{Tot} = F_u\left[2(99.99-1)\right] = 197.98\,F_u = 1.5\,x10^6\,N$$

This results in a required lifting force, F_u, of 7.4 x 10^3 N.

Since x = 0.5°, the arc, s, covered by the air bearing with a radius of 1.0 m is 8.7 x 10^{-3} m. The surface area for a 1.0 m long air bearing that F_u acts upon is 8.7 x 10^{-3} m^2. This gives a pressure of 8.5 x 10^5 N/m^2 or 124 lb/in^2. This is the maximum pressure required for a 6g launch.

2.c.2 Air Bearing Mass

The main air bearing (fig. 7) spans an arc of 120° and is 1.0 cm thick. The bearing will be modeled as a curved beam with simple supports and a uniform load distribution, where w is the uniform load in N/m, l is the length of the span in meters, E is the elasticity in N/m^2, and I is the area moment of inertia for a hollow circle.



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

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

Figure 7. Main Air Bearing

The area moment of inertia for a hollow circle is,

$$I = \frac{\pi}{64}\left(d_o^4 - d_i^4\right) \qquad \text{(Shigley, J. and Mitchell, L. 1983)}$$

where d_o and d_i are the outer and inner radius of the air bearing respectively. Since the span between the supports is 60°, the area moment of inertia is reduced by 60/360.

The maximum load on the air bearing is 1.5 x 10^6 N. There are six columns in the axle which support the air bearing. Therefore, assuming uniform load distribution, each column supports 2.4 x 10^5 N. This gives a load per unit length, w, along the arc between R_1 and R_2 equal to 4.7 x 10^5 N/m. For Al/MWNT composite, the modulus of elasticity, E, is 110.1 x 10^9 N/m^2. The area moment of inertia for the 60° arc is 5.2 x 10^{-3} m^4 (for d_o = 2.0 m and d_i = 1.98 m). This gives the maximum deflection as,

$$y_{\max} = \frac{-5\left(4.7\,x10^{5}\right)\left(1.047\right)^{4}}{384\left(110.1x10^{9}\right)\left(5.2\,x10^{-3}\right)} = 1.3\,x10^{-5}\,m$$

This is an acceptable deflection since a typical air gap thickness is on the order of 0.13 mm.

The air bearing is 1.0 cm thick. The hoop stress on the air bearing should not exceed the tensile strength of the material. The hoop stress for thin walled vessels is,

$$\sigma_t = \frac{P_u d_i}{2t} \qquad \text{(Shigley, J. and Mitchell, L. 1983)}$$

where t is the thickness of the air bearing equal to 1.0 cm, d_i is the diameter of the air bearing equal to 2.0 m, and P_u is the pressure on the air bearing equal to 8.5 x 10^5

N/m^2. The vessel is considered thin walled if the radius is 20 times larger than the wall thickness. Therefore, since the wall thickness is approximately 1.0 cm and the radius is 1.0 m, the radius is approximately 100 times the wall thickness and the hoop stress equation above is valid. Evaluating the equation gives the hoop stress as 8.5×10^7 N/m^2. This is an acceptable hoop stress since the tensile strength of the Al/MWNT composite is 2.0×10^8 N/m^2.

Knowing the length of the air bearing, its inner and outer radius, and the 120^o arc, gives the mass of the main air bearing equal to 55.2 kg. The top air bearing is made of the same material with the same dimensions but spans an arc of 60^o. Therefore, its mass is 27.6 kg.

In addition to the queen-post truss axle beams and columns, there are 2 beams and 6 struts that provide additional support for the top and main air bearings. Each beam and strut has a cross sectional area of 1.2×10^{-3} m^2. There are 2 beams each 1.7 m long and 6 struts each 1.4 m long for a total length of 11.8 m. Therefore, the mass of the beams and struts is 38.5 kg.

The mass of the air bearing is summarized in table V below.

Main Air Bearing	= 55.2 kg
Top Air Bearing	= 27.6 kg
Beams and Struts	= <u>38.5 kg</u>
Total	= 121.3 kg

Table V. Mass of Air Bearing

2.c.3 Pressurant and Pressure Tank Mass

The air bearing design and pressure requirements determined in section 2.d.1 and 2.d.2 above where calculated for maximum load just prior to second stage launch. The overcarriage and second stage launch vehicle start from a rest position at the axis of rotation. The load increases as the acceleration of the launch vehicle increases. Therefore, the pressure requirements at the beginning of launch are much less than that required at launch.

2.c.3.a Pressurant Requirement

Since the load increases with acceleration, the pressurant mass flow rate is a function of the acceleration. To determine the total mass of pressurant required, the mass flow rate is calculated in increments of 50 seconds, plotted, and the area under the curve is calculated for the entire launch interval.

The mass flow rate is given by (Huzel, D. K. and Huang, D. H., 1967),

$$\dot{w} = \frac{C_d A_g Z P}{\sqrt{RT}}$$

where C_d is the flow coefficient approximately equal to 0.85 for discharge into a vacuum, A_g is the total area for the air gap, Z is the compressibility factor, P is the pressure required, R is the gas constant equal to 53.3 ft/^{o}R for nitrogen, and T is the pressurant temperature equal to 527.4^{o}R. The mass flow rate is given in English units. Therefore, the flow rate is first calculated in English units and then converted to the metric system.

The total area of the air gap, A_g, is equal to the perimeter multiplied by the gap thickness. Both the main air bearing and top air bearing are 1.0 m wide with a radius of 1.0 m and span an arc of 120^o and 60^o respectively. This gives a combined perimeter for the main air bearing and top air bearing of 10.27 m. Air gap thickness for air bearings is typically on the order of 0.13 mm. Therefore, the area of the air gap is 1.34 x 10^{-3} m^2 or 2.07 in^2.

The compressibility factor is given by,

$$Z = \sqrt{g\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \quad for\ \frac{P_d}{P_u} \le \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

where g is the acceleration due to gravity, 32.2 ft/sec^2, the specific heat ratio is 1.4 for nitrogen, and P_d is the downstream pressure equal to 0 for a vacuum. This gives the compressibility factor equal to 3.886$\sqrt{ft}/\sec$.

Now that all of the constants are determined, the mass flow rate is calculated as a function of the working gas pressure. This gives the mass flow rate as,

$$\dot{w} = \frac{(0.85)(2.07in^2)(3.89\sqrt{ft}/\sec)}{\sqrt{(53.3\,ft/{}^oR)(527.4^oR)}} P = 4.1x10^{-2}\ in^2/\sec(P_u)$$

The working gas pressure for each air bearing is given by,

$$P_u = \frac{(25{,}000kg)(Acceleration)}{(197.98)(8.73x10^{-3}m^2)}$$

At t=0, the acceleration is 9.81 m/s^2. This gives the required pressure equal to 1.42 x 10^5 N/m^2 or 20.6 lb/in^2 which, in turn, gives the mass flow rate equal to 0.84 lb/sec.

The acceleration on the launch vehicle is calculated using the FORTRAN program given in a previous paper on second stage launch requirements (Fisher, J.F., 2009). With these accelerations, the mass flow rate in 50 second increments is shown in figure 8 below.

Time (sec)	Flow Rate (lb/s)
0	0.9
50	0.9
100	1.0
150	1.4
200	2.3
250	4.1
300	7.5

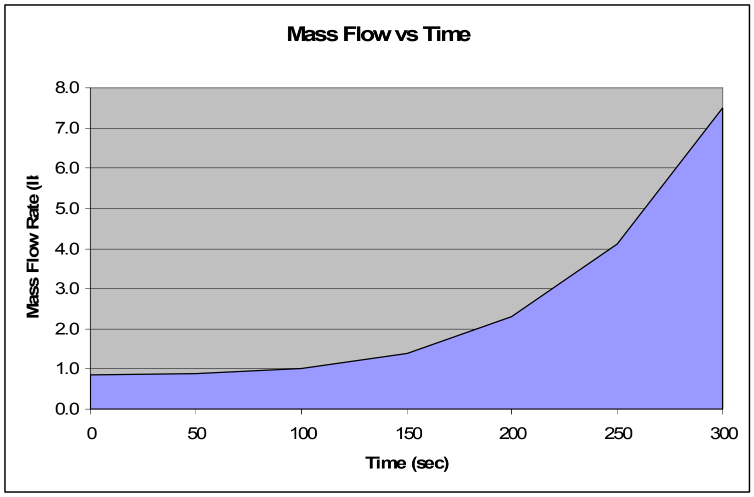


Figure 8. Mass Flow Rate Vs Time

Summing the area under the curve gives the total mass of nitrogen required per air bearing to be approximately equal to 695 lb or 315 kg. At 10,000 psi or 6.90 x 10^7 Pa, the volume required is 0.41 m^3. For a spherical tank, a radius of approximately 0.5 m meets this requirement.

2.c.3.b Pressure Tank Mass

The pressure tank mass is given by,

$$M = \rho V = \rho\left[\frac{4}{3}\pi\left(r_o^3 - r_i^3\right)\right]$$

where ρ is the density of the pressure vessel material, r_o is the outer radius, and r_i is the inner radius of the pressure vessel.

Cylindrical pressure vessels that have been tested to 1.72 x 10^8 N/m^2 (25,000 lb/in^2) are made of composite materials. One such design (Odegard, B. C. and Thomas, G. J., 2001) is made of 5 mm fiberglass outer wrap, 8 mm graphite epoxy structural wrap, and 7 mm high density polymer liner. This design is typical of high pressure composite vessels.

Starting with an inner radius of 0.5 m and inserting the appropriate values for the density and thickness of fiberglass, carbon/epoxy, and the liner gives a total mass of 63.7 kg for the spherical tank. The head, valves, flow meters, and plumbing gives an additional mass of 50.0 kg, making the total approximately 113.7 kg. There are four pressure tanks; one for each air bearing.

From the equation above, the hoop stress for the fiberglass outer wrap and the carbon/epoxy structural material is approximately equal to the working tensile strength of the materials. Therefore, some additional engineering is required to increase the margin of safety for the pressure tank. However, the dimensions above are adequate for an initial design.

2.c.4 Wheel

The wheel (fig. 9) is made of a rim and a tire. The rim is made from Al/MWNT metal matrix composite and acts as a reaction surface for the air bearing. The tire is made of M5 composite (M5®, 2006) which wraps around the rim for structural support.

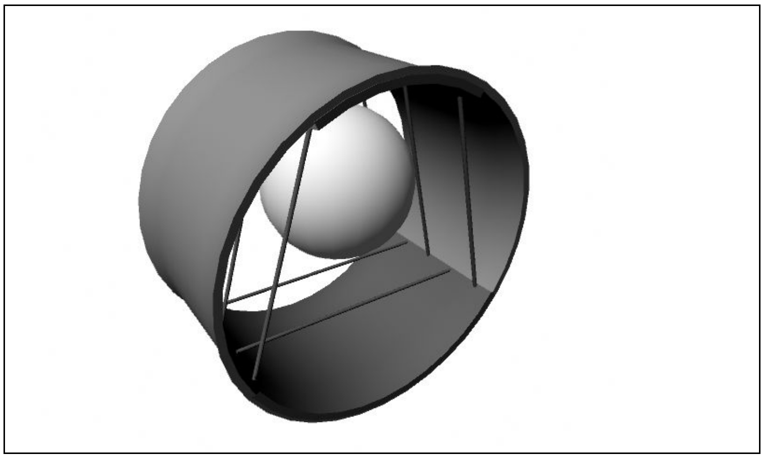


Figure 9. Overcarriage Wheel

The rim is 2.0 m in diameter and 1.0 cm thick. A point on the rim travels with a velocity of approximately 3,200 m/s. A 1.0 cm x 1.0 m section of rim gives a mass of 0.265 kg. With the section velocity, mass, and radius, the centripetal force is calculated to be 2.7×10^6 N, resulting in a pressure equal to 2.7×10^8 N/m^2. This gives a hoop stress of 1.4×10^{10} N/m^2. The hoop stress is 200 times the tensile strength of Al/MWNT. Therefore, the rim is wrapped with an M5 composite to strengthen the rim.

The M5 composite serves as the tire for the wheel assembly. The thickness of the tire is given by the hoop stress formula above. By setting the hoop stress equal to the working tensile strength of the M5 material (3.3 GPa), the thickness of the tire is approximately 5.0 mm. Taking into consideration the density and volume of the Al/MWNT rim as well as the M5 composite tire gives a mass of approximately 219.0 kg for the wheel assembly.

The compressive strength of M5 is 2.0×10^9 N/m^2. The wheel must withstand the compressive force of a 6g launch. At launch, the ribbon makes a 5^o angle at the tower end and a 1^o angle at the counter weight end. As shown in figure 10 below, the contact surface area is the arc, S, multiplied by the width of the wheel.

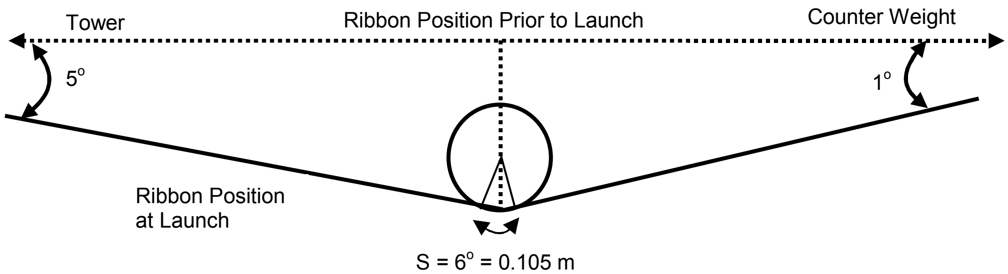


Figure 10. Contact Surface Area

The ribbon intersects the wheel at a tangent point. The triangles formed by the ribbon/wheel intersection and the triangles formed by the perpendicular to the ribbon are similar triangles. Therefore, the arc form by the ribbon and wheel contact is 6^0 resulting in an arc length of 0.105 m. For a 1.0 m wide wheel, the contact surface area is 0.105 m^2. For a 6g launch, the wheel load is 1.5×10^6 N resulting in a contact pressure of 1.4×10^7 N/m^2 which is much less than the compressive strength of the M5 material.

The masses are summarized in table VI below.

Air Bearing Mass	= 121.3 kg
Pressurant Mass	= 315.0 kg
Tank Mass	= 113.7 kg
Wheel Mass	= 219.0 kg
Total	= 769.0 kg
X4	= 3076.0 kg

Table VI. Mass of Air Bearing and Wheel Assembly

3. Reentry Flight Profile

At launch, the altitude of the overcarriage is approximately 120 km and it is traveling approximately 3,360 m/s. From this point on, it is basically a spacecraft on reentry and must contain all the subsystems necessary for reentry and landing. It is assumed that the overcarriage will follow a similar flight profile of that shown in figure 11 below, the reentry trajectory of the Apollo capsule (Lee, D. B, Bertin, J. J., and Goodrich, W. D., 1970).

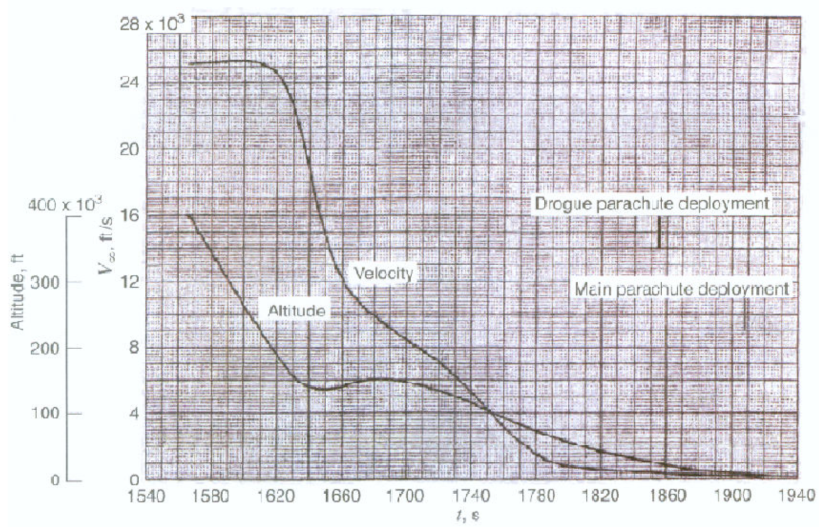


Figure 11. Reentry Trajectory of the Apollo Capsule

If the overcarriage launches at an angle of 10^o to the horizontal, its horizontal velocity is 3,310 m/s and its vertical velocity is 1,584 m/s. The vertical velocity gives approximate 200 sec to re-enter the atmosphere at an altitude of 70 km. Therefore, on re-entry, the overcarriage is approximately 662 km downrange from the tower. The overcarriage will reach a terminal velocity at an altitude of approximately 23 km. The deployment of the drogue chute occurs at an altitude of about 14 km. Full deployment of the ram air parafoil occurs at approximately 12 km. With a 5:1 glide ratio (AS Airborne Systems, 2007), the overcarriage has a cross range capability of approximately 60 km. Upon landing, the overcarriage is ferried back to the launch site for refurbishment and readied for the next launch.

4. Overcarriage Reentry Subsystems Mass Estimate

The mass estimating relationships (MERs) for the conceptual design of launch vehicles compiled by George Tech (Rohrschneider, R. R., 2002) will be used to estimate the mass for the overcarriage reentry subsystems. The data was taken from multiple design organizations from around the country and is freely available for use. To validate the equations, Space Shuttle component masses were predicted and a percentage error was reported. Therefore, the MER that gives the best result for the particular component of the Space Shuttle will be used to estimate the mass of that component for the overcarriage reentry subsystem.

All equations in the database are set up for use in the English unit system. Standard measures for this database are feet, pounds, and seconds, with pressure in psi, and power in kilowatts, unless otherwise noted. Therefore, the weight estimates will be converted to the metric system after the calculations are completed.

4.a Fuselage

The fuselage for the overcarriage is of a conventional aircraft design. The fuselage housing contains the ejector, the queens-post frame, the air bearings and wheels, the avionics, the ram air parafoil recovery system, the landing gear, the reaction control system (RCS) propellant tanks, and the RCS engines. The MER for the fuselage is shown below.

$$M_{fuse} = 2.167 A_{body}^{1.075}$$

M_{fuse} – Weight of the fuselage
A_{body} – Surface area of vehicle body.

The first task is to determine the surface area of the vehicle body. The fuselage will be large enough to cover the overcarriage frame, as shown in figure 12 below.

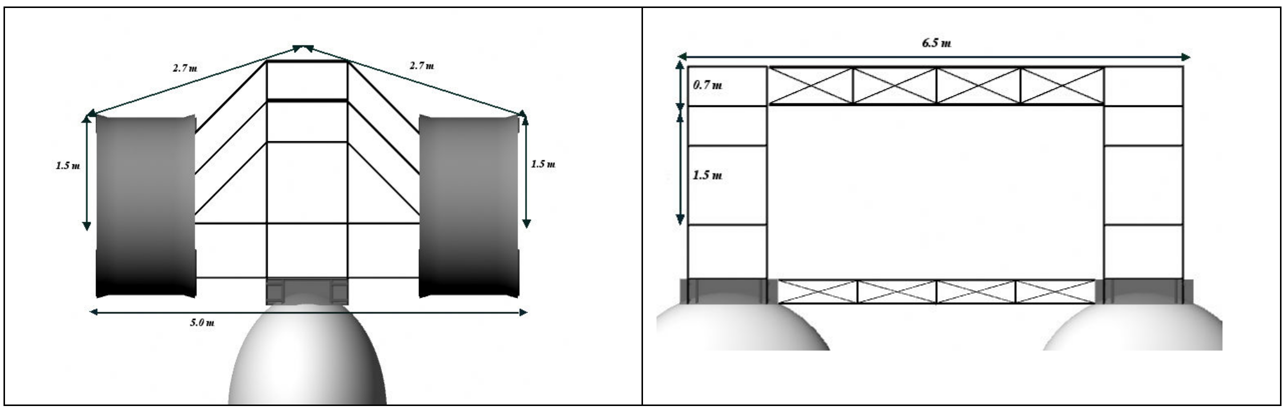


Figure 12. Fuselage Dimensions

The aerodynamic shell covering the top of the overcarriage frame will approximate a triangular solid in shape with a base of 5.0 m, a height of approximately 0.7 m, and a length of approximately 6.5 m. The aerodynamic shell covering the sides of the overcarriage will be a rectangular box 5.0 m wide, 6.5 m long, and 1.5 m high. This results in a surface area of about 59.1 m^2 or 635.8 ft^2. Evaluating the MER gives the weight of the fuselage as 2,235.9 lb. A technology reduction factor (TRF) of 0.38 results in a weight of 1,386.2 lb or a mass of 629 kg.

4.b Body Flap

The overcarriage has 4 body flaps attached to the fuselage at each wheel. The purpose of the body flaps is to protect the RCS during reentry and provide control of the overcarriage during the atmospheric flight portion of reentry. Each body flap is 1.0 m

(3.28 ft) wide at the attachment to the fuselage and 0.5 m (1.6 ft) long. The MER for the body flap is shown below.

$$M_{bf} = 3.135 S_{bf}$$

M_{bf} – Weight of body flap
S_{bf} – Surface area of body flap = 5.25 ft^2

Evaluating the MER gives the weight for each body flap at 16.3 lb. For 4 body flaps, the total weight is 65.4 lb or 30 kg.

4.c Landing Gear

The landing gear for the overcarriage is of a standard tricycle landing gear design. The landing gear is housed in the top truss of the overcarriage frame. Reference 6 from the Georgia Tech study will be used to estimate the mass. The MERs for the main and nose landing gear are shown below.

$$M_{maingear} = 0.00927 M_{land}^{1.0861}$$

$$M_{tai\lg ear} = 0.001514 M_{land}^{1.0861}$$

$M_{maingear}$ – Weight of the main landing gear
$M_{tailgear}$ – Weight of the nose gear
M_{land} – Landed weight of vehicle = 44,090 lb

Evaluating the MERs gives a weight for the main gear of 1,026 lb and a weight for the tail gear of 168 lb. The total weight is 1,194 lb. A TRF of 0.09 reduces the weight to 1,089 lb or 493 kg.

4.d Reaction Control System

The RCS consists of thrusters for pitch, yaw, and roll. The RCS is used to control the overcarriage and position it for atmospheric interface. It is assumed that the RCS will use the same nitrogen gas that is used for the air bearings. This simplifies the design and negates the need for a dedicated cold gas supply system. Reference 3 from the Georgia Tech study will be used for the mass estimate. The MER for the RCS is shown below.

$$M_{rcs} = 0.014 M_{entry}$$

M_{rcs} – Weight of the RCS
M_{entry} – Entry weight of the vehicle = 44,090 lb

Evaluating the MER gives a weight of 617 lb or 280 kg. There is no TRF for the RCS system.

4.e Prime Power

Prime power for the overcarriage will be provided by batteries. Reference 3 from the Georgia Tech study will be used for the mass estimate. The MER is shown below.

$$M_{batt} = 216 + 952\left(\frac{N_{days}}{7}\right)$$

M_{batt} – Weight of batteries
N_{days} – Number of days in orbit = 350 sec = 0.004 days

Evaluating the MER gives the weight for the batteries as 217 lb or 98 kg. There is no TRF for prime power.

4.f Electrical Conversion & Distribution System

The electrical conversion and distribution (EC&D) system weight for the overcarriage is estimated using reference 1 from the Georgia Tech study. The MER is shown below.

$$M_{ecd} = 0.02\,M_{land}$$

M_{ecd} – Weight for the electrical conversion & distribution system
M_{entry} – Entry weight of the vehicle = 44,090 lb

Evaluating the MER gives the electrical conversion & distribution system weight at 882 lb. A TRF of 0.18 reduces this weight to 723 lb or 328 kg.

4.g Hydraulic Systems

The hydraulic systems mass on the overcarriage is based on reference 1 of the Georgia Tech study. The MER is shown below.

$$M_{hyd} = K_{hyd} S_{tot-cont} + K_e T_{vac-gimb}$$

M_{hyd} – Weight of hydraulic system
K_{hyd} – 1.23 for 5000 psi system
$S_{tot-cont}$ – Total control surface area = 42 ft^2
$S_{tot-cont}$ - Vacuum thrust of main engines = 0

It is assumed that the hydraulic system can use the same nitrogen gas that is used for the air bearings. This simplifies the design and negates the need for a dedicated hydraulic supply system.

The control surface area must include both sides of the body flap, resulting in twice the surface area. Evaluating the MER gives the weight of the hydraulic system as 52 lb or 23 kg. There is no TRF for hydraulics.

4.h Surface Control and Actuators

The surface control and actuators on the overcarriage are based on standard aircraft control systems. Reference 10a of the Georgia Tech study will be used to estimate the weight. The MER is given below.

$$M_{sca} = 2.6S_{bf} + 10$$

M_{sca} – Weight of surface control and actuators
S_{bf} – Surface area of body flap = 21 ft^2

Evaluating the MER gives a weight for the surface control and actuators of 65 lb or 29 kg. There is no TRF for the weight of the surface control and actuators.

4.i Avionics

The avionics for the overcarriage is based on Space Shuttle technology. Reference 6 of the Georgia Tech study will be used for the mass estimate. The MER is shown below.

$$M_{av} = 544 + 1067\left(\frac{N_{days}}{7}\right) + 3027\left(\frac{N_{crew}}{7}\right) + 0.27A_{body}$$

M_{av} – Weight of the avionics
N_{days} – Number of days spent on orbit = 0.004
N_{crew} – Number of crew = 0
A_{body} – Surface area of vehicle body = 679 ft^2

Evaluating the MER gives the weight for the avionics at 727.9 lb. A TRF of 0.5 reduces the weight to 364 lb or a mass of 165 kg.

4.j RCS Propellant

The RCS propellants are needed to perform reentry operations. Reference 3 from the Georgia Tech study will be used to estimate the weight of the RCS propellants. The MER is shown below.

$$M_{rcs-entry} = 0.00336 M_{entry}$$

$M_{rcs\text{-}entry}$ – Weight of the RCS reentry propellants
M_{entry} – Weight of the vehicle at reentry = 44,090 lb

Evaluating the MER gives the reentry propellant weight to be 148 lb or 67 kg.

4.k Ram Air Parafoil

The overcarriage is basically a blunt body design which uses a ram air parafoil for final approach and landing. After slowing down to subsonic speeds, the ram air parafoil goes through a five stage opening procedure in which the parafoil is deployed. Commercially available parafoils can safely land payloads from 20,000 lb to 30,000 lb with a 65 km/hr landing speed and a sink rate of 3.7 m/s (AS Airborne Systems, 2007). With a weight of approximately 900 lb including the shroud hardware, the ram air parafoil is a viable option for final approach and landing. With the addition of an airborne guidance unit the total weight increases to 1,260 lb or 572 kg.

The mass estimate for the overcarriage reentry subsystem is shown is table VII below.

Fuselage	= 629 kg
Body Flap	= 30 kg
Landing Gear	= 493 kg
RCS	= 280 kg
Prime Power	= 98 kg
EC&D	= 328 kg
Hydraulic Systems	= 23 kg
SCA	= 29 kg
Avionics	= 165 kg
RCS Propellant	= 67 kg
Ram Air Parafoil	= 572 kg
Total	= 2,714 kg

Table VII. Mass Estimate for Overcarriage Reentry Subsystem

5. Summary

The total mass estimate for the overcarriage and reentry subsystem is shown in table VIII below.

Ejector	= 912 kg
Overcarriage Frame	= 1,150 kg
Air Bearing/Wheel	= 3,076 kg
Reentry Subsystem	= 2,714 kg
Total	= 7,852 kg

Table VIII. Overcarriage Mass Estimate

The mass budget for the overcarriage was 20,000 kg. The total mass estimate for the overcarriage is 7,852 kg. As shown, the mass estimate is approximately 1/3 of the mass budget, leaving a substantial mass budget for design improvements.

6. Conclusion

The overcarriage is a load bearing structure which rides on top of the ribbon and carries the second stage launch vehicle down the ribbon to the launch position. The overcarriage and launch vehicle for the Space Track Launch System (STLS) make up the second stage of a two stage system.

The second stage is a liquid fueled vehicle designed to launch from the STLS. The launch vehicle attaches to an ejector which is attached to the overcarriage frame. Four tapered wheels are attached to the overcarriage frame. The wheels rest on top of the ribbon. The overcarriage and launch vehicle travel down the ribbon and are accelerated by the forces 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 launch vehicle proceeds into orbit. The overcarriage is launched from the ribbon and returns to the launch site to be refurbished and reused.

This paper addressed the initial design and mass estimate for the overcarriage. The initial design is two queen-post bridges connected by two box beam trusses. The ejector segments and truss assembly is connected to the port and starboard tanks of the second stage launch vehicle. After launch from the ribbon, the overcarriage is basically a reentry vehicle and requires all of the subsystems for a reentry spacecraft. The initial mass estimates of the overcarriage were based on an 80,000 kg second stage launch vehicle and a 20,000 kg overcarriage under a 6g load. The final mass estimate was 7,852 kg, resulting in a significant mass budget for design improvements.

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