Problem Set 5 Report
16.851 SATELLITE ENGINEERING

From: Students
To: Prof. Miller, Col. Keesee & Marilyn Good
Subject: PS5 Problem Report
Date: 11/14/2003

Subject: Preliminary Design of the Next Space Station
Topics: Cost, Structures, and Environment

Motivation

The US manned space program is entering an era of mutation, as NASA now has to deal with new challenges, after recent events such as the Columbia tragedy or the symbolical first "taikonaut" in space. It is clear that this New Deal and a revived international cooperation will create opportunities for space agencies to move the frontiers a little farther and extend the presence of man on orbit, possibly on board a new Space Station. This problem will deal with a rough first design of such a new Space Station.

Problem statement

You, a recent MIT grad, have been approached by NASA to design the next US Space Station. At the time, NASA's states that the main goals for the new Space Station design should be the minimization of cost. NASA has also developed the following requirements, which are to be applied towards the design of the station:

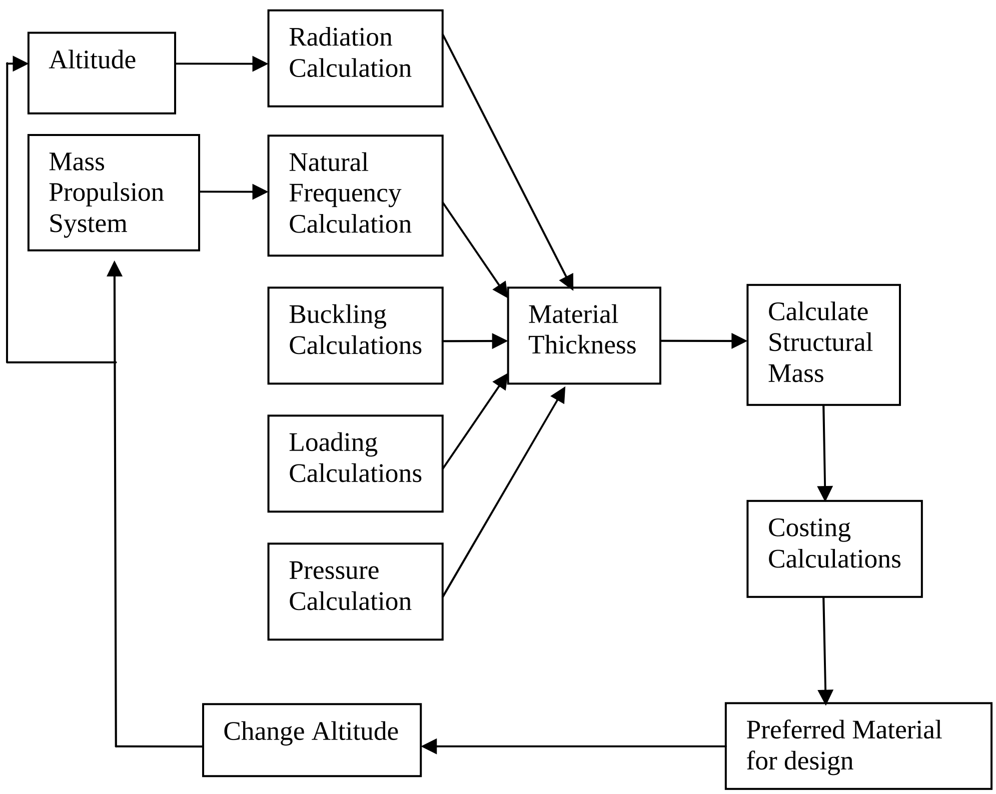
1. The crew area of the Space Station must be cylindrical in shape (20m long by 5m in diameter).
2. The Space Station may either be located at LEO (300km), GEO (36,000km), or at 8,000km (just within the two Van Allen Belts).
3. The inclination of the station must be zero degrees
4. You may choose from the following materials for the composition of the station: Al 2014-T6, Al 2024-T4, Lead (Pb), Titanium (Ti-Pure), High Strength Steel Gold (Au).[i]
5. Depending on which altitude the station is located at, the following are the available propulsion systems:
   LEO - 10,000kg Chemical system (LOX/H2)
   GEO - 1000kg Xenon ion propulsion system (XIPS)
   8,000km - 6,000kg Chemical system (LOX/H2)
6. The crew will be limited to an annual radiation exposure limit of 50 REMs, NASA-STD-3000 requirement.

7. The Station must be capable of sustaining launch loads, as well as maintaining a safety factor of 3.
8. It will cost ~$10K per kilogram to final orbit.
9. Assume a Research, Development, Test and Evaluation (RDT&E) cost of $200M.

What is the best material for the new Space Station? What is the preferred orbit altitude for the station? What is the resulting cost?

Approach

The general approach to the problem was to determine how changes in material selection for the space station were effected by environmental conditions and how these selections affected the cost of the space station. In order to visualize the approach to the problem, the following is a flow diagram for the problem set:



Problem Flow Diagram

The first step to the problem was to determine all the environmental factors due to the various target altitudes that would affect the space station. Due to the large number of factors that could affect the space station, the field of environmental factors was limited to radiation and drag. The environmental radiation has a direct effect on the design of the structure of the space station by placing a minimum requirement on the thickness of the structure. Drag however is a much more complicated problem and instead of determining the drag of the spacecraft a general requirement on the size of the space station's propulsion systems was provided in the problem statement. The purpose of this assignment was not to get into the finer points of drag and therefore generic sizes of propulsion systems were developed in order to save time and account for the varying conditions. One future addition to the problem would be to further refine the drag calculations and propulsion systems sizing for the space station.

Radiation considerations

Both Ionizing and non-ionizing radiation are present inside the spacecraft. Ionizing radiation is produced by the environment and can be extremely damaging to both spacecraft and humans. Non-ionizing radiation is man-made and is generally considered harmless.

Ionizing radiation consists of varying sizes of charged and uncharged particles and electromagnetic radiation. The charged particles consist of protons, electrons, alpha particles and HZE (High Z and Energy, where Z is the atomic number) particles[ii]. The uncharged particles are generally neutrons. The electromagnetic radiation consists of X-rays and Gamma rays. An important contribution of X-ray radiation is through the interaction of charged particles with the space station. The production of X-ray radiation in this manner is known as the Bremsstrahlung X-ray dose.

Ionizing radiation comes from three major sources: trapped radiation, galactic cosmic radiation, and solar particle event radiation. Trapped radiation is due to the Earth's magnetic field, which traps high-energy protons and electrons in bands, known as the Van Allen belts, around the Earth. Galactic cosmic radiation generally originates outside of the solar system and consists of high-energy atomic nuclei [ii]. Solar particle event radiation occurs in association with solar flares and consists primarily of high-energy protons released from the sun. The solar cycle has been found to vary in maximums around a highly regular 11-year cycle. Although, the spacecraft is affected by large amounts of radiation from varying sources, at this point, only the proton and electron radiation from the Van Allen belts is considered.

Trapped Radiation

Research into the intensity of the Van Allen belts began once it became obvious that there was a serious potential for harm to humans and to equipment. For this reason, a great deal of time and money was spent in the 1960's to exact an accurate picture of the radiation environment.

The Van Allen belts mostly consist of electrons and protons with varying energy levels, which can cause a range of damage to the spacecraft, as shown in Table 1. As one can see, radiation damage occurs with protons energies greater than 10 MeV and electrons with energies greater than 1 MeV, which is the regime that will be considered in this report.

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Table 1: Effects of Different Particle Energies on the Spacecraft[iii]

TABLE I
EFFECTS SUMMARY

Particle	Energy	Typical Effects
proton	100 keV–1 MeV	surface damage;
proton	1–10 MeV	surface material & solar cell damage;
proton	10–100 MeV	radiation damage (both ionizing and nonionizing); background in sensors;
proton	>50 MeV	single-event effects; nuclear interaction-caused background;
electron	10–100 keV	surface electrostatic charging;
	>100 keV	deep-dielectric charging background in sensors solar cell damage;
	>1 MeV	radiation damage (ionizing);

During the 1960's, a great deal of work was done to understand how the Van Allen belts vary with position and time. NASA created two programs, AE8 and AP8, which calculate the electron flux and proton flux, respectively. Both AE8 and AP8 have versions corresponding to solar minimum and solar maximum data. During a solar maximum, atmospheric density increases which causes the protons at lower altitudes to collide with the atmosphere, which decreases the proton flux. Therefore, the code corresponding to a solar minimum is generally used as a worst-case approximation.

It is important to note that the models developed by NASA have been criticized for inaccuracies. Some important reasons for discrepancies in the models are that the radiation environment, especially at high altitudes is extremely dynamic. Since the calculations are based on a 1960 magnetic field model, they are not necessarily representative of the environment today. In addition, the models only predict solar minimum and solar maximum variations, without accounting for how the radiation varies over the 11-year cycle [iii]. Although other programs have been created to more accurately represent the radiation environment of the Van Allen belts, none have been shown to be completely successful and the NASA models AE8 and AP8 are still the most widely used method for calculating the radiation environment [iii].

The NASA model calculates the electron and proton fluxes as a function of energy, L-value and the ratio, B/B_0. For AP8, proton energies are in the range of 100 keV to greater than 400 MeV. For AE8, electron energies are in the range of 40 keV to 5 MeV. The L-value is the equatorial radius, measured in Earth radii and can be calculated from the equation

$$L = R/\cos^2\lambda$$

where R is the distance in Earth Radii, and λ is the magnetic latitude. The ratio B/B_0 is the ratio of the magnetic field intensity to the magnetic field at the equator on the Earth's surface ($B_0 = 0.3$ gauss). The magnetic field intensity is a function of both the radial distance, in Earth radii and the magnetic latitude.

$$B/B_0 = (1+\cos^2\lambda)^{1/2}/R^3$$

Surface contours using AE8Min and AE8Max are given to evaluate electron and proton fluxes, respectively, as a function of radius and magnetic latitude. Figure 1 represents the proton flux for protons with energies greater than 10 MeV. Figure 2 represents the electron flux for electrons with energies greater than 1 MeV.

Fig. 1: Proton Flux for protons > 10MeV[iii]

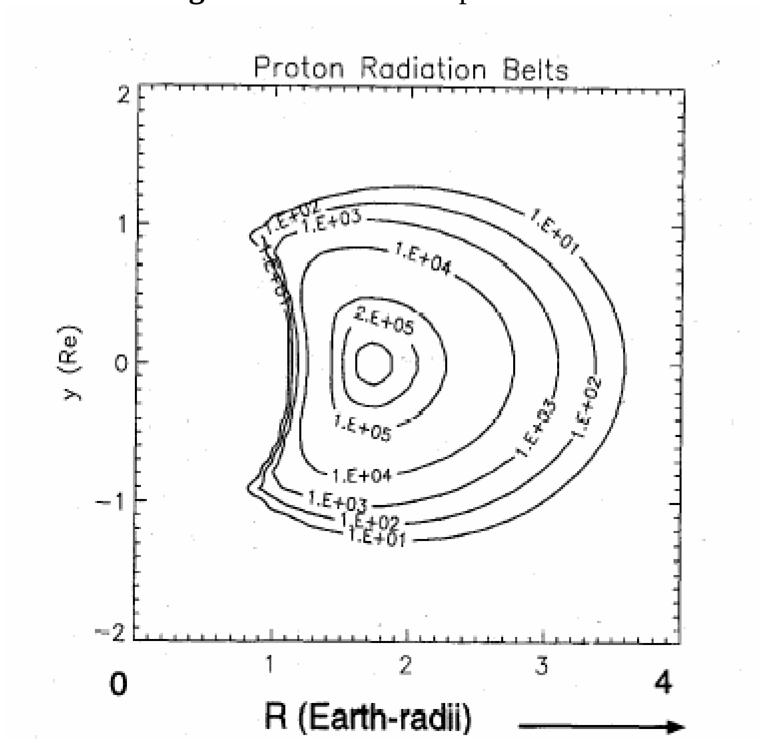
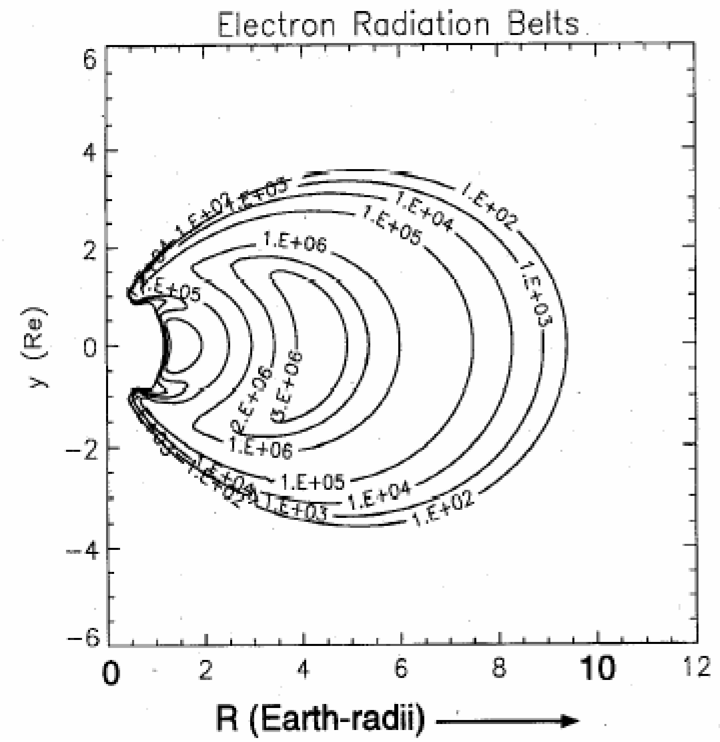
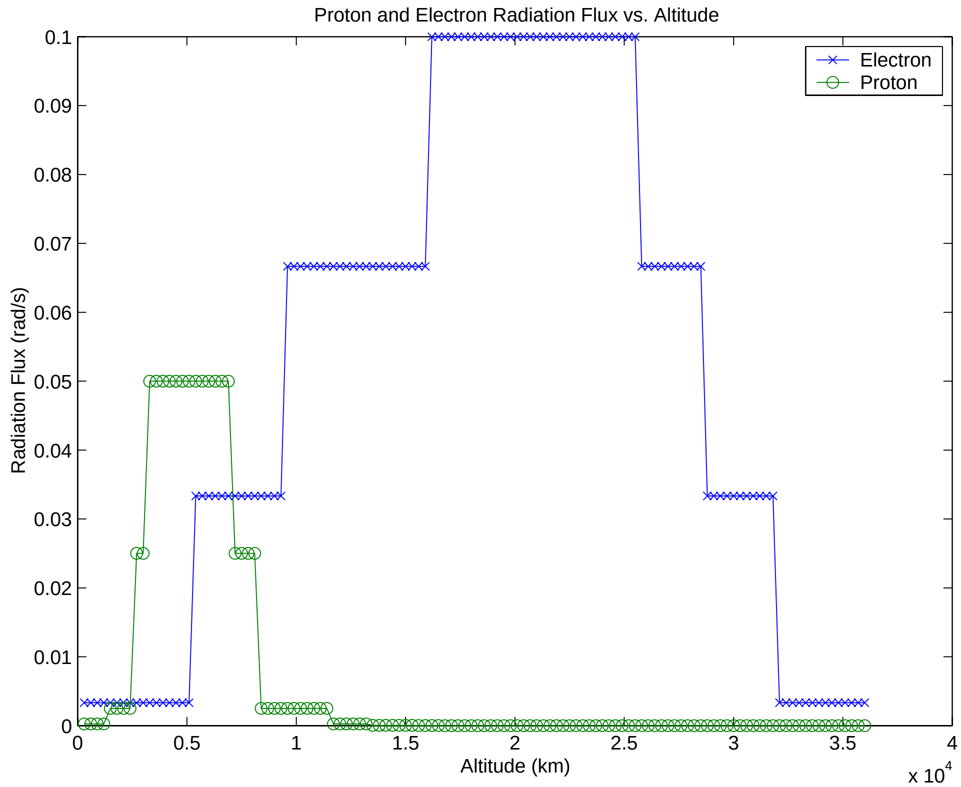


Fig. 2: Electron Flux for Electrons >1 MeV [iii]



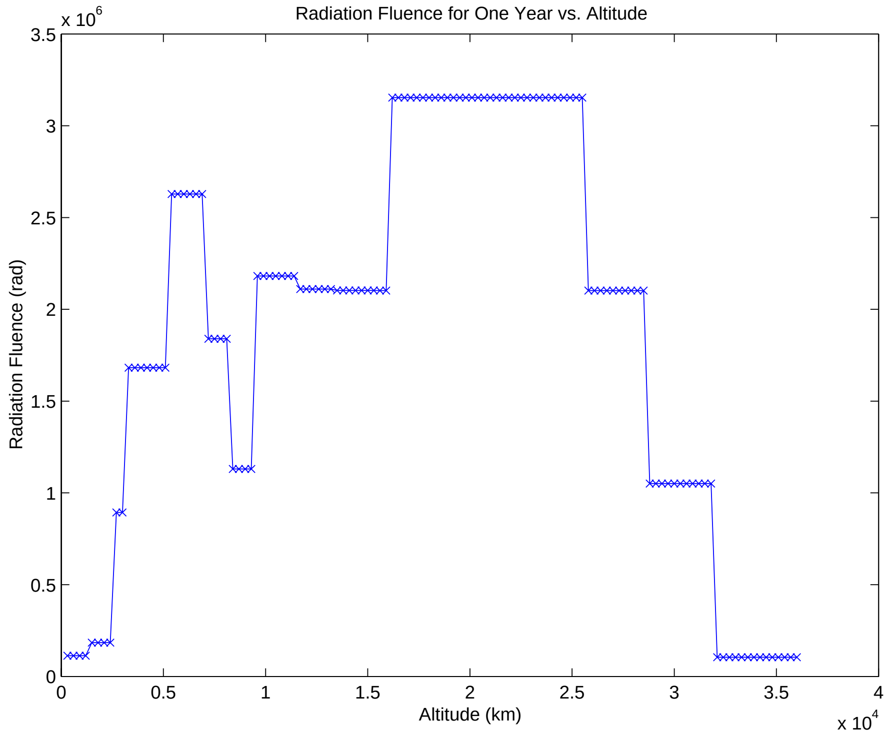
For the calculations required in this report, an estimate of the radiation flux for a given range of Earth radii are taken from Figures 1 and 2 by inspection. Figure 3 shows the worst-case radiation doses from both electrons and protons for a range of Earth radii. Although, Figure 3 does not span the entire range given in Figures 1 and 2, it yields a representative sample for the orbits considered in this memo.

Fig. 3: Proton and Electron Radiation Flux for Various Altitudes



The radiation fluence is the integral of flux over time. For a circular orbit, the flux is considered constant, since the altitude is constant. Thus the radiation fluence is just the radiation flux time the time. Figure 4 gives the radiation fluence in a year for a range of altitudes.

Fig. 4: Radiation Fluence Over one Year for Various Altitudes



For the purposes of this research, a script was created that calculates the flux due to each particle and the total fluence accumulated in a specified time period (one year for this work). In this investigation, the primary interest is for three circular orbits; at LEO (300 km alt), at MEO (8000 km alt), and at GEO (36000 km alt). Table 2 gives the calculated flux and fluence over one year for each orbit considered.

Table 2: Radiation flux and fluence for three circular orbits

Orbit	Altitude (km)	Radiation fluence (rad)	Electron Flux (rad/s)	Proton Flux (rad/s)
LEO	300	113,004	.0033	.00025
MEO	8000	1,839,600	.033	.025
GEO	36000	105120	.0033	0

The total flux, which is the sum of both the electron flux and proton flux, is the flux in the near environment of the spacecraft. However, this is not equivalent to the radiation environment within the spacecraft. To determine the amount of radiation inside the spacecraft, a calculation of the radiation transport through the spacecraft shield would need to be performed[iv]. This calculation, however, is quite involved and beyond the scope of this report.

Radiation shielding is necessary in order to limit equipment and humans from over-exposure to radiation. According to NASA regulations, the maximum amount of radiation a human can absorb in a year, the dose equivalent (DE), is 50 REM. In order to determine the dose equivalent from the radiation dose (D), the quality factor (Q) of the type of radiation must be accounted for, such that

$$DE = Q*D$$

where Q varies for different radiation sources. Table 3 lists values for Q depending on different radiation sources.

Table 3: Quality Factors for Different Radiation Sources [iiv]

Quality Factors	
Type of radiation	**Quality factor, Q**
X-rays	1
Gamma rays and bremsstrahlung	1
Beta particles, electrons, 1.0 MeV	1
Beta particles, 1.0 MeV	1
Neutrons, thermal energy	2.8
Neutrons, 0.0001 MeV	2.2
Neutrons, 0.005 MeV	2.4
Neutrons, 0.02 MeV	5
Neutrons, 0.5 MeV	10.2
Neutrons, 1.0 MeV	10.5
Neutrons, 10.0 MeV	6.4
Protons, greater than 100 MeV	1-2
Protons, 1.0 MeV	8.5
Protons, 0.1 MeV	10
Alpha particles (helium nuclei), 5 MeV	15
Alpha particles, 1 MeV	20

Radiation experts determine the quality factor after looking at the effects of different types of radiation on tissue samples[vi].

The transport of radiation from the space environment and into human tissue is beyond the scope of this research. However, following NASA standards, an estimation of the amount of shielding required for each orbit will be given. Referring to Table 2, the amount of radiation accumulated over one year in MEO is greater than 10 times the amount of radiation accumulated in LEO or GEO. Thus, the amount of shielding should be greater. To compensate for the higher radiation levels, a shielding of 5 gm/cm^2 will be used for LEO and GEO orbits and a shielding of 7 gm/cm^2 of MEO.

Material sizing

Once all the environmental factors were taken into consideration, the next step was to determine the structural thickness required for the space station. Since the shape and internal size of the space station was defined in the problem statement the only unknown about the size of the structure would be the thickness. Several different cases were studied each of which had a different effects on the minimum thickness required for the structure. The various cases were: natural frequency requirements, launch tensile loads and compressive loads (buckling), Internal pressure stress and Radiation exposure/shielding.

Sizing for Rigidity to Meet the Natural Frequency Requirement

The model for the calculation of natural frequencies is the "complex" model defined in Figure 11-42 in SMAD, where the tip mass is the mass of the propulsion system. The natural frequencies of the space station are the following:

$$f_{nat}^{lat} = 0.276\sqrt{\frac{EI}{m_p L^3 + 0.236 m_s^* L^3}} \qquad (1)$$

$$f_{nat}^{axial} = 0.160\sqrt{\frac{AE}{m_p L + 0.333 m_s^* L}} \qquad (2)$$

where f_{nat}^{lat} is the natural lateral frequency and f_{nat}^{axial} is the natural axial frequency. E is the modulus of elasticity of the structure and I the area momentum of inertia of the structure's cross-section of area A. m_p is the mass of the propulsion system (tip mass), and $m_s^*(t)$ is the mass of the structure, augmented by the mass of the other systems distributed on the structure. The propulsion system does not fall in this category, because its mass was assumed concentrated at one end of the structure, rather than distributed on it. The following assumption was made: the mass of the structure is 30% of the mass of the whole spacecraft, which is expressed by the following equation:

$$0.3\left(m_p + m_s^*(t)\right) = m_s(t) \qquad (3)$$

We can solve the equation to get $m_s^*(t)$:

$$m_s^*(t) = \frac{m_s(t)}{0.3} - m_p \qquad (4)$$

We can substitute m_s, I and A by their expressions depending on the geometry of the structure (D is the diameter, L is the length and t the thickness of the structure, ρ is the density of the material):

$$I = \pi\left(D/2\right)^3 t \qquad (5)$$

$$A = \pi D t \qquad (6)$$

$$m_s = \rho\, L\, \pi D\, t \qquad (7)$$

and then solve in t to get the minimum thickness that fits the two frequency requirements:

$$t_{\min}^{lat} = \frac{m_p L^3 \left(f_{imp}^{lat}\right)^2}{\pi D} \frac{.236 - 1}{\frac{.236}{.3} \rho L^4 \left(f_{imp}^{lat}\right)^2 - \frac{.276^2}{8} E D^2} \quad (8)$$

$$t_{\min}^{axial} = \frac{.667 \left(f_{imp}^{axial}\right)^2 m_p L}{\pi D \left[.16^2 E - \frac{.333}{.3} \rho L^2 \left(f_{imp}^{axial}\right)^2 \right]} \quad (9)$$

$$t_{\min} = \max\left(t_{\min}^{lat}, t_{\min}^{axial}\right) \quad (10)$$

where f_{imp}^{lat} and f_{imp}^{axial} are the frequencies imposed by the launch vehicle.

Sizing for Axial Tensile Stress

We can use the following equation to calculate the ultimate axial load P_{eq} on the structure (depending on the value for the thickness t):

$$P_{eq}(t) = f_s \left(P_{axial}(t) + \frac{2M(t)}{D/2} \right) \quad (11)$$

where f_s is the factor of safety, P_{axial} is the actual axial load and M is the bending moment. P_{axial} and M are determined by the following equations:

$$P_{axial}(t) = f_{axial}^{load} g \left(m_p + m_s^*(t)\right) \quad (12)$$

$$M(t) = f_M^{load} g \left(m_p L + m_s^*(t) \frac{L}{2} \right) \quad (13)$$

where f_{axial}^{load} and f_M^{load} are respectively the load factors relative to the axial load and the bending moment.

We can then derive the ultimate axial stress σ_{axial}:

$$\sigma_{axial}(t) = \frac{P_{eq}(t)}{A(t)} \quad (14)$$

where $A(t)$ is the section area calculated from equation (6). This value of axial stress must never be greater than the ultimate tensile strength F_{tu} of the material, so we can solve the previous equation in t to get the minimum value of the thickness meeting the axial stress requirement:

$$t_{\min}^{axial\ stress} = \frac{2 f_s g m_p f_M^{load} \frac{L}{D}}{\pi D F_{tu} - \frac{f_s g \pi \rho L D}{0.3} \left(f_{axial}^{load} + 2 f_M^{load} \frac{L}{D} \right)} \quad (15)$$

The module chooses the more conservative value of minimum thickness between $t_{\min}^{axial\ stress}$ and the previously calculated $t_{\min}$:

$$t_{\min} = \max\left(t_{\min}^{axial\ stress}, t_{\min}\right) \quad (16)$$

Sizing for Compressive Strength

The equation for cylinder buckling stress σ_{cr} is the following:

$$\sigma_{cr}(t) = 0.6\gamma(t)\frac{Et}{D/2} \tag{17}$$

where $\gamma(t)$ is derived from the equations:

$$\gamma(t) = 1.0 - 0.901\left(1.0 - e^{-\varphi(t)}\right) \tag{18}$$

$$\varphi(t) = \frac{1}{16}\sqrt{\frac{D/2}{t}} \tag{19}$$

The value of σ_{cr} must always be greater than the applied compressive stress σ_{axial} (from equation 14), so solving the following equations in *t* gives us the minimum thickness $t_{\min}^{comp}$ of the structure (as $\sigma_{cr}(t)$ increases when *t* increases and $\sigma_{axial}(t)$ decreases when *t* increases):

$$\sigma_{cr}(t) = \sigma_{axial}(t) \tag{20}$$

$$\sigma_{cr}(t) = 0.6\frac{2E\ t}{D}\left(1.0 - 0.901\left(1.0 - e^{-\frac{1}{16}\sqrt{\frac{D}{2\,t}}}\right)\right) \tag{21}$$

$$\sigma_{axial}(t) = \frac{f_s\left(gm_p\left(f_{axial}^{load} + \frac{4}{D}f_M^{load}L\right) + g\left(f_{axial}^{load} + \frac{2}{D}f_M^{load}L\right)\left(\frac{\rho\, L\ \pi D\ t}{0.3} - m_p\right)\right)}{\pi D\ t} \tag{22}$$

The Matlab module can solve this non-linear equation by finding the minimum of the following function *f*:

$$f = abs\left(\sigma_{cr}(t) - \sigma_{axial}(t)\right) \tag{23}$$

Then the modules chooses the more conservative value of minimum thickness between $t_{\min}^{comp}$ and the previously calculated $t_{\min}$:

$$t_{\min} = \max\left(t_{\min}^{comp},\, t_{\min}\right) \tag{24}$$

Sizing for Internal Pressure

Stresses due to internal pressure are considered separately from other stresses from load factors, because these two sources of stress are time-inconsistent: load stresses take place during launch, whereas internal pressure stresses are only relevant once in orbit, when external atmospheric pressure is considerably lower than internal pressure. The hoop stress σ_h in the space station can be calculated through the following equation:

$$\sigma_h = \frac{p\,D/2}{t} \tag{25}$$

where *p* is the internal pressure. The value of σ_h must stay beyond the value F_{tu} of the ultimate tensile strength of the material, so we can derive the minimum required thickness of the structure:

$$t_{\min}^{pressure} = \frac{p\,D/2}{F_{tu}} \tag{26}$$

The module then chooses the more conservative value of minimum thickness between $t_{\min}^{pressure}$ and the previously calculated $t_{\min}$:

$$t_{\min} = \max\left(t_{\min}^{pressure}, t_{\min}\right) \tag{27}$$

Sizing for Radiation Shielding

Given the surface mass density δ required to protect the crew from radiation, the module can easily derive the corresponding thickness:

$$t_{\min}^{rad} = \frac{\delta}{\rho} \tag{28}$$

where ρ is the density of the material considered. The module then once again chooses the more conservative value of minimum thickness between $t_{\min}^{rad}$ and the previously calculated $t_{\min}$:

$$t_{\min} = \max\left(t_{\min}^{rad}, t_{\min}\right) \tag{29}$$

The above calculations for the thickness of the structure were done for the different types of material. This resulted in a different required minimum thickness and consequently structural mass for each type of material.

Inputs

Table 4 Input Parameters and Requirements for the Sample Run

Launch Lateral Frequency [Hz]	f_{imp}^{lat}	10
Launch Axial Frequency [Hz]	f_{imp}^{axial}	25
Length of the Structure [m]	L	20
Diameter of the Structure [m]	D	5
Axial Launch Load Factor	f_{axial}^{load}	6.5
Launch Factor Relative to Bending Momentum	f_{M}^{load}	3
Safety Factor	f_s	3
Internal Pressure [atm]	P	1

Outputs

Table 5 Sample Output of the Structure Module

Material	Thickness [cm]	Structure Mass [10^3 kg]	Limiting Factor
LEO (300km)			
Al 2014-T6	2.01	17.7	Compressive Stress
Al 2024-T4	1.99	17.5	Compressive Stress
Pb	24.2	863.0	Compressive Stress
Ti pure	2.13	30.2	Compressive Stress
High Strength Steel	4.66	115.1	Tensile Stress
Au	8.74	530.6	Compressive Stress
MEO (8,000km)			
Al 2014-T6	2.50	22.0	Radiation Shielding
Al 2024-T4	2.50	22.0	Radiation Shielding
Pb	24.2	862.0	Compressive Stress
Ti pure	2.09	29.6	Compressive Stress
High Strength Steel	2.80	69.0	Tensile Stress
Au	8.73	529.8	Compressive Stress
GEO (36,000km)			
Al 2014-T6	1.84	16.2	Compressive Stress
Al 2024-T4	1.83	16.1	Compressive Stress
Pb	24.2	860.9	Compressive Stress
Ti pure	2.02	28.7	Compressive Stress
High Strength Steel	1.84	45.5	Compressive Stress
Au	8.71	528.8	Compressive Stress

One can see from that table that, as far as mass is concerned, Aluminum is always the best choice. Mechanical properties of Lead and Gold are so poor that they would require high (even very high) thickness and mass to handle compressive strength and buckling hazard during the launch phase. High Strength Steel does better, but it is still too heavy.

Titanium is an interesting material: its density is too high (compared to its mechanical properties) to be preferred to Aluminum at LEO and GEO. But as radiation levels and shielding requirements get higher at MEO, the thickness of the Aluminum structure is no longer driven by mechanics: radiation shielding become the limiting factor. As a consequence, the required thickness becomes greater than the thickness of a Titanium structure, which design is still driven by mechanical constraints. Total structure mass is still a little lower for Aluminum, but more stringent radiation shielding requirements would probably make Titanium become a better choice than Aluminum. Cost also has to be taken into account, since Aluminum is much cheaper than Titanium.

Once the mass of the structural component for the different materials was calculated, the next step was to use the mass of the structure to evaluate the cost of the station.

Station Cost Estimate

A space station has a large number of subsystems: Structures, Thermal, Environmental, Reaction Control, Avionics, Propulsion, etc. Simply basing the design and cost of the space station off of one of these subsystems would be both inaccurate and unintelligent. Then in order to price the design of the space station the various subsystem masses of the space station were estimated. All of the calculations up until this point have dealt with the development of the structural components of the space station. The next step was to determine the mass of the entire space station from the mass of the structural components. In reviewing SMAD it was found that it is common for approximately 25-30% of the entire mass of the system to be the structural mass. Therefore the mass of the entire station was found by applying a structural mass ration of .3 to the mass of the station structure. In order to determine the mass of the remaining station subsystems various estimated mass ratios were used.

Subsystem Mass Estimate

Estimated mass fractions were used to give a relative size of the various subsystems of the space station. The following is a list of the mass fractions used. It is important to note that this is not a complete list; the list reflects the cost estimating relationships that were available at the time. Future additions to the problem set could be the addition of more subsystems estimates and the refinement of current subsystem estimates.

Table 6: Mass Fraction Estimates

Mass Margin	0.2
Avionics Mass Fraction	0.05
Structural Mass Fraction	0.3
Thermal Mass Fraction	0.05
Power Mass Fraction	0.2
Attitude Mass Fraction	0.1
Reaction Control Mass Fraction	0.1

The estimated total mass of the space station was calculated by dividing the mass of the structural components by the structural mass fraction. Once the estimated mass of the space station was determined the next step was to apply the mass fraction estimates for each subsystem in order to determine the mass of all the subsystems. Note that the propulsion system mass is not included among the list of mass fractions. The propulsion system is assumed to fall under the marginal mass parameter, which is calculated by the mass margin. Once all the subsystem masses for the entire station were calculated the next step was to estimate their costs. This procedure will be accomplished through the use of cost estimating relationships, which are based on the mass of each subsystem.

Subsystem Cost Estimate

Cost Estimating Relations (CERs) based on total system mass were used to price the various subsystems of the space station. The CERs took on the form of a power function with the form:

$$\$K2002 = A\left(Mass_{Subsystem}\{Kg\}\right)^{B}$$

Table 7: Values of A and B for the various subsystems.[vii]

	Nonrecurring		First Unit	
Item	**A**	**B**	**A**	**B**
Structure (complex)	**587.5**	**0.623**	**77.1**	**0.789**
Power System	**104.6**	**0.893**	**52.36**	**0.894**
Avionics System	**1382**	**0.762**	**203.1**	**0.971**
Attitude Control System	**798.6**	**0.768**	**177.2**	**0.888**
Reaction Control System	**557.9**	**0.667**	**337.4**	**0.536**
Thermal Control System	**341**	**0.572**	**129.1**	**0.584**
Solid prop. motor	**49.82**	**1.000**	**149.5**	**1.000**

Space Station Cost Estimate

Once the cost for each subsystem was calculated, the costs of each subsystem were then summed together to give a total system cost. The total system cost was then summed with the material costs, research and development costs, and launch costs in order to determine the estimated total space station costs. A list describing the cost of each material is shown below. The estimated space station costs for each material were then compared and the material that provided the minimal cost was selected. The entire process was then repeated for each of the remaining orbital altitudes. The final result was the material the provided the lowest cost space station and its corresponding orbital altitude.

Table 8: Cost of Different Materials per Kilogram

Material	Cost ($/Kg)
Al 2014-T6	1.43
Al 2024-T4	1.43
Lead-Pb	0.99
Titanium-Pure	9.35
High Strength Steel	0.396
Gold-Au	9630

Results

The following are the results of the sample runs for orbital altitudes corresponding to LEO, MEO, and GEO.

Table 9: Cost Breakdown

Altitude	Radiation requirement (g/cm^2)	Mass Propulsion system	Material	Minimum required thickness (m)	Limiting Factor	Structural Mass (Kg)	System Mass (Kg)	Station Costs ($M2002)
LEO	5	10,000 kg	*Al 2014-T6*	0.0201	Compressive Stress	17,664	58,880	$6,260
			Al 2024-T4	**0.0199**	**Compressive Stress**	**17,488**	**58,293**	**$6,230**
			Lead-Pb	0.2422	Compressive Stress	862,960	2,876,533	$120,100
			Titanium-Pure	0.0213	Compressive Stress	30,253	100,843	$8,600
			High Strength Steel	0.0466	Tensile Stress	115,060	383,533	$22,300
			Gold-Au	0.0874	Compressive Stress	530,590	1,768,633	$83,900
MEO	7	6,000 kg	***Al 2014-T6***	**0.0250**	**Radiation Shielding**	**21,991**	**73,303**	**$6,290**
			Al 2024-T4	**0.0250**	**Radiation Shielding**	**21,991**	**73,303**	**$6,290**
			Lead-Pb	0.2420	Compressive Stress	862,010	2,873,367	$119,200
			Titanium-Pure	0.0209	Compressive Stress	29,576	98,587	$7,700
			High Strength Steel	0.0280	Tensile Stress	69,038	230,127	$14,350
			Gold-Au	0.0873	Compressive Stress	529,820	1,766,067	$83,000
GEO	5	1,000 kg	*Al 2014-T6*	0.0184	Compressive Stress	16,215	54,050	$4,190
			Al 2024-T4	**0.0183**	**Compressive Stress**	**16,057**	**53,523**	**$4,160**
			Lead-Pb	0.2417	Compressive Stress	860,930	2,869,767	$118,057
			Titanium-Pure	0.0202	Compressive Stress	28,662	95,540	$6,500
			High Strength Steel	0.0184	Compressive Stress	45,491	151,637	$9,500
			Gold-Au	0.0871	Compressive Stress	528,800	1,762,667	$81,900

After all the calculations had been completed, the preferred material for the construction of the space station was Al 2024-T4 with a corresponding structural mass of 16,057kg, a total station mass of 53,523kg, a total system cost of $4,160 in $M2002, and to be located at GEO. Although Al 2024-T6 was the preferred material given any orbital altitude, it is important to note that the limiting factors into the sizing of all the structural component variations was not always the same for each material at each orbital location.

Validation

In order to verify the realism of the spreadsheet, the results were compared with NASA's Advanced Missions Cost Model. The estimator can be found at http://www.jsc.nasa.gov/bu2/AMCM.html. The estimator accepts a mission type and the total mass of the system and outputs the total costs in FY$M1999.

In order to compare the prices of the two designs on the same basis the cost of NASA's cost estimator is computed in $2002 dollars by the following equation with a discount rate of 5%.

$$Cost_{2002} = Cost_{1999}(1 + Rate)^{(2002-1999)}$$

NASA's Cost Model, with a mission type = 'Manned Habitat' and a Total Mass of 117,997lbs, estimated the price of that space station at $4,281 in $M1999, this corresponds to $4,955 in $M2002.

Another cost estimator was used in order to compare the results of the problem set. Very much like the CERs used to price the subsystems, a power function was used to estimate the price of the station. The power function has the following form[viii]:

$$C\{\$M\,2002\} = A(Mass\{Kg\})^{B}$$

$$Cost_{Non-Recurring} = 18.06(Mass)^{0.55}$$

$$Cost_{Recurring} = 0.5686(Mass)^{.662}$$

The above cost estimation results in a total cost of $7,969 in $M2002 for a space station with mass of 53,523 kg.

The result of NASA's cost estimator was $4.9B, while our estimator resulted in cost calculation of $4.1B. However if NASA had a discount rate of 0% then our calculation results and NASA estimator's result are even more accurate: $4.1B and $4.2B respectively. Overall the two results are very accurate considering the scope of the problem.

A sample run of all the calculations can be found as a supplement to this report.

Future Work

The cost estimate provided in this report is a first level estimate of the cost for a station. Future work for this topic would include a second level estimate of the cost parameters to more clearly define the environment and structure. For instance, a better definition of the radiation environment, including other sources of radiation, might change shielding requirements for some orbits. In addition, a better understanding of the factors that affect the propulsion system mass, such as drag, would help refine the problem. Also, a second level look at materials, such as two materials for shielding might improve the amount of mass for the same amount of protection.

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[ii] *Vette, J. L.* AE/AP Trapped Particle Flux Maps 1966-1980*, NASA GSFC, Greenbelt, Maryland 20771*.

[iii] Daly, E. J., Lemaire, J. Heynderickx, D., Rodgers, D. J., *Problems with Models of the Radiation Belts*, IEEE Transactions on Nuclear Science, Vol. 43, No.2, April 1996.

[iv] Fortescue, P., Stark, J., *Spacecraft Systems Engineering*, John Wiley and Sons, January 2001, New York, New York.

[v] NASA-STD-3000. *Man-Systems Integration Standards*, Revision B, July 1995

[vi] Vana, N. et al. *Measurements of Absorbed Dose and Average LET in Space Station MIR and During Space Shuttle Missions*, Austrian Society of Aerospace Medicine

[vii] Akin, Dave. *Advanced Costing*, Lecture Notes. ENAE483 Fall 2002.

[viii] Akin, Dave. *Costing*, Lecture Notes. ENAE483 Fall 2002.

Material

	$/Kg	density (Kg/m^3)	density (g/cm^3)	Ultimate -Tension (Mpa)	Ultimate -Shear (Mpa)	E (Mpa)
Al 2014-T6	1.43	2800	2.8	455	275	72000
Al 2024-T4	1.43	2800	2.8	470	280	73000
Pb	0.99	11340	11.34	18	***9***	14000
Ti-Pure	9.35	4511	4.511	551.5	***275.75***	102000
High Strength Steel	0.396	7860	7.86	480	***240***	200000
Au	9630	19320	19.32	120	***60***	74400

Bolded Values are assumed to be equal to 1/2 Ultimate Tension

***************Change Only the Fields in Blue***************

Constants

		MERs	
Cost $/Kg to orbit	10000	Mass Margin	0.2
Proplusion Mass (Kg)	1000	Avionics Mass Fraction	0.05
Cost - Research, Development,		Strutural Mass Fraction	0.3
Test and Evaluation (RDT&E)	200000000	Thermal Mass Fraction	0.05
		Power Mass Fraction	0.2
		Attitude Mass Fraction	0.1
		Reaction Control Mass Fraction	0.1

Material

	Mass (Kg)	Total System Mass	Material costs	Total System costs ($M)
Al 2014-T6	16,215	54050	23187.45	4187.880897
Al 2024-T4	16,057	53523	22961.51	4156.902819
Pb	860,930	2869767	852320.7	118057.0692
Ti-Pure	28,662	95540	267989.7	6521.90948
High Strength Steel	45,491	151637	18014.436	9464.82067
Au	528,800	1762667	5092344000	81866.0333

CERs

	Nonrecurring		First Unit	
Item	**A**	**B**	**A**	**B**
Structure (complex)	587.5	0.623	77.1	0.789
Power System	104.6	0.893	52.36	0.894
Avionics System	1382	0.762	203.1	0.971
Attitude Control System	798.6	0.768	177.2	0.888
Reaction Control System	557.9	0.667	337.4	0.536
Thermal Control System	341	0.572	129.1	0.584
Solid prop. motor	49.82	1	149.5	1

Costs

Al 2014-T6

Systems Level Components

	Non-recurring ($K2002)	1st Unit ($K2002)	Total
Solid Motor	49,820	149,500	199,320,000
Structure	246,483	161,688	408,170,921
Thermal control	31,313	13,034	44,346,968
Power System	418,541	211,466	630,006,659
Avionics	569,526	436,470	1,005,995,961
Attitude Control	587,647	365,752	953,398,489
Reaction Control	172,318	33,801	206,118,712
Vehicle Total			3,447,357,710
Launch Costs			540,500,000

Al 2024-T4

Systems Level Components

	Non-recurring	1st Unit ($K2002)	Total
Solid Motor	49,820	149,500	199,320,000
Structure	244,983	160,444	405,427,521
Thermal control	31,138	12,960	44,097,755
Power System	414,897	209,623	624,519,768
Avionics	565,292	432,340	997,632,080
Attitude Control	583,244	362,585	945,829,395
Reaction Control	171,196	33,624	204,820,006
Vehicle Total			3,421,646,524
Launch Costs			535,233,333

Pb

Systems Level Components

	Non-recurring	1st Unit ($K2002)	Total
Solid Motor	49,820	149,500	199,320,000
Structure	2,927,473	3,713,163	6,640,635,503
Thermal control	303,706	132,589	436,294,957
Power System	14,528,088	7,369,454	21,897,542,198
Avionics	11,749,037	20,652,795	32,401,832,339
Attitude Control	12,415,250	12,446,048	24,861,298,871
Reaction Control	2,437,474	284,152	2,721,626,327
Vehicle Total			89,158,550,195
Launch Costs			28,697,666,667

Ti-Pure

Systems Level Components

	Non-recurring	1st Unit ($K2002)	Total
Solid Motor	49,820	149,500	199,320,000
Structure	351,487	253,437	604,923,966
Thermal control	43,374	18,178	61,552,455
Power System	696,076	351,889	1,047,965,660
Avionics	879,072	758,874	1,637,945,758
Attitude Control	910,147	606,552	1,516,699,290
Reaction Control	251,965	45,870	297,834,362
Vehicle Total			5,366,241,490
Launch Costs			955,400,000

High Strength Steel

Systems Level Components

	Non-recurring	1st Unit ($K2002)	Total
Solid Motor	49,820	149,500	199,320,000
Structure	468,701	364,886	833,586,856
Thermal control	56,492	23,808	80,299,311
Power System	1,051,501	531,814	1,583,314,491
Avionics	1,249,960	1,188,422	2,438,381,751
Attitude Control	1,297,738	914,151	2,211,888,659
Reaction Control	342,888	58,757	401,644,922
Vehicle Total			7,748,435,989
Launch Costs			1,516,366,667

Au

Systems Level Components

	Non-recurring	1st Unit ($K2002)	Total
Solid Motor	49,820	149,500	199,320,000
Structure	2,160,819	2,527,734	4,688,553,022
Thermal control	229,813	99,744	329,557,296
Power System	9,401,160	4,766,467	14,167,627,332
Avionics	8,104,102	12,865,926	20,970,027,651
Attitude Control	8,538,626	8,073,519	16,612,144,983
Reaction Control	1,760,970	218,823	1,979,792,348
Vehicle Total			58,947,022,632
Launch Costs			17,626,666,667

```
function [material, thickness, mass,
limiting_factor]=DesignStructure(frequency_lat, frequency_axial, load_axial,
load_M, fs, p, altitude, L, D, mat);

% Function designing the structure of the crew area
% Inputs:
%     frequency_lat     [Hz] lateral frequency imposed by the launch vehicle
%     frequency_axial [Hz] axial frequency imposed by the launch vehicle
%     load_axial      axial load factor
%     load_M                load factor relative to bending moment
%   fs              safety factor
%     p               [Pa] internal pressure
%   altitude        structure describing the altitudes to be considered:
%       altidute(i).description     [string] description of altitude i
%       altitude(i).mp      [kg] mass of the propulsion system at altitude i
%       altitude(i).shield  [kg/m2] shielding requirement at altitude i
%     L               [m] length of the crew area
%     D                   [m] diameter of the crew area
%   mat             structure containing the list of materials to be
%                       considered and their characteristics:
%       mat(i).name    string containing the name of material i
%       mat(i).rho     [kg/m3] density of material i
%       mat(i).Ftu     [N/m2] allowable tensile ultimate stress
%       mat(i).E       [N/m2] Young's modulus
% Output:
%     material        material chosen (minimizing mass, which is not optimal
because cost is an important factor)
%   thickness         [m] thickness of the crew area
%   mass            [kg] total mass of the structure
%   limiting_factor most conservative requirement, acting as a limiting
%                       factor on the choice of thickness

[x,y] = size(altitude);
% For each altitude:
for h = 1 : y
    delta = altitude(h).shield;
    mp = altitude(h).mp;
    material = 'Fake Material';
    thickness = 10;
    mass = 1e12;
    limiting_factor = 'blah blah';
    [nj, ni]=size(mat);
    % For each material:
    for i = 1 : ni
        [thickness2, mass2,
limiting_factor2]=SolveThicknessForGivenMaterial(frequency_lat, frequency_axial,
load_axial, load_M, fs, p, delta, mp, L, D, mat(i).E, mat(i).rho, mat(i).Ftu);
        '################################'
        altitude(h).description
        mat(i).name
        thickness2
        mass2
        limiting_factor2
        if (mass2 <= mass)
            material = mat(i).name;
            thickness = thickness2;
            mass = mass2;
```

```
            limiting_factor = limiting_factor2;
        end
    end
end

% Uncomment to output the lower mass design:
% material
% thickness
% mass
% limiting_factor


% #######################

function [thickness, mass,
limiting_factor]=SolveThicknessForGivenMaterial(frequency_lat, frequency_axial,
load_axial, load_M, fs, p, delta, mp, L, D, E, rho, Ftu, Fcy);

% Function calculating the minimum thickness of the crew area that meets all
requirements
% Inputs:
%     frequency_lat     [Hz] lateral frequency imposed by the launch vehicle
%     frequency_axial [Hz] axial frequency imposed by the launch vehicle
%     load_axial      axial load factor
%     load_M                load factor relative to bending moment
%   fs              safety factor
%     p               [Pa] internal pressure
%     delta             [kg/m2] surface mass density
%     mp                  [kg] mass of the propulsion system
%     L               [m] length of the crew area
%     D                   [m] diameter of the crew area
%     E                   [N/m2] Young's modulus of the material
%     rho         [kg/m3] density of the material
%     Ftu         [N/m2] ultimate tensile strength of the material
%     Fcy         [N/m2] allowable compressive yield stress of the material
% Output:
%     thickness       [m] minimum thickness of the crew area
%   mass            [kg] total mass of the structure
%   limiting_factor most conservative requirement, acting as a limiting
%                       factor on the choice of thickness

thickness = FrequencySizing(frequency_lat, frequency_axial, mp, L, D, E, rho);
limiting_factor = 'Natural Frequency Requirement';

thickness2 = TensileStressSizing(load_axial, load_M, fs, mp, L, D, rho, Ftu);
thickness = max(thickness, thickness2);
if (thickness == thickness2)
    limiting_factor = 'Tensile Stress Requirement';
end

thickness2 = CompressiveStressSizing(load_axial, load_M, fs, mp, L, D, E, rho);
thickness = max(thickness, thickness2);
if (thickness == thickness2)
    limiting_factor = 'Compressive Stress Requirement';
end

thickness2 = PressureStressSizing(D, p, Ftu);
```

```
thickness = max(thickness, thickness2);
if (thickness == thickness2)
    limiting_factor = 'Internal Pressure Requirement';
end

thickness2 = RadiationShieldSizing(delta, rho);
thickness = max(thickness, thickness2);
if (thickness == thickness2)
    limiting_factor = 'Radiation Shielding Requirement';
end

mass = rho * L * pi * D * thickness;




% #######################

function thickness=FrequencySizing(f_lat, f_axial, mp, L, D, E, rho);

% Function calculating the minimum thickness of the crew area that meets the
frequency requirements
% Inputs:
%     f_lat             [Hz] lateral frequency imposed by the launch vehicle
%     f_axial     [Hz] axial frequency imposed by the launch vehicle
%     mp              [kg] mass of the propulsion system
%     L               [m] length of the crew area
%     D               [m] diameter of the crew area
%     E               [N/m2] Young's modulus of the material
%     rho         [kg/m3] density of the material
% Output:
%     thickness   [m] minimum thickness of the crew area

t_lat_min = mp * L^3 * f_lat^2 / (pi * D) * (0.236 - 1) / (0.236/0.3 * rho * L^4
* f_lat^2 - 0.276^2/8 * E * D^2);
t_axial_min = .667 * f_axial^2 * mp * L / (pi * D * (.16^2 * E - .333/.3 * rho *
L^2 * f_axial^2));
thickness = max(t_lat_min, t_axial_min);


% #######################

function thickness=TensileStressSizing(f_axial, f_M, fs, mp, L, D, rho, Ftu);

% Function calculating the minimum thickness of the crew area that meets the
tensile stress imposed
% by the launch loads requirement
% Inputs:
%     f_axial     axial load factor
%     f_M             load factor relative to bending moment
%   fs          safety factor
%     mp              [kg] mass of the propulsion system
%     L               [m] length of the crew area
%     D               [m] diameter of the crew area
%     rho         [kg/m3] density of the material
%     Ftu         [N/m2] ultimate tensile strength of the material
% Output:
```

```
%     thickness   [m] minimum thickness of the crew area

thickness = 2 * fs * 9.81 * mp * f_M * L/D / (pi * D * Ftu - fs * 9.81 * rho * L
* pi *D / 0.3 * (f_axial + 2 * f_M * L / D));



% #######################

function thickness=CompressiveStressSizing(f_axial, f_M, fs, mp, L, D, E, rho);

% Function calculating the minimum thickness of the crew area that meets the
compressive stress requirement
% Inputs:
%     f_axial     axial load factor
%     f_M             load factor relative to bending moment
%   fs          safety factor
%     mp              [kg] mass of the propulsion system
%     L               [m] length of the crew area
%     D               [m] diameter of the crew area
%     E               [N/m2] Young's modulus of the material
%     rho         [kg/m3] density of the material
% Output:
%     thickness   [m] minimum thickness of the crew area

f = inline(strcat('abs(', num2str(.6*2 * E/D), '* t * (1-.901*(1 - exp(-1/16 *
sqrt(', num2str(D), ' / (2*t))))) - ', num2str(fs), ' * (9.81*', num2str(mp *
(f_axial + 4*f_M * L/D)), ' + 9.81 * ', num2str(f_axial + 2*f_M * L/D), ' * (',
num2str(rho * L * D), ' * pi * t / 0.3 - ', num2str(mp), ')) / (pi * ',
num2str(D), ' * t))'),'t');

thickness = fminbnd(f,0.0001,1);


% ######################

function thickness=PressureStressSizing(D, p, Ftu);

% Function calculating the minimum thickness of the crew area that meets the
stress created by the internal pressure
% Inputs:
%     D               [m] diameter of the crew area
%     p               [Pa] internal pressure
%     Ftu       [N/m2] ultimate tensile strength of the material
% Output:
%     thickness   [m] minimum thickness of the crew area

thickness = p * D / (2 * Ftu);


% ######################

function thickness=RadiationShieldSizing(delta, rho);

% Function calculating the minimum thickness of the crew area that meets the
radiation shielding requirement
% Inputs:
```

```
%     delta             [kg/m2] surface mass density
%     rho         [kg/m3] density of the material
% Output:
%     thickness   [m] minimum thickness of the crew area

thickness = delta / rho;



% ######################

% All units are IS.

% The following structure contains the characteristics of the various
% altitudes to be considered:
altitude(1).description = 'LEO (300km)';
altitude(1).mp = 10000;     % mass of the propulsion system at this altitude
altitude(1).shield = 50;    % [kg/m2] shielding requirement at this altitude

altitude(2).description = 'GEO (36,000km)';
altitude(2).mp = 1000;
altitude(2).shield = 50;

altitude(3).description = '8,000km (just within the two Van Allen belts)';
altitude(3).mp = 6000;
altitude(3).shield = 70;


% the following structure contains the characteristics of the materials that
% will be tested by the module:
material(1).name = 'Al 2014-T6';
material(1).rho = 2.8e3;
material(1).Ftu = 455e6;
material(1).E = 72e9;

material(2).name = 'Al 2024-T4';
material(2).rho = 2.8e3;
material(2).Ftu = 470e6;
material(2).E = 73e9;

material(3).name = 'Pb';
material(3).rho = 11.34e3;
material(3).Ftu = 18e6;
material(3).E = 14e9;

material(4).name = 'Ti pure';
material(4).rho = 4.511e3;
material(4).Ftu = 551.5e6;
material(4).E = 102e9;

material(5).name = 'High Strength Steel';
material(5).rho = 7.86e3;
material(5).Ftu = 480e6;
material(5).E = 200e9;

material(6).name = 'Au';
material(6).rho = 19.32e3;
```

```
material(6).Ftu = 120e6;
material(6).E = 74.4e9;



% ##################################################################



function [radfluence,erad,prad]   =   radflux(r,t)

%This function takes both the position (scalar in km) and the time (in sec) and
%calculates the flux of both electron and proton radiation particles in the Van
Allen Belt's
%The fluence is the total radiation flux (sum of both electron and proton) times
the time and
%has units of rad

%Convert radius in km to Earth Radii
CONVERT.RE2km   =   6378.145;
CONVERT.rad2eflux   =   3e7;    %Converts electron flux in rad to flux in
particles/cm^2sec
CONVERT.rad2pflux   =   4e6;    %Converts proton flux in rad to flux in
particles/cm^2sec

%Convert radius to units of Earth Radii
rad     =   r/CONVERT.RE2km;

%Define the ranges for the known flux
erad_range=[.4, 9.5;.45,8.8;.5,8.3;.7,7.5;1.8,6;2.5,5.5;3.5,5];
prad_range=[.8,3.6;.9,3.4;1,3.1;1.2,2.8;1.4,2.3;1.5,2.1];

%Define the value of the flux for both proton and electron for the given range
erad_flux   =   [1e2;1e3;1e4;1e5;1e6;2e6;3e6];
prad_flux   =   [1e1;1e2;1e3;1e4;1e5;2e5];

%Determine the amount of electron radiation flux in particles/cm^2 sec
eradlength= length(erad_range);
index =0;
for i=1:eradlength
    if(rad>=erad_range(i,1) & rad<=erad_range(i,2))
        index = index +1;
    end
end
%If we are out of the data range, we assume that there is no electron radiation
flux
if index ==0
    eradflux = 0;
else
    eradflux = erad_flux(index);
end

%Determine the amount of proton radiation flux in particles/cm^2 sec
pradlength  =   length(prad_range);
index   =   0;
for i =1:pradlength
    if(rad>=prad_range(i,1) & rad<prad_range(i,2))
```

```
        index = index +1;
    end
end
%If we are out of the data range, assume no proton radiation flux
if index ==0
    pradflux = 0;
else
    pradflux = prad_flux(index);
end

%Convert the electron radiation flux and the proton radiation flux to units of
rad/s
erad    =   eradflux/CONVERT.rad2eflux;
prad    =   pradflux/CONVERT.rad2pflux;

%The total radiation flux in rad/sec
radflux =   erad + prad;

%The total fluence in rad
radfluence  =   radflux*t;
```