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Chapter 1

Introduction

1.1 Scene

After many years of successful missions such as, lunar and Mars rover missions. In addition, plans have been made to establish pioneering lunar and mars bases. Thus, the next leap for space exploration is not to just travel further but to establish longer durations of time in space, from 6-12 months to multiple years. Over decades of being in space multiple health issues have been found with many of the people who have experience 0g's (0 gravity) for long periods of time, for example, Muscle Atrophy, Osteopenia (decrease in bone density), Cardiovascular changes, radiation exposure, etc.

1.2 Project aims and work streams

Mitigating the physiological effects of long-term space habitation through the design of a rotating space station to simulate artificial gravity, via using the centripetal force. This project is broken into 5 subsystems, Attitude and Orbit Control System (AOCS), Structures, Thermal Regulation and debris/radiation shielding, Power, and Life support. Each will play a crucial role, for example:

Attitude and Orbit Control System (AOCS): Responsible for maintaining the station's orbit, orientation, and the optimal rotational speed necessary to generate artificial gravity.

Structures: Ensures the station's framework can withstand the forces induced by rotation, the stresses of launch, and the space environment.

Thermal Regulation and Debris/Radiation Shielding: Provides protection against space debris, micrometeorite impacts, temperature fluctuations, and harmful electromagnetic radiation such as UV and gamma rays.

Power: Supports all station operations, including life support systems and propulsion, by providing a reliable energy source through solar panels and energy storage systems.

Life Support: Manages air quality, water recycling, food supply, and waste treatment to ensure a habitable environment for the crew.

1.3 Brief description of Thermal Regulation and Debris/Radiation

This subsection is what this report will be tailored towards. This work stream priorities the stability and safety of the rotating space station. The subsystem is crucial in the protection of the integrity of the station the inhabitants (the crew) from micrometeorites, harmful radiation, and fluctuations in temperature.

Key Responsibilities:

Radiation Shielding: The use of advanced materials to remove the exposure and effects of solar radiation, via contamination and irradiation. This is ideal for reducing the exposure for long-duration missions, such as this one.

Thermal Regulation: The temperature difference from inside the space station and the vacuum of space vary drastically. By installing materials within the Whipple Shield, e.g., Aluminium. These types of materials could provide passive insulation, i.e., not allowing heat to escape from the inside to the outside. This is highly necessary to prevent malfunction in the equipment as well as, a providing a comfortable environment for the people onboard.

Debris Protection: As mentioned earlier the aim of this section is to safeguard the crew and machines onboard from high-speed space debris and micrometeorites. This is done using the same Whipple shield structure as mentioned earlier for the thermal regulation. Thus, this will ensure there is minimal structural damage and integrity of the station. This subsystem is crucial for long term habitation as well as the safety and longevity of the rotating space station. In this will also enable a sustained presence of humanity in orbit.

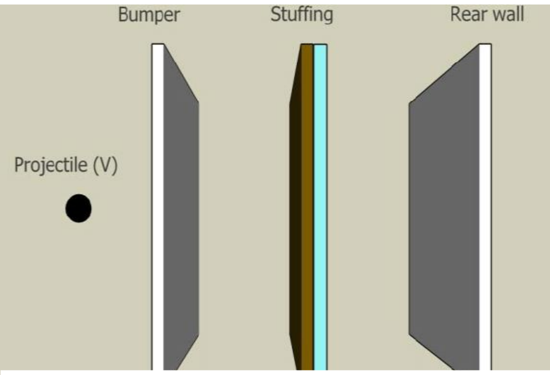

Figure 1.1. *Micro debris about to collide with Whipple Shielding at high-speed [1].*

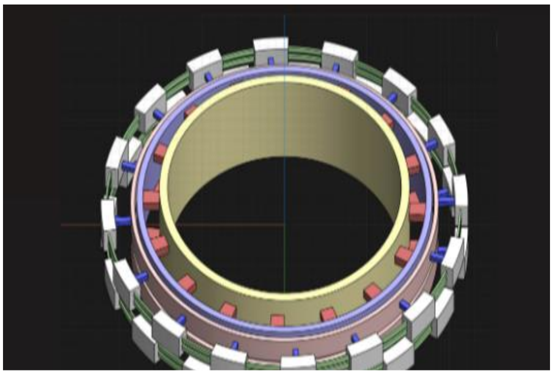

Figure 1.2. *The entire structure of the rotating space station, drawn by structures (Wania).*

Looking at figure 1.2, the initial station design is approximately 446m in diameter and 100m in height. It is also made up of 4 wheels with the inner rings (1st, 2nd & 3rd) having micro gravity and the outer ring where the modules are located having 1g.

The inner rings: Here will be where most scientific research and specific operations will take place as well as docking in the very centre. A key design of this is that these rings have no gravity due to them not having a rotation thus no centripetal force acting as the artificial gravity.

The outer rings: This ring will be made up of 2 levels. the top and bottom rings. Both will have 16 modules on each level, thus, there is a total of 32 modules. Here is where the simulation of Earths gravity will take place as it will be the location where rotation will occur. A key thing to understand is that both the 1st and 2nd levels will rotate in opposite directions to not interfere with the stillness of the inner rings. This acts like a stabiliser for the rings that are more central to not move and create its own artificial gravity, which is not what is required.

Table 1.1 The dimensions of each wheel of the rotating space station.

	Central Wheel	Both inner wheels (2nd & 3rd)	Outer wheel
Height (m)	100	70	27
Depth (m)	304	359	374
Width (m)	20	15	10

Chapter 2

Results, Research and Design Process

2.1 Research:

There is a growing number of manmade debris, which increases the probability of impact in low Earth orbit. Thus, it is critical to integrate more robust shielding that can endure harsher and a higher rate of collisions than what would be found at a sun synchronous orbit (SSO). This means ensuring longevity and safety [1]. Abaqus came up as a tool to use to analyse the dissipation of energy and deformation in the shielding.

The ISS uses mostly empty space and materials like Nextel, Kevlar, Aluminium within the Whipple shielding given a direction to follow in what to use. However, looking into more papers it was found that using metallic foams and Aluminium honeycombs instead of just having large empty spaces. It has also given more of an insight into using a both radiation absorbing and MMOD's materials such as polyethylene, which currently offers dual shielding from both [2]. Using this new path, determining the appropriate thickness for the entire Whipple Shielding as well as the layers of different materials. The impact velocity, which approximates between a few kilometres per second to about 16km/s, [3], can be used to help calculate the thickness necessary for the shielding. Furthermore, it has indicated that the typical debris diameter in LEO is between 1 to 10cm and due to this a shielding of 10cm is required [4]. However, in cases of larger debris than 10cm there is a limitation, thus, it was looked at of using a hybrid shielding system or an active debris removal.

To calculate the thickness of the layers the Cour-Palais equation will be used, which indicates the affect the debris dimensions and speed has with the size if the Whipple shield [5], as shown on Eq.1 and 2

(For debris between 1 to 10cm) $t_w = 0.055(\rho_p \rho_b)^{\frac{1}{6}} * m_p^{\frac{1}{3}} * \frac{V_n}{S^{0.5}} \left(\frac{70}{\sigma}\right)^{0.5}$ **[1]**

Valid for $\frac{t_d}{d}$ $\geq$**0.1** **[2]**

Table 2.1 Shows the necessary parameters used in this equation. [6]

$\boldsymbol{t_w}$ = Outer bumper Thickness(cm)
$\boldsymbol{t_b}$ = rear wall Thickness(cm)
d = Diameter of debris(cm)
m_p = Mass of Projectile
$\boldsymbol{\rho_d}$ = Density of Bumper(g/cm^3)
$\boldsymbol{\rho_b}$ = Density Projectile (g/cm^3)
V = Debris Velocity (km/s)
$\boldsymbol{V_n}$ = Normal Component of the Projectile velocity ($\boldsymbol{V_n}$ **= Vcos**$\boldsymbol{\theta}$)
$\boldsymbol{\theta}$ = Impact angle measured from surface Normal (deg)
S = spacing between bumper and rear-wall (cm), as shown on **figure 2.2**
$\boldsymbol{\sigma}$ = rear-wall yield stress (KSI).

In addition, more ballistic limit equation such as, frost, fish-Summers, and Christiansen/ Cour-Palais, have been investigated to the further identify the conditions under what projectiles will penetrate the shielding. This includes the velocity and properties of the projectile as well as the material of the shield [6].

The initial idea was to use was to use a Whipple shield, which is a multi-layered protective barrier designed to encase the entire rotating space station, and it is a safeguard from high impacts from high-velocity space debris. This further enhanced the uses of certain such as a Titanium Alloy (Ti-Al-Nylon), [7], that can counteract these projectiles with minimal damage. In addition to this requirement, materials like Beta cloth would need to be installed to the outer bumper to also mitigate the effects of radiation from cosmic rays and maintain the temperature from within the structure.

As shown on figure 1.1, the majority of the Whipple Shield is empty space as used on the International Space Station. This is used to reduce to impact by the micrometeorites after penetrating the outer layer of the shielding. The way this is done is that after impact the space debris become fragmented (breaks apart) and has a reduce in kinetic energy. The fragments loses its momentum and then spreads out while travelling within that empty space, thus increases in surface area and in turn increases the points of contact with the more inner layers of the shield, which is made of materials such as Kevlar. This drastically, reduces the load applied to the structure.

To identify the ideal materials to use in the Whipple shielding, multiple comparisons were done to indicate which are best not only for impact toughness against the thermal conductivity, as shown on figure 2.1.

2.2 Initial Experiments

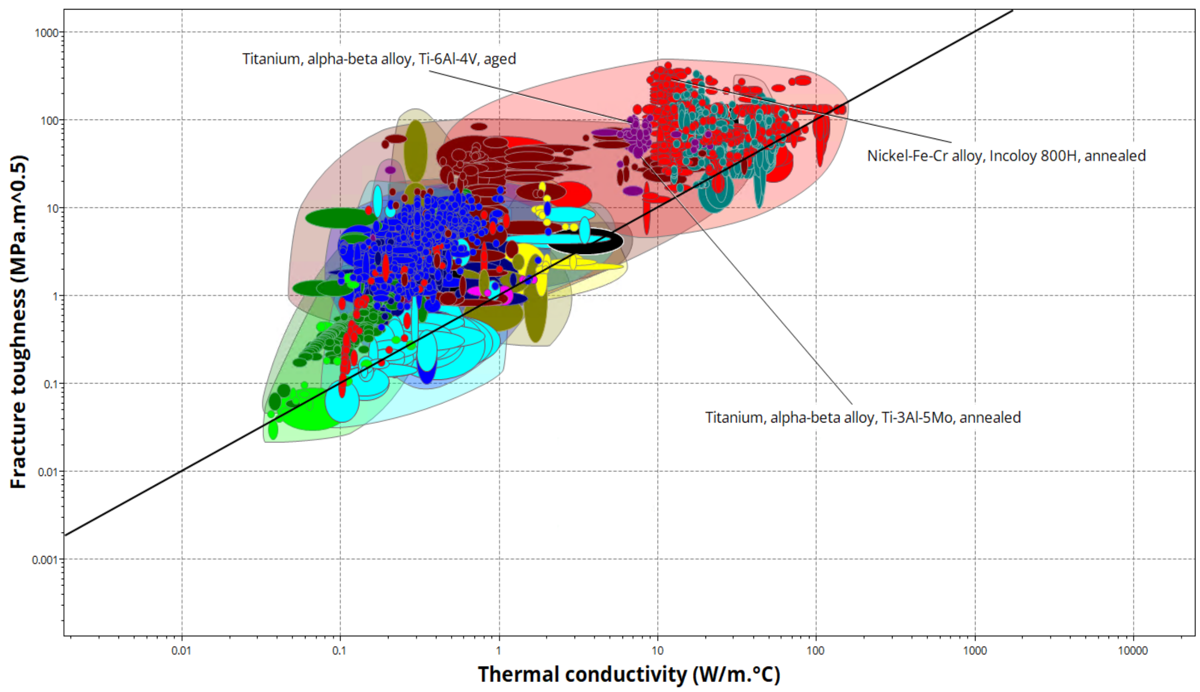

Figure 2.1*: Shows the fracture toughness against the thermal conductivity properties of materials.*

Taking the max values for both the projectile (debris or micrometeorites) velocity (16km/s) and a high diameter (10cm) in low-Earth orbit to calculate the max thickness the Whipple shielding would need to be, would be highly ideal. This would ensure that all parts of the station would have the highest level of protection. Using eq.1 an example calculation is made only using the typical values for each parameter to show the estimated thickness of the shielding.

The outer bumper density of Ti-6Al-4V = 4.5g/cm^3

The debris with a high density, e.g., steel = 8.0g/cm^3 and volume = 524cm^3

θ (impact angle) = 0 deg, therefore V_n = 16cos0 = 16km/s

Typical rear-wall stress of outer bumper = 75ksi

$t_w = 0.055(4.5 * 8)^{\frac{1}{6}} * 4192^{\frac{1}{3}} * \frac{16}{10^{0.5}} (\frac{70}{75})^{0.5}$ = 7.876958703cm ≈ 7.88cm (3.sf)

To further show the affect that the projectile dimensions and velocity has with the thickness, fig 2.2 was conducted via [8] and it shows that the Cour-Palais equation is more specific conserved in the requirements for the thickness, which really indicates the esurience in higher safety brackets.

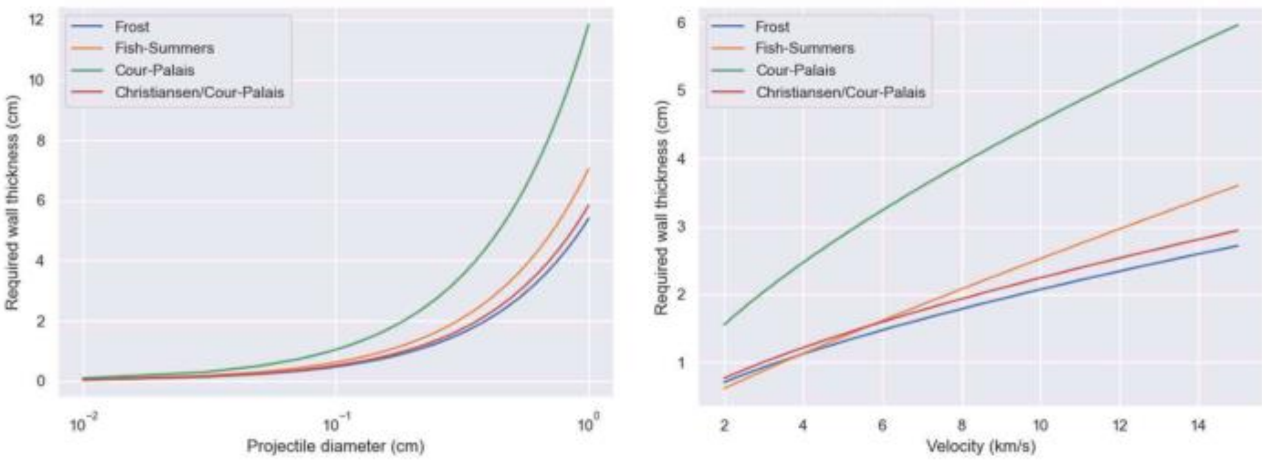

Figure 2.2:*Comparison of the effects between both the projectile diameter and velocity has with the required wall thickness of shielding.[8].*

2.3 Impact

The integration of the Whipple shielding against radiation, thermal deviation, and debris/micrometeorites impacts should create a balance between the weight, cost, choice in materials, all of this without compromising safety. These measures are taking place to ensure both the safety crew and integrity station. Furthermore, materials such as Aluminium, Titanium and Polyethylene (UHMWPE) are currently used in space missions, [9], to reduce their ecological footprint. This is due to being recyclable and sustainable materials. In a commercial standpoint, the advancement of the technology in Whipple shielding can induce a new idea for the aerospace industry as well as creating more opportunities economically.

Chapter 3

Analysis & Conclusion

3.1 Discussion:

Over the course of developing a rotating space station, the importance in the design of the Whipple shielding has been noted. For this ensures both the sustainability and safety for long term habitation. The research conducted highlights the improvements made from the conception of the traditional Whipple shield to the now modern variants. Some shielding has now gone from using empty space, which had helped to reduce impact, to now incorporating materials such as aluminium honeycomb, polyethylene, metallic foams and other dual functioning materials to protect the station from both comic rays and impacts. These changes significantly helps with the long-term durations of the shielding and mitigates the constant dangers that lurks in the environment of space.

Utilising the Cour-Palais equation, eq.1, the approximate value for the thickness was calculated and with this it ensures a way to find the true thickness value via using the debris size and velocity. Looking at the left graph on figure 2.2, the thickness of the wall is more sensitive to the magnitude of the projectile than it is to the velocity. This is more clearly seen where the diameter surpasses the about 0.1cm. Furthermore, the lines on the velocity graph are more linear, and the Cour-Palais line is at a higher position because unlike the other ballistic limit equation, frost, fish-Summers, and Christiansen/ Cour-Palais because it considers more assumptions to reconcile the uncertainties at the higher projectile velocity impact.

EDUPACK was used to help further help understand why most Whipple shielding, especially on the ISS, use a Titanium-Aluminium-Nylon alloy (Ti-6Al-4V), polyethylene, and Kevlar. The main reason the uses of these materials is that they all provide multiple enhancements to the protection of the station as mentioned before and are very cost effective, which will need to be shown on a graph using this software. Furthermore, fig2.2 was created to compare the impact toughness and thermal conductivity of multiple varying materials, such the Ti-6Al-4V, Ti-3Al-5Mo, and Nickel-Fe-Cr alloys, etc. There reasoning of why using the Aluminium alloy rather than the Nickel alloy which make up most of the top right on the graph, is that Nickel is a lot heavier. However, the Titanium alloy is more expensive, but this is reasonable considering the high strength in Titanium and Kevlar, the lightness and radiation shielding of Aluminium. [10]

The usage of materials like aluminium helps with the control of thermal energy because it can do it passively insulate [11] and ensures stability. This significantly decreases the transfer of heat between the interior of the station and vacuum of space. This is critical for the comfortability of the crew over an extended period of time and functionality of the equipment onboard the station.

Lastly, looking at that thickness for the outer bumper seems a bit big if it were for the ISS. However, since this station is a substantially larger, table 1.1, it does make it more feasible to utilise this thickness of Ti-6Al-4V, which would be the material most likely used for that layer.

3.2 Future work:

In future comparisons should be made regarding the cost, radiation resistance, and life span by the usage of EDUPACK as well as finding more materials to help. Debris Risk Assessment and Mitigation (DRAMA) will be crucial to find out the probability of collisions at low-Earth orbit as well as finding the end of life of the station. This will further help in enabling engineers to indicate scenarios of high risks and improve on the configuration of the safety accordingly. Using Abaqus Finite element analysis (FEA) would also be highly impactful in creating simulations of stress applied on the outer bumper material by the projectiles. This also gives us the means in optimising the physical and mechanical behaviour of the materials under the extreme stress. These will be instrumental in refining both the safety and design of the station.

In addition, work would need to be done to further understand how aluminium honeycomb and beta cloth are used to reduce the impact force and radiation exposure in the shielding including aerogel, which will help with regulating the thermal energy released from the inside and not allowing external factors affecting it. More materials will be essential to be investigated will need to withstand an angular velocity of 0.2094rad/s, which gives the station 2rpm to simulate the 1g we feel on Earth. Lastly, more research and calculations will need to take place in future to use the optimum number of layers of Whipple shielding, thus have the correct ratio of strength and weight.

3.3 Conclusion:

Overall, the creation of a rotating space station with the task of imitating 1g and supporting long-term habitation would present a substantial milestone in the progression of space exploration. Regarding the thermal regulation and debris/radiation protection, the installation of an improved Whipple shield will be crucial in supporting the sustainability of life in the station. Furthermore, this report/research will lay a robust foundation for future work in this field, i.e., helping in collating materials that will vastly improve the physical, mechanical and thermal properties of the shielding. This is further strengthened via being able to now calculate the truer thickness of each layer necessary to provide the optimum protection against high-speed space debris using the Cour-Palais equation and other ballistic limit equations. This allows a straight path to follow in the future development of the Whipple shielding and outlines more materials that be used with a multitude of beneficial characteristics.

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