

Team Blue: Vehicle Concept and Layout

Final Report

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Abstract

In this project, a design and concept for a space hotel is developed, considering the requirements and constraint that arise from the subsystems involved in maintaining a functional space station. These include orbital and attitude control, communications, power supply, radiation protection and thermal control, as well as specific design choices such as providing a specific observation module. The proposed space hotel concept consists of five interconnected modules, with two docking ports, one airlock as well as the necessary solar arrays and radiators. In order to provide a measure of redundancy, the hotel is essentially comprised of two space stations, each with sufficient capabilities to function largely independently.

Introduction

Space tourism is a growing industry, and a space hotel would be able to provide space tourists with the ultimate space experience. The space hotel is essentially a space station focusing at providing a pleasant and exciting stay for the passengers. Since the seventies, there have been space stations in orbit around the Earth, but these have always had scientific and military priorities. Keeping a hotel in orbit presents many challenges, and possibilities for technical problem solving. These range from keeping the passengers safe from radiation, to supplying enough power. The perhaps most eye-catching of these is the overall layout of the station itself.

1 Overall Design and Layout

The chosen design will be constructed using individual modules that connect together to form a final fully functional space hotel. Each module has a specific purpose and as a whole serve as a comfortable, safe and appealing space for both the guests and staff who reside on board. The core segments of the space hotel will consist of solid modules, a choice primarily based on the fact that these are currently used on the ISS and utilize well-established technologies. This implies minimized development times and thus an initial core station can be placed in orbit at an early stage. Apart from these, a specially designed observation module will be included to provide an unparalleled view of the Earth and the surrounding universe. Guest accommodation and common areas will be provided by an inflatable module developed by Bigelow Aerospace [4]. The final design is presented in figure (1).

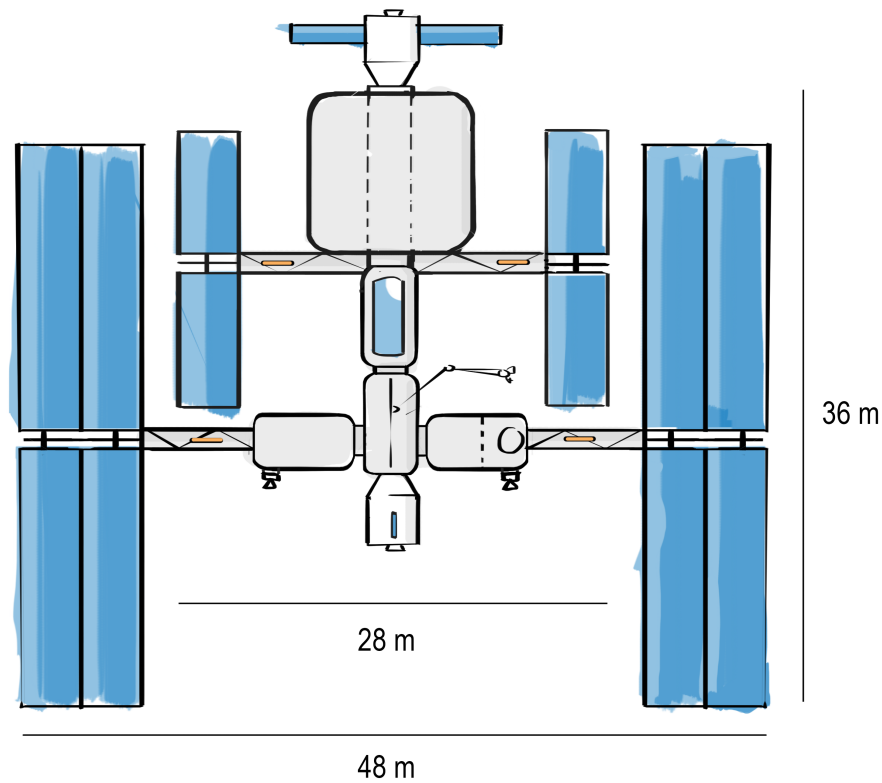


Figure 1: Final design of the space hotel.

The overall reasoning behind the design has been to maximize the view from the observation module, while ensuring functionality and safety. The external layout of the hotel is also developed to enable guest EVA's to be performed in a safe area, centered around the observation module. Furthermore, the docking ports for the capsules are placed in line with the direction of orbital progression, facilitating docking procedure. Ultimately, the size of the payload fairing used, as well as the design of the different subsystems have given rise to limitations, shaping the final layout.

1.1 Sectional Redundancy

To ensure maximum safety and full evacuation capabilities, even in case of catastrophic events, the station is divided in two sections, each self-sustainable. The hotel is essentially comprised of two individual stations connected through the observation module, both including separate life-support systems. The sections are visualized in figure (2).

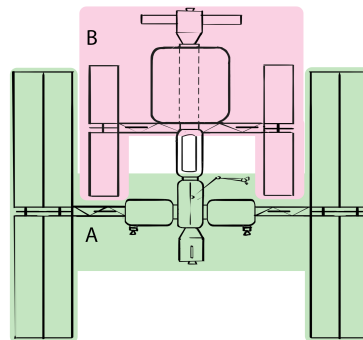


Figure 2: The two separate sections of the space hotel.

As can be seen in figure (2), each section is equipped with its own set of solar arrays, and its own capsule. Section A contains the operational features of the station while section B is mainly for guest accommodation and recreation. In case of an emergency, where people are forced to evacuate, the two capsules will be able to bring everyone down to Earth safely. However, situations could arise where a whole part of the station is incapacitated and perhaps only one of the capsules can be reached. In such an event, the sections can be completely sealed off from each other. All the guests, along with one crew member, will be evacuated with the capsule, while two crew members will have to stay behind. Since each section can sustain life separately, they can wait safely until a rescue vehicle arrives.

1.2 Modules and Mass Distribution

The mass has been distributed with the intention to obtain a center of mass that is as close as possible to the symmetry axis. An overview of the different type of modules, external components are presented in figure (3), along with their mass.

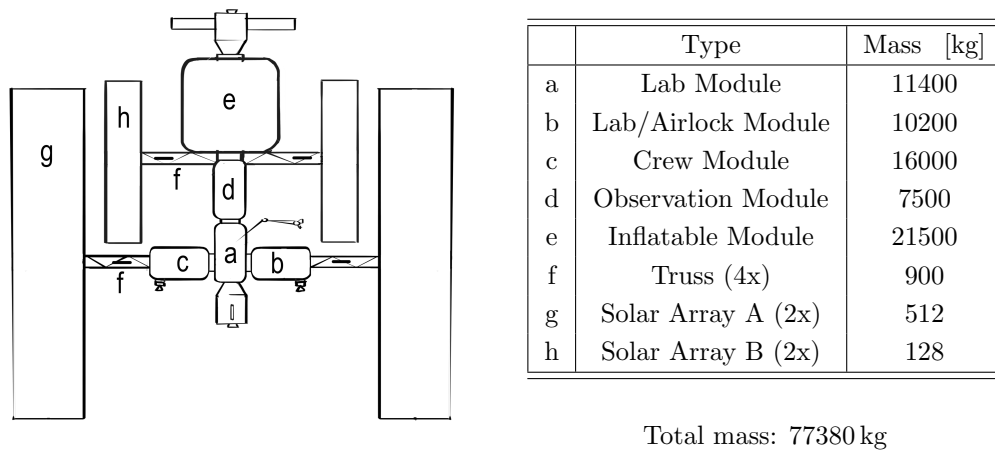


Figure 3: Modules and mass distribution. In determining the total mass, an additional 4900 kg is added for the arm and 1000 kg for the radiators.

1.3 Solid Core Modules

The requirements of the materials used in space are demanding, they must be light enough to launch into orbit yet strong enough to withstand impacts at 27000 km hr^{-1} . Lightweight aluminium, rather than steel, is used and comprises the shell of the modules. Aluminium however does not provide enough protection against impacts and so the aluminium shells are wrapped in a 10cm thick coat made by layering Kevlar, ceramic fabrics and other advanced protective materials; teflon coated silica, Nextel and aluminized polyimide MLI [3].

1.4 Observation Module

In order to provide the guests on the hotel with an unparalleled view of the Earth and the stars, the observation module will include two large panoramic windows. Since the attitude of the hotel will be pointing with respect to a local vertical local horizontal (LVLH) frame of reference at all times in orbit, it will have one panoramic window pointing towards zenith and one towards nadir. Basically, the Earth will be seen on one side and the stars on the other side, providing a remarkable view. A sketch of the observation module is presented in figure (4) along with the window pane configuration, which is the same as for the ISS cupola [8].

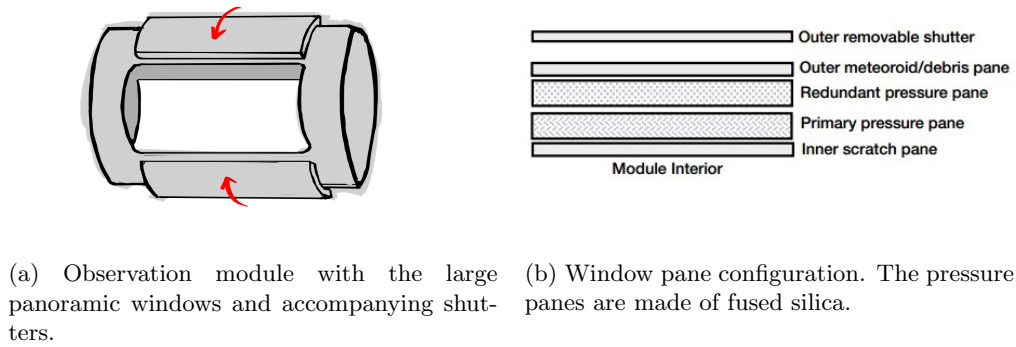


Figure 4: Panoramic windows on the observation module.

As can be seen in figure (4a), the windows are provided with protective shutters, that can be opened and closed at will. Apart from this, they will also be provided with UV-protection.

1.5 Inflatable Module

The inflatable module is a module which is collapsible for transport to orbit and is then inflated while in space, this method of construction is highly useful as it decreases the transport size limit on solid modules as their max size is that of the payload bay. The walls are made up of 24-36 layers of material providing ballistic, thermal and radiation protection. The materials used are woven Kevlar, Combitherm and Nomex cloth. Figure (5) shows an example of the internal layout of an inflatable module of this type.

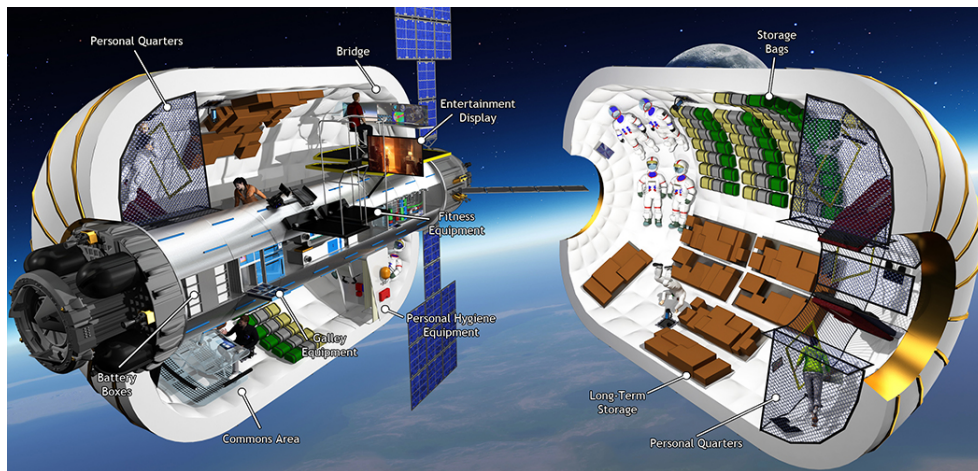


Figure 5: Proposed internal layout of the Bigelow B330 inflatable module.

2 Orbital Control System

2.1 Orbital Decay

An object in LEO will continuously lose altitude due to atmospheric drag. The drag force acting on the object is proportional to the frontal area of the object and the density at a given altitude. As the density varies for day and night cycles, it is hard to estimate a numerical value of the drag-force without any reference values. The chosen altitude for the space hotel is the same as the ISS standard operating altitude, and the orbital decay over time for ISS is well documented [1]. When the orbital decay is known for ISS at a specific altitude, the drag force acting on ISS at that altitude can be determined as

$$F_{D_{ISS}} = m_{ISS} \frac{\Delta v}{\Delta t} \quad (1)$$

where Δt is the time-interval from one altitude to another and Δv is given from orbital equation:

$$\Delta v = \sqrt{\frac{GM}{a_2}} - \sqrt{\frac{GM}{a_1}} \quad (2)$$

where G is the gravitational constant and M is the mass of earth.

The drag force acting on the space hotel can be determined as a fraction of the frontal areas of the two objects, ISS and the hotel.

$$F_{D_{Hotel}} = F_{D_{ISS}} \frac{A_{Hotel}}{A_{ISS}} = 58 \text{ mN} \quad (3)$$

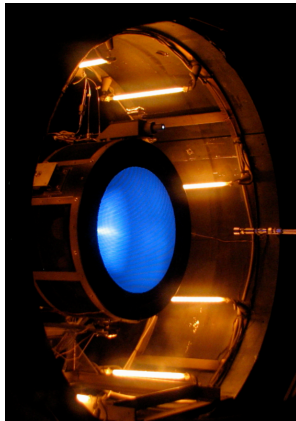
The Δv per month for the hotel is finally obtained.

$$\Delta v = \frac{F_{D_{Hotel}} \Delta t}{m_{Hotel}} = 1.9 \text{ m s}^{-1} \quad (4)$$

2.2 Propulsion System

The two choices of propulsion system considered for the space hotel are chemical propulsion and electrical propulsion. These two options give two different approaches to keep the hotel in orbit. The chemical propulsion system utilizes shorter impulse burns with given intervals to raise the hotel to desired altitude. The electrical propulsion system is not able to provide the same amount of thrust, but can run for longer periods of time to acquire the same amount of Δv . As electrical propulsion systems operate with much higher specific impulse (I_{sp}) than the chemical propulsion system, the propellant needed to generate the same Δv will be lower with electrical propulsion. Due to the high cost of sending mass to space, a lower propellant consumption is preferred and electrical propulsion is therefore chosen.

The electrical propulsion system needs to be able to apply the same amount of thrust as the drag force to be able to keep it in stable orbit. As stated earlier, the drag force applied at 400 km altitude is 58 mN, but if the station would be at lower altitude, the thrust required will be larger. The thrusters chosen for the hotel are two NEXT ion propulsion systems developed by NASA [13]. These will be able to apply up to 472 mN in total and will be able to keep the hotel in stable orbit at lower altitude, or raise the orbit if required.



(a) NEXT Ion propulsion system

Characteristic	NEXT
Thruster Power Range, kW	0.5-6.9
Throttle Ratio	> 12:1
Max. Specific Impulse, sec	>4100
Max. Thrust, mN	236
Max. Thruster Efficiency	>70%
Max. PPU Efficiency	94%
Propellant Throughput, kg	>530
Specific Mass, kg/kW	1.8

(b) Numerical values for thruster

Figure 6: Electrical propulsion chosen for orbital control.

If the thrusters run continuously at the thrust level required to keep stable orbit, the power required to run the electrical thrusters is:

$$P = \frac{F g_0 I_{sp}}{2\eta} = 1.75 \text{ kW} \quad (5)$$

where η is the total efficiency of the thruster and the PPU. The the propellant consumed per month is:

$$m_p = \frac{F\Delta t}{g_0 I_{sp}} = 3.85 \text{ kg month}^{-1} \quad (6)$$

The power required for the thrusters is quite small in comparison to the total power requirement of the hotel and can easily be supplied by the electrical power supply. The propellant consumed per month is low, and can easily be transported to the hotel by the crew vehicle.

In off-nominal cases, if the thrusters need to run at higher thrust levels, for example if the hotel is at a lower altitude, up to 13.8kW of power will be required. The electrical propulsion system will suffice for the everyday orbital control, but in case of main propulsion system failure, a backup system is needed. As the hotel will have dragon capsules docked both in the front and rear, these can be used to perform emergency evade maneuvers and act as backup for orbital control.

3 Attitude Control System

There are several methods of attitude control available both with their own advantages and drawbacks. A good system should be efficient in achieving large changes in attitude without expending excessive fuel. Such existing systems include, reaction wheels and control moment gyroscopes (CMG). Both of these systems work by creating a torque, achieved by a change in their momentum. The reaction wheel does this by changing the rotational speed of the wheel, while the CMGs always spin at great speed and are using gimbals to change the orientation of the wheel, hence creating manoeuvre torques. Another difference is that the CMG is generally capable of creating higher torque for a given weight and power, which makes this an alternative that is favourable in the case of a larger spacecraft[12].

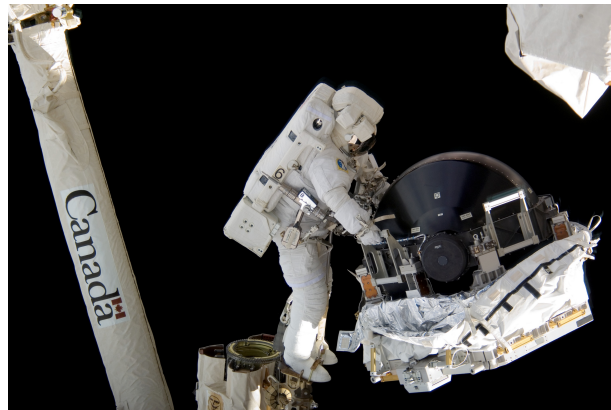


Figure 7: Astronaut Dave Williams during a mission to replace one of the four CMGs into the ISS's Z1 truss.

Among the already existing CMG systems, almost all are intended for ordinary satellites. However, in the case of the space hotel something bigger is needed. The only existing system found that stores a sufficient amount of angular momentum is the the one used on the ISS. The system used there consists of four CMGs, manufactured by L3 communications, each having a mass of about 272 kg [6]. They rotate at a constant rate of 6600rpm and develops an angular momentum of about 4880 N.m.s. The expected life time of one CMG is about 10 years. Finally, a problem that might arise when using momentum storing devices is the saturation of momentum, which could happen due to environmental disturbances. Examples of these disturbances are stated in table (1)

Table 1: Sources of torque disturbances[9].

External torque source	Altitude range over which it is potentially dominant [km]
Aerodynamic	< 500*
Magnetic	500–35000
Gravity gradient	500 – 35000
Solar radiation	> 700*
Thrust misalignment	All altitudes
Internal torque source	
Mechanisms	
Fuel movement	
Astronaut movement	
Flexible appendages	
General mass movement	

*Values are dependant on the level of solar activity

To counteract this problem, a secondary system needs to be implemented, which will act to desaturate the CMGs when necessary. It is possible to achieve this by using a non-propellant dependant system, for example magnetic torquers, however, this would take much more time than using a high-torque system, such as thrusters[12]. When using thrusters for desaturation, the angular momentum impulse is given by the following equation:

$$\Delta H = \tau \Delta t \quad (7)$$

Where τ is the torque applied from the thrusters and Δt is the impulse time. Given the specific impulse, I_{sp} , and thrust, F , of the thruster model used, it is possible to estimate the amount of propellant needed to desaturate the CMGs. Assume that each CMG stores the angular momentum H , then time needed to desaturate them would be:

$$\Delta t = \frac{H}{\tau} = \frac{H}{F r_{cm}} \quad (8)$$

Here, r_{cm} is the distance from the thruster to the center of mass of the space hotel. furthermore, the mass flow rate is given by the equation below:

$$\dot{m} = \frac{F}{g_0 I_{sp}} \quad (9)$$

Finally, the mass of propellant needed to desaturate one CMG can be expressed as:

$$m_p = \dot{m} \Delta t = \frac{F}{g_0 I_{sp}} \frac{H}{F r_{cm}} = \frac{H}{g_0 I_{sp} r_{cm}} \quad (10)$$

To get a rough estimate of the amount of propellant needed each year, it can be assumed that we use a thruster with $I_{sp} = 250$ s, and that the distance from the hotels center of mass is $r_{cm} = 12$ m. Now, using the angular momentum stored in the CMGs, $H = 4880$ N m s, the mass of propellant needed to desaturate one completely saturated CMG would be $m = 0.17$ kg. It could be interesting to look at how much fuel is needed over the course of one year for an unfavorable scenario, where all four CMGs are desaturated once every orbit. The hotel will be approximately in the same orbit as the ISS, which has a orbit period of approximately 92.69 minutes, and so the number of orbits per year would be:

$$N = \frac{365.25 \text{ d/yr} \cdot 24 \text{ hr/d} \cdot 60 \text{ min/h}}{92.69 \text{ min/orbit}} \approx 5674 \text{ orbits /yr} \quad (11)$$

Which would suggest that the propellant needed for the desaturation alone could go up to 3858 kg yr^{-1} , however, this is for a total of almost 23000 desaturations.

Other uses for the thrusters includes for example in off-nominal cases, when a large change in orientation is needed faster than the CMG system can produce it.

4 Communication

The communication system on a space station, or in this case, space hotel, serves to maintain contact with the ground control, but also to allow ground control to directly send commands and control the station without having to use the astronauts aboard as middlemen. The system used in this project, based on the ISS, will be using S-band frequencies for space-to-ground communications, UHF-band for space-to-space, and Ku-band frequencies will be used for high rate data such as video and payload data. Typical parameters for the S-band and Ku-band subsystems are stated in Table (2).

Table 2: Typical parameters for the S-Band and Ku-Band subsystems.[12]

Component	Qty	Mass [kg]	Power [W]	Dimensions [m]
S-Band				
Transponder	2	6.87		$0.14 \times 0.33 \times 0.07$
-Receiver			17.5	
-Transmitter			40.0	
Filters	1	2.0	0.0	$0.15 \times 0.30 \times 0.06$
Antennas				
-Hemisphere	2	0.4	0.0	$0.10\text{dia} \times 0.13$
-Parabola	1	9.2	0.0	$1.50\text{dia} \times 0.70$
-Turnstile	1	2.3	0.0	$0.10\text{dia} \times 0.15$
Total		28.04	57.5	
Ku-Band				
Transponder	2	4.45		$0.17 \times 0.34 \times 0.09$
-Receiver			4.3	
-Transmitter			20.0	
Filters	1	1.2	0.0	$0.08 \times 0.19 \times 0.04$
Antennas				
-Earth coverage	1	0.5	0.0	$0.04\text{dia} \times 0.20$
-Parabola	1	2.0	0.0	$0.60\text{dia} \times 0.22$
-Waveguide	1	0.7	0.0	1.25 long
Total		13.30	24.3	

To enable the guests to call home once in a while, a device called a Softphone, where 'soft' refers to software, will be available in the hotel. This system works like an IP phone, but modified to be able to handle the one second time delay due to the distance [14].

5 Power Supply

The power system is one of the most integral parts of a spacecraft. To be functional, the space hotel will need a lasting source of power. The most obvious source of energy in space is the sun. The hotel will be in direct sunlight for much of the time, without the scattering effect of the atmosphere on earth. Other (unmanned) spacecraft, going further away from the sun may opt for nuclear power. This is not considered here, on account of the safety issues regarding nuclear power. In fact, many of the deadliest nuclear power accidents have occurred on nuclear submarines [11], a situation not so far removed from that of a space station in orbit.

5.1 Power Consumption

The approximate power demands from the following systems are; electrical thrusters 2 kW, life support 25 kW, and 13 kW for background systems such as thermal control and communications, giving us 40 kW of consumed power. Another 10 kW for crew and guest usage lands the total power consumption at 50 kW. This energy must be provided by the solar arrays while in direct sunlight. Simple geometrical arguments (see figure 8) suggests that this is true for approximately 60 % of the time, for a low earth orbit at 400 km:

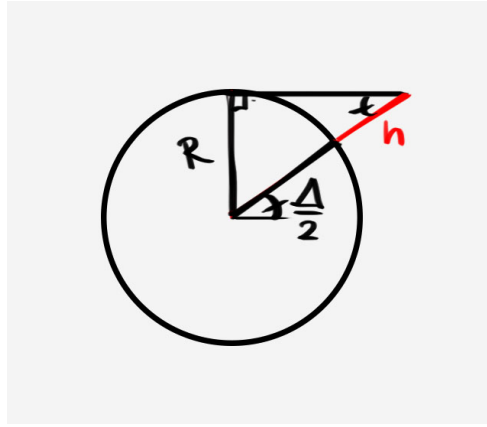


Figure 8: Simple geometrical representation of orbit.

$$\Delta = 2 \sin^{-1} \left(\frac{R}{R+h} \right) \Rightarrow \frac{\Delta}{2\pi} \approx 0.4 \quad (12)$$

5.2 Batteries

This energy also needs to be stored in batteries. A contemporary example, the lithium-ion battery Tesla Powerwall has an efficiency 92 % [20]. Other larger (although scaleable) batteries such as those made by Imergy has DC-DC conversion efficiencies of 70 – 75 % [10].

The batteries should last for at least 15 years without noticeable degradation. Tesla has a 10-year warranty on their Powerwall battery, whereas the Imergy flow batteries should not degrade per number of cycles at all [10]. In light of this, it is reasonable to assume that at the time of development, a battery with 80 % efficiency, and a lifespan of 15 years may be available. Tesla Powerwall at 3.3 kW weighs 100 kg. Linearly scaling this to 80 kW gives an approximate mass of 2.5 tonnes.

5.3 Solar Arrays

Modern multi-junction solar cells have conversion efficiencies ranging from 20 – 44 % [18]. Here, triple-junction X4 solar arrays in flexible blanket arrays with an efficiency of 29 % are used in the calculations as an example [7]. These yield a power/mass ratio of 136 W kg⁻¹ and a surface density of 1.96 kg m⁻². Triple-junction solar cells combine three different semiconductor materials, each absorbing a different range

of wavelengths. This way, the solar cell gains a broader bandwidth and a higher efficiency than regular cells [21].

The efficiency of the solar arrays on the ISS is expected to degrade by a factor of 0.84 within 15 years in the space environment [15]. We will dimension the arrays to be able to provide enough power even at the end of the hotel's lifetime. Assuming that the entire solar arrays are kept in direct sunlight while not in the shadow of the Earth by clever use of gimbals, a 108 kW output is needed directly from the arrays to provide 50 kW continuously, including margins for degradation.

In order to have a large margin and possibly be able to run the important systems despite a malfunction in one of the solar array wings, the original power requirement is set to 80 kW instead of 50 kW. This results in a total mass of about 1.3 tonnes, a total area of 652 m² and a total power of 174 kW from the arrays while in sunlight. The solar arrays are placed out to the sides of the station for several reasons. Firstly, we want the view from the large windows of the observation module to be unobstructed. The solar panels should for safety reasons be well out of the way of guests on EVAs. Thirdly, the arrays should be out of the shadow left by the hotel itself.

Boeing subsidiary Spectrolab cites 400 USD/W as a cost approximation for their space solar arrays, which leaves us at about 30 million euros for the entire set of arrays [19].

6 Thermal Control System

6.1 Excess Heat

The power system, as well as other systems on board will produce excess heat. This needs to be controlled and properly dissipated to keep a habitable temperature on board. For simplicity, it is assumed that there is no exchange of heat between the hotel body and the space around it. The thermal control will be similar to that of the ISS, with one passive and one active thermal control system, relying on radiators.

The energy that is not properly converted by the batteries, is generally released as heat. In this case, this results in 12 kW of heat being emitted from the batteries. Therefore radiators should be on the trusses close by the batteries and solar arrays. Furthermore, assuming a daily intake of 2500 kcal, supposing most of this energy is released as heat in some way, a total power of

$$\frac{9 \cdot 2500 \text{ kcal}}{24 \text{ hr}} \approx 1 \text{ kW}$$

is emitted by the nine passengers. For all the other electronics aboard, the heat generation is approximated by an efficiency of 90 %. The remaining ten percent of the power is then thermal energy corresponding to about 8 kW. In total, this results in an approximate heat generation of roughly 21 kW. Much of this should ideally be dissipated by a passive thermal control system.

6.2 Radiators

Ammonia is pumped through the radiators, radiating the heat away from the hotel. If the approximate temperature difference is assumed to be 300 K, a heat transfer away from the radiators by black body radiation is assumed:

$$\frac{P}{A} = e\sigma T^4 \quad (13)$$

As a perfect black body, the radiator area required then becomes $A \approx 0.0022P$. To be able to radiate 21 kW, an area of approximately 46 m² is needed. Using the same approach on figures from the ISS radiators gives an approximate value of $e = 0.73$, and this result is used to get a new radiator area: $A \approx 63 \text{ m}^2$. Applying the mass/area ratio from the ISS radiators yields an approximate mass of 1 tonnes for the radiators [5].

In order to keep the radiators cooler, they may be placed in the shadow behind the solar array wings. Alternatively, they could be pointing away from the heat of the earth, and so towards the cooler space above. Finally, minding the large power margins, significantly larger radiators would be preferable to be able to eject energy in the form of heat, and also be ready for malfunctions or excess heat from other sources.

6.3 System Design

Implementing large windows on the space hotel will in fact generate a lot of heat loss [17]. At the same time, the hotel needs to be cooled down because of all the heat generated from electronics and people on board. Thus, the thermal control system is designed taking both these aspects into account. The hotel is provided with external radiators, dissipating heat from both solar panels and modules. Furthermore, the observation module is provided with internal radiators. Section A and B of the station (see figure 2) are cooled and the warm cooling liquid, which consists of water internally, is partly used to counteract the heat loss in the observation module. The rest of the heat is exchanged to the outer loop, containing ammonia, and dissipated in space via the external radiators. The thermal system will be automatically controlled, distributing heat between the external and internal radiators in order to retain a stable habitable internal temperature throughout the whole station. A schematic of the thermal control system on board the space hotel is shown in figure (9).

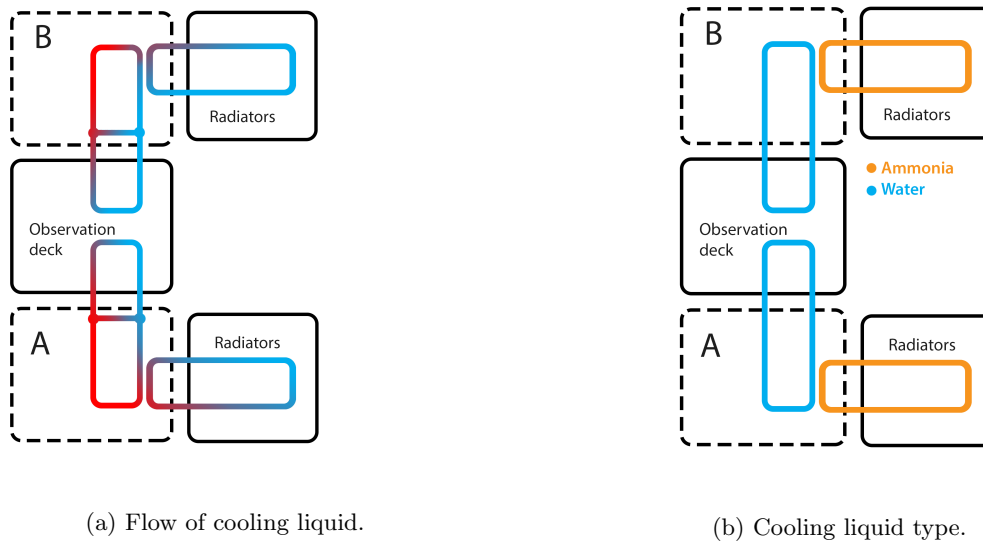


Figure 9: Schematic of the thermal control system on board the space hotel.

7 Radiation Protection

Extended stays in space will continuously expose humans to the harmful radiation which is a part of the hostile space environment. Without sufficient protection, absorbed doses can be lethal, and thus any space habitat must be able to shield from the ionizing radiation. It is also important to take into account that the Earth's magnetic field still provides some protection while in LEO. Consequently, the radiation intensity is not as high as would be the case on interplanetary missions, for instance, and the radiation protection can thus be designed accordingly [16]. Since the modules of the space hotel are primarily based on those used on the ISS, the same solutions for radiation protection are used. Furthermore, the inflatable module provides radiation protection equivalent to or even better than existing ISS modules [4].

There are mainly two types of sources of radiation that are of interest in this context, namely galactic cosmic radiation (GCR) and solar particle events (SPE). Additionally, since the space hotel is placed on the same orbit as the ISS, a passage through the South Atlantic Anomaly is unavoidable. The outer walls

of the space hotel modules provides the basic protection needed to shield against the background radiation of space. It is, however, in the event of a large solar storm (SPE) that an extra shelter would be needed in order to ensure a safe stay on-board the space hotel.

This problem is solved by introducing a concept initially designed as part of NASA's TransHab program [2]. In the space hotel, both the guest sleeping compartments and the crew cabins will be enclosed in two separate Radiation Shield Water Tanks (RSWT) that will act as safe havens during periods of maximum solar activity. Simultaneously, these water tanks will be integrated in the water processing system to hold intermediate or final stages of water. In this way, these tanks serve two purposes that are both critical, and mass can thus be saved.

The RSWT is basically a cylinder with the wall comprised of an annular water tank. Its original dimensions are used on the space hotel as well, with a height of 2.13 m and an outer diameter of 3.35 m. In order to protect against a solar storm equal in magnitude to one of the larger storms recorded, a water wall thickness of 5.74 cm is sufficient. The water tank itself contains features, including the combination of hydrophobic membranes and wetting surfaces, allowing it to be operated in microgravity. These features have been successfully tested in parabolic flight [2].

As mentioned before, two tanks will be used on-board the space hotel. One tank will fit 6 guest compartments and one tank will fit 3 crew compartments, which is shown in figure (10). Since these tanks are equal in size, the crew compartments will be larger. Although, these will also be used as private offices for the crew members, justifying the extra space.

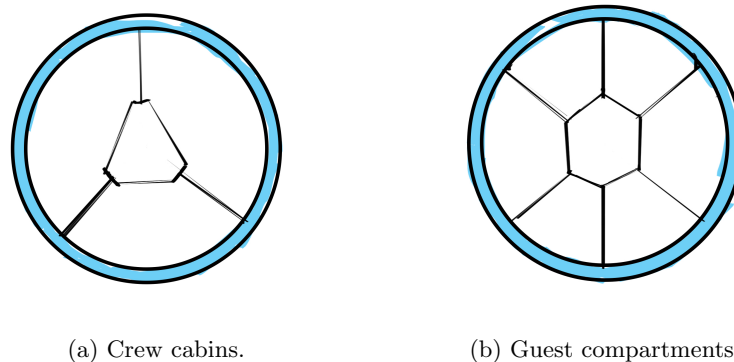


Figure 10: Sketch of the RSWT's used on the space hotel.

The placement of these safe havens is carefully chosen so that there is a shelter present in both sections of the space hotel (see figure 2). The crew compartments are placed in the far end of the crew module (see figure 11), in section A, while the guest compartments are placed in the middle cylindrical segment of the inflatable module, in section B. In the absence of harmful solar storms, the guests are free to choose not to sleep in the compartments and instead find a suitable place in the inflatable module. This is to account for the fact that some people are uncomfortable sleeping in enclosed compartments. However, should a solar storm be detected, all guests must seek protection in their compartments.

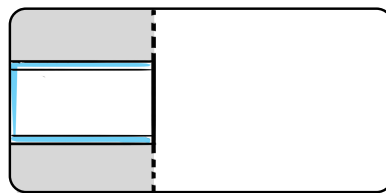


Figure 11: Sketch showing the placement of the RSWT inside the crew module. The gray area around the tank can be used for additional storage or instrumentation.

8 Conclusion

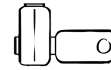
Given the requirements, constraints and objectives of the project, a design for a space hotel and its subsystems has been developed. The hotel will consist of 5 modules divided in two sections, utilizing current and near-future space technologies. The design aims to provide a safe, pleasant and exciting hotel stay.

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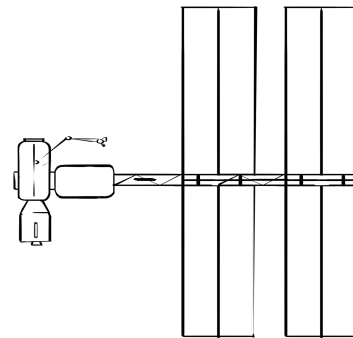
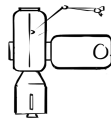
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Appendix - Sequence of Assembly



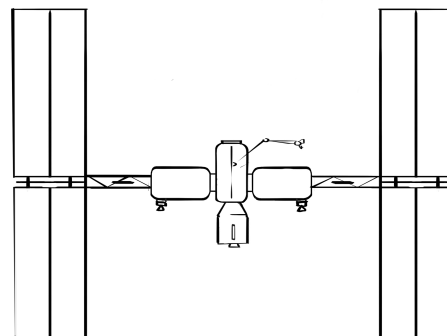
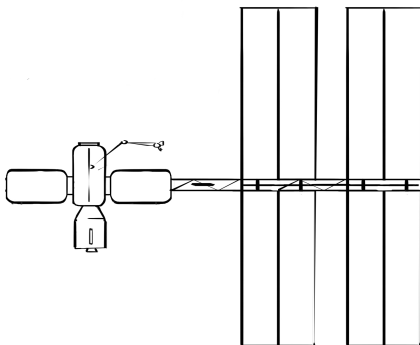
1. [Launch 1] The lab module is launched and placed into orbit. It will also contain a robotic arm.

2. [Launch 2] The airlock module, including a life-support system, is launched and docked to the lab module.



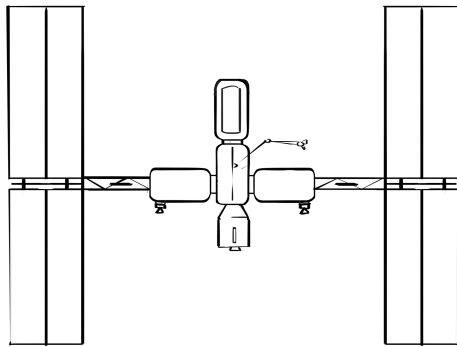
3. [EVA 1] A crew vehicle arrives and the robotic arm is attached during an EVA. The crew stays.

4. [Launch 3] [EVA 2] The first solar arrays and trusses are launched and attached to the airlock module, during an EVA.

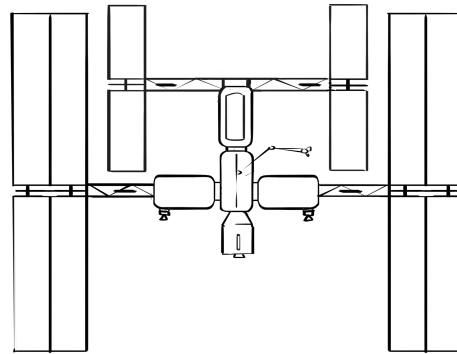


5. [Launch 4] The crew module is launched and docked to the lab module.

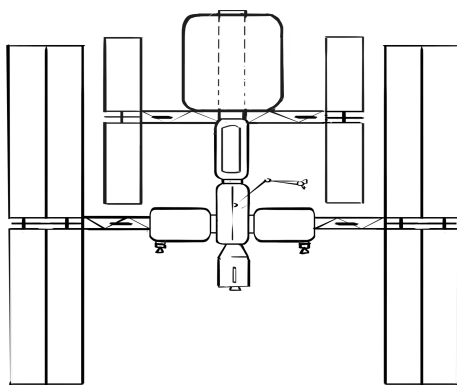
6. [EVA 3] One truss and its solar array is moved and attached to the crew module, during an EVA.



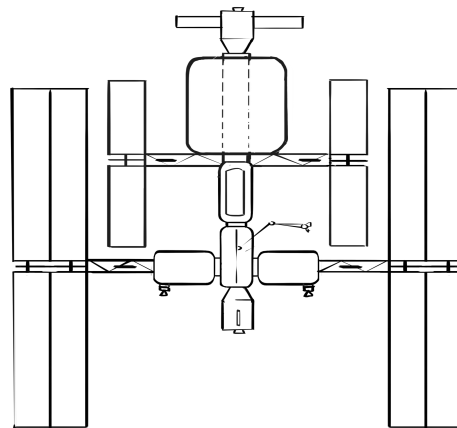
7. [Launch 5] The observation module is launched and docked to the lab module.



8. [Launch 6] [EVA 4] The remaining solar arrays and trusses are launched and attached to the observation module, during an EVA.



9. [Launch 7] The inflatable module is launched and docked to the observation module.



10. The first guests arrive in a Dragon capsule which docks with the inflatable module.