A design guide for a space habitat for 30 habitants.

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DECLARATION

This report entitled

A design guide for a space habitat for 30 habitants.

Was composed by me and is based on my own work. Where the work of the others has been used, it is fully acknowledged in the text and in captions to table illustrations. This report has not been submitted for any other qualification.

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Abstract

Space travel and habitation will be part of the future. This will require humanity to have a space hub/ space dock as a steppingstone to outer space. And so, in this report a design guide has been set out for a space habitat for 30 habitants. A set of main design points have been set out. Them being: a favourable orbit, fitting design, and desired materials. Then robotic construction, overall design, and cost, from this a final list of design parameters have been set out and considered. They were then simulated using the open-source Orbit.M program. This was to calculate the orbital decay of the habitat and the delta v needed to sustain orbit.

Contents

List of symbols

$F, Force, N$
$G, Gravitational\ constant, 6.67259 * 10^{-11}\ m^3kg^{-1}s^{-2}$
$M_E, mass\ of\ the\ earth, 5.9736 * 10^{24}\ kg$
$r, radius, m$
$m_h, mass\ of\ the\ habitat, kg$
$v, orbital\ velocity, ms^{-1}$
$a, acceleration, ms^{-2}$
$T, Time\ period$
$n, number\ of\ revolutions$
$\alpha_{drag}, atmospheric\ drag, ms^{-2}$
$\rho(R), atmospheric\ density, kgm^{-3}$
$C_d, drag\ coefficient, approx\ 2.2$
$A_h, habitat\ cross\ sectional\ area, m^2$
$V_h, linear\ velocity\ of\ habitat\ about\ earth, ms^{-1}$
$\alpha_{solar}, solar\ radiation\ drag, ms^{-2}$
$r_f, reflection\ factor$
$P, solar\ radiation\ flux\ at\ 1AU$
$\Delta V, Total\ delta\ v, ms^{-1}$
$\sigma_\theta, maximum\ stress\ for\ pressure\ vessel, Pa$
$P, Atmospheric\ pressure, Pa$
$r_h, radius\ of\ habitat, mm$
$h, height, m$
$\rho, density, kgm^{-3}$
$A_{sphere}, area\ of\ sphere, m^2$

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1. Introduction

1.1. Introduction

As we move further into the future the prospect of space travel, tourism and colonisation becomes more and more likely. With billionaires like Jeff Bezos and Richard Branson visiting space with Blue Origin and Virgin Galactic and are now offering spaceflight to those willing to pay. And so, we are at the very beginnings of space tourism and hopefully, space colonisation.

For this future, a space colony/habitat will have to be built. However, this habitat will not only serve for science and research like the ISS but would also function as a tourism spot or as a space hub to further travels in space similar to the idea of a space dock. So, with this idea comes many design challenges which will be discussed in this report. The first design point being orbit height. This will be an extremely important mission criteria as many following points like propellant calculations are based on this choice. Secondly, a fitting design which relates to how the habitat will be designed, size and shape. Then materials and robotic construction will be briefly discussed. To arrive at these design points, I will investigate previous designs of space habitats and look at recent research relating to space habitats to come to a solution for each design point. After these points are finalised, I will construct a python simulation to model and simulate the orbit of the space habitat about the earth.

The overall objective of this project is to design a space habitat for 30 habitants, one that acts as a hub for further space travels. This means it will not be self-sufficient and will require aid from Earth, however, future developments and additions could lead to the habitat being self-sufficient.

2.Summary of literature review

2.1. Orbital height

A favourable orbit is an extremely important aspect when designing a space habitat. As there are many factors to consider. A previous habitat designed by NASA set their orbit at the L5 point [1]. At this point the habitat would receive constant sun exposure and stay stationary in free space. However, this applies to their design criteria which is not similar to ours. We wish to have a habitat that is accessible to Earth as stated previously, the habitat would not be self-sufficient and will require aid. Recent research by Globus et al [2] has theorised that an equatorial low earth orbit would reduce the typical mass of a space settlement by 90 percent. This research is extremely promising however the values given are just theoretical calculations and real measurements have not been taken.

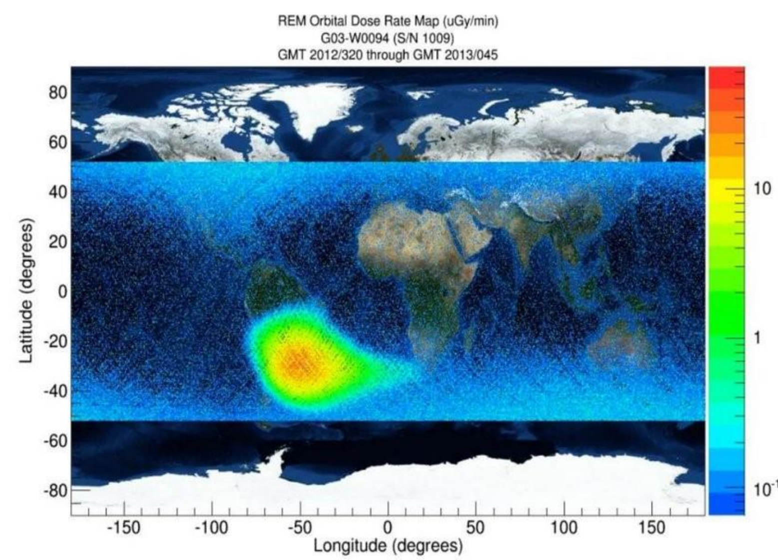

Figure 1. Radiation distribution at 400km orbit height [1]

2.2. Fitting design

For a space habitat there are many designs to choose from. A modular design similar to the ISS, bola, torus, spiral and cylinder amongst others. Then picking a design, size requirements must be considered. This would be for living space, life support, waste systems and many more. Currently, we know a modular design would not work to rotate and produce an artificial gravity unless constructed in a certain way and shape, however the other designs can allow for artificial gravity. This will be further discussed in chapter 4.

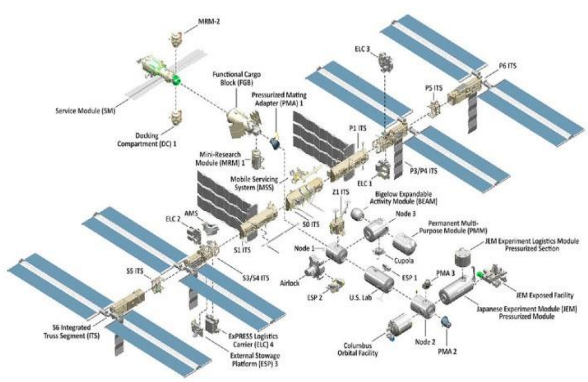

Figure 2. Exploded ISS view

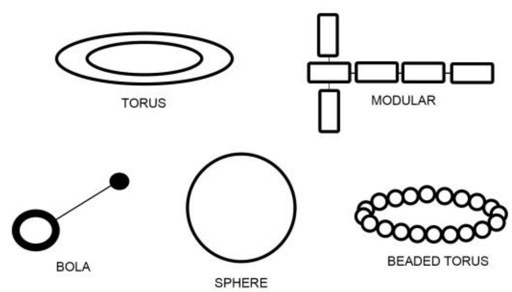

Figure 3. Potential space habitat designs

2.3. Robotic construction

Depending on the design chosen, to construct the habitat on Earth then launch into space would be impractical and would cost hundreds of millions to complete. Similar to NASA's design study [1] and Dr. Nanjangud et al's paper on robotic construction in space [3] it would be easier for the habitat to be constructed in space with multiple launches. For this we are limited to two robots.

2.4. Python simulations

After all the design points have been finalised, to verify the design points and monitor the orbit of the space habitat, simulations in python will be run to verify these design points. Various other points will be discussed like materials, cost, amount of launches further in the report.

3. Favourable orbit

3.1. Introduction

To look at a favourable orbit we must initially look at current space habitats and at what heights they orbit at. The main and most current example would be the ISS. The space station orbits the Earth at an orbit height of roughly 400km [4] and uses visiting or currently docked spacecraft to boost the habitat to keep its orbit height due to orbital decay. With the research from Globus et al, [2] we would aim to have the space habitat at an equatorial low Earth orbit however, this does come with challenges that will be talked through.

3.2. Equatorial orbit

Firstly, as we aim for an equatorial orbit we would ideally need a launch site on the equator. These could be Guiana Space Centre in Kourou, French Guiana, or Alcantara Launch Centre in Brazil. Or potential future launch sites on/near the equator. These launch sites would be perfect for our desired orbit as we would not need to use additional propellant to change our inclination angle and so would be most efficient. Not only that but, if we launched in an easterly direction we would also benefit from the angular rotation of the Earth at a rotation speed of 460 m/s [5]. If we launched at for example Cape Canaveral which is at 28 degrees from north latitude then additional propellant would have to be used to adjust inclination. This would mean a reduction in payload size and weight for additional propellant.

3.3. Investigation of orbital height for space height

In this section we will investigate the effects of orbital height on mean motion around the Earth and orbital velocity. We will initially start from first principles using Newton's law of gravitation. This shows the force the Earth exerts on our space habitat *Equation 1*, From this we can relate acceleration with the velocity of our space habitat using *Equation 2.* By substituting *Equation 2* into *Equation 1* we achieve *Equation 3*. From this we can see m_h is cancelled out just leaving the mass of the Earth. If we look at one circular orbit we can calculate the time period, T equal to the distance travelled divided by velocity giving us *Equation 4*. When we substitute *Equation 3* into *Equation 4* we get *Equation 5*. If we want to find the mean motion, the number of orbits achieved in a day, we get *Equation 6*. From this if we take G and M_E as constants equal to $G = 6.67259 * 10^{-11}$ and $M_E = 5.9736 * 10^{24}$ this gives us a table of values, *Table 1* , correlating orbit height to velocity, period, mean motion. For R_E we took the equatorial radius of the earth $R_E = 6371km$.

$$F = \frac{GM_E m_h}{r^2}$$

Equation 1.

$$a = \frac{v^2}{r}$$

Equation 2.

$$v = \sqrt{\frac{GM_E}{r}}$$

Equation 3.

$$T = \frac{2\pi r}{v}$$

Equation 4.

$$T = 2\pi\sqrt{\frac{r^3}{GM_E}}$$

Equation 5.

$$n = \frac{86400}{T}$$

Equation 6.

Table 1. Orbit height investigation parameters

Height (km)	R (km)	velocity (km/s)	Period (mins)	Mean motion (rev/day)
200	6571	7.79	88.35	16.30
220	6591	7.78	88.75	16.22
240	6611	7.76	89.16	16.15
260	6631	7.75	89.56	16.08
280	6651	7.74	89.97	16.01
300	6671	7.73	90.38	15.93
320	6691	7.72	90.78	15.86
340	6711	7.71	91.19	15.79
360	6731	7.70	91.60	15.72
380	6751	7.68	92.01	15.65
400	6771	7.67	92.42	15.58

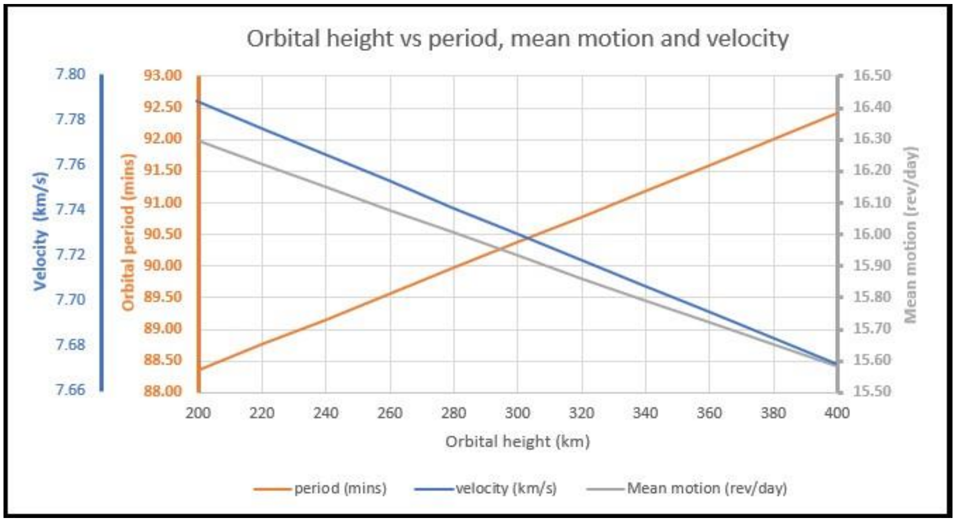

Figure 4. Orbital height vs time period, mean motion and velocity

From *Table 1* and *Figure 4* we can see that the greater our orbital height, the greater our orbital period. Therefore, we achieve slower velocities and less rotations around the Earth. Based on these calculations and the points made so far the **orbit will be an equatorial low earth orbit at 400km.** With potential to be at a further orbital height based on radiation measurements at these orbital heights.

3.4. Gravity decay and propellant formulae

One important aspect to discuss when choosing to orbit at 400 km is the orbital decay due to atmospheric drag and solar radiation pressure that the habitat will experience. At 400 km there is still atmospheric drag and thus orbital decay. So, in this section we will look at the formula required to calculate the propellant needed to keep our space habitat at the desired orbit. We will heavily rely on formulae from [6] and have the following *Equation 8*, *Equation 9*, *Equation 10* and *Equation 11*. These derivations will be in appendix 10.1.

$$\alpha_{drag} = -\frac{1}{2}\rho(R)C_d\left(\frac{A_h}{m_h}\right)V_h^2$$

Equation 7. Atmospheric drag

$$\alpha_{solar} = \frac{A(1+r_f)}{m} * P = 2.56 * 10^{-8}\ ms^{-2}$$

Equation 8. Solar radiation drag

$$\alpha_o = \alpha_{solar} + \alpha_{drag}$$

Equation 9. Total acceleration drag from perturbing forces

$$\frac{dR}{dt} = \frac{\alpha_o(R).T(R)}{\pi}$$

Equation 10. Simplified decay model

$$\Delta V_{total} = \int_0^t (\alpha_{drag} + \alpha_{solar}) dt$$

Equation 11. Total delta V to sustain orbit height

These equations assume a near circular orbit throughout the decaying process. And holds true for orbits that begin as circular orbits due to drag forces at the periapsis are greater than at the apoapsis which reduces the overall eccentricity and holds the circular shape. Provided we have the values for each parameter, we can estimate the orbital decay and thus calculate how much ΔV is needed to sustain the equatorial low Earth orbit. However, the timing of the burns must be found to be most economical and so for this transfer from decayed orbit to target orbit height we will use a Hohmann transfer [7]. This will be further discussed in chapter 8 where I shall, using these equations, calculate the ΔV_{total} necessary to sustain the orbit height as well as the timings for most efficient propellant burns.

4. Fitting design

4.1. Types of design

When designing a space habitat one important aspect would be the overall design of the habitat. As discussed previously and as seen in *Figure 2* there is a wide range to choose from. So initially we will look at what is currently being used which is once again the ISS. The ISS has a modular design that over time has grown to 17 modules total. The main benefits of a modular system would be that over time modules can be added and replaced. Deployment and assembly in space is quite easy as modules would be prebuilt and then assembled using space docking technology. However, the main limitations of a modular design would be no artificial gravity. This means that to prevent the muscle loss due to micro gravity, habitants would need to exercise roughly 2 hours a day [8]. For a bola design, as seen in *Figure 3*, 2 space crafts are held together by a cable and are spun to create artificial gravity. The main benefit of this design would be that we have artificial gravity however as we have two bodies and a cable. We have to think about how much propellant would be needed to sustain rotation. And at what speed this would be at amongst other design challenges.

4.2. Artificial gravity, human rotation

When designing our space habitat one consideration would be whether we had artificial gravity or not? As we have talked about before, the negatives about having no gravity are well documented with thanks to the ISS. With the main downsides being muscle loss and bone density loss [9]. With other downsides being imprecise hand movement [10] space motion sickness high stress [11] and weak immune response [12]. However, our habitat is going to act as a hub/space dock and so these downsides can be negated as visiting humans shouldn't spend too much time aboard. However, this does mean servicemen/women that must stay to maintain and service the habitat will have to consistently train and exercises. And hopefully with prior training this can be done most efficiently and effectively.

4.3. Modules needed

For our habitat we will require several modules to keep the habitat running. For the habitat our modules would require power and propulsion systems, guidance systems and communication systems to relay information amongst other requirements. For the habitants living in space, they would require the basic requirements for human survival: Food, water, and shelter. However, there are other requirements like sleeping quarters, waste management and harder to quantify requirements like effects on human psychology for long term habitation that will need to be considered when designing and implementing our modules.

If we approximately aim to have habitants stay **for 1 year maximum** they will need to have food and water brought up with them or have it brought up it additional care package launches. Based on the what the ISS feeds their astronauts, an average human needs 1900 to 3100 calories per day depending on the gender and size of the individual [13]. This amounts to about 1.8 kg of food per person per day. The average human also needs 4.5 litres of water per day which equals to about 4.5 kg per person per day [14]. This amount is for drinking water but also sanitation, rehydrating food, and other necessary uses of water. If we extrapolate these results for 30 habitants we would need 54 kg of food per day and 135 kg of water per day. But most of the water can be recycled from their urine using the waste management and sweat from water recovery systems. Due to this we will assume 50% of water gets recycled. This means that for a yearlong mission we would require around **44.35 tonnes of food and water.**

For our habitat we must think about modules needed to sustain the habitat like guidance and propulsion modules. As discussed earlier in chapter 3.4 we will need propulsion to sustain our orbit however we could use the thrusters initially used for launch as our propulsion module. For our GNC (guidance, navigation, and control) it will help control and monitor our satellites movement and so must be accounted for.

4.4. Size of components

For our modules they must fit into our preferred launch vehicle which would be a rocket with the largest fairing size. This would either be SpaceX's star ship with a fairing volume of 1100 m^3 [15] or Nasa's future space launch system SLS block 2 with a fairing volume of 1320 m^3 [16]. Currently, Starship is looking the most promising as a launch vehicle due to current tests and progression. And so, SpaceX's Starship is the preferred launch vehicle however, for future launches if block 2 or other launch vehicles are available to launch and are economically viable then they will become the preferred launch vehicle. The Starship has a volume size of 18 meters high and 9 meters in diameter, but the useable size can be better seen in *Figure 5* and so, our modules will have to be constrained to this payload volume.

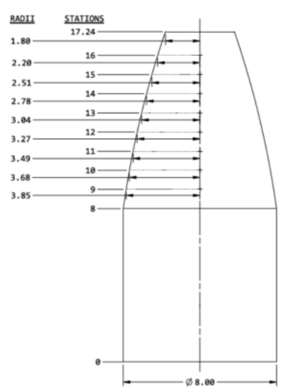

Figure 5. Starship payload volume [15]

In this case we will have our modules **16 meters long** with a **diameter of 4.4 meters** with later modules potentially varying in height and diameter depending on varying use cases. This should provide ample space for our habitants for day-to-day activities, for our main life support systems as well as subsystems. For our first launch the module will comprise of living quarters for a small number of habitants and with further launches providing more living quarters for the 30 total habitants.

The modules would be a **volume of 243.28 $\boldsymbol{m^3}$** however this comprises of the primary and secondary structures. The primary structure acts as the main pressure structure sustaining the habitant's atmosphere and protection from space. With the secondary structure dealing with all the internal fixtures and fittings of the habitat [17]. Assuming that from chapter 3 we would need little to no radiation shielding we can minimise the primary structure with minimal radiation shielding. Due to this we can calculate the thickness of the pressure vessel using basic pressure vessel equations for our secondary structure.

4.5. Thickness of modules

$$\sigma_\theta = \frac{\mathrm{Pr}_h}{t}$$

Equation 12. Thickness formula

$$t = \frac{\mathrm{Pr_h}}{\sigma_\theta} = \frac{(10^5\ Pa)(2200\ mm)}{(250MPa)} = 0.88mm$$

The maximum stress chosen was 250 MPa but this can vary depending on our chosen material. The ISS's maximum factor of safety when designing components is 1.4 [18]. So, in our use case we will use a similar factor of safety.

$$FOS(1.4) = 1.232mm$$

But we must also consider MMOD (micrometeoroid and orbital debris), and sufficient shielding will be needed to protect our habitat for long term use. One form of shielding used is a "Whipple shield". This works by dissipating the energy and overall velocity of the debris by breaking up the debris into smaller pieces and dispersing this energy into little fragments across a large shield [19]. This estimates that for a ¼ inch skin with a 1mm thick shield at a 1-inch distance, it can dissipate meteorites to the eighth magnitude. However, the Whipple shield concept has been known for a long time and many developments have been made to further improve this shield and so there are many configurations, A.Pai et al [20] discusses these developments. And so, for our Whipple shield configurations we will have a **200 mm standoff distance**, **1mm thickness bumper shield** and a **rear wall thickness of 3 mm.** These measurements can be understood using *Figure 6.* These walls will be made from aluminium (this will be discussed in chapter 5) and so our configuration should be sufficient to shield MMOD of mass 0.183g at 0.85 km/s to 10 km/s [21].

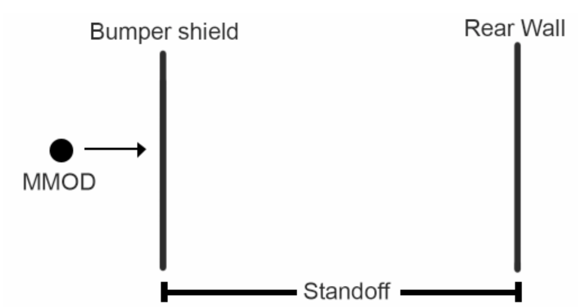

Figure 6. Whipple shield configuration

However, we must consider other thicknesses of the modules. Like: the use of paint to potentially mitigate any corrosion and/or other effects, insulation to protect the astronauts and sustain the atmosphere and temperatures within the habitat. Also, other materials used in the shield like Kevlar and other composites to strengthen the shield. And finally, radiation shielding thickness must be considered, as although we have assumed minimal radiation shielding is needed due to our orbit, some will be required for overall safety. Due to this, the overall habitat thickness of primary and secondary structures would be approximately **215mm**.

4.6. Number of modules needed

Now that we know the size of our modules we can now approximate the number of modules needed for our 30 habitants. These modules assembled together should have enough space for living, sleeping quarters, work areas, common space etc. Initially we will look at sleeping in space and how much space is required. As the sleeping arrangements on the ISS are similar to small shut away pods they require little space and can be built in similar to shelves and other equipment is built into the structure. And so, with two of our modules, this should be sufficient enough to house all our habitants with future module launches available if needed.

5. Materials

5.1. Material investigation

Another important aspect to discuss when designing a space habitat is what materials we would like to use to construct our habitat. We would like to use a material that would be easy to manufacture with, lightweight enough to launch into orbit with and as low cost as possible but strong enough to deal with any man made or small asteroid debris. Not only that but the material will have to act as a pressure vessel to keep our space habitat atmosphere and our habitants safe.

The first module of the international space station, Zarya was launched in 1998. It was made up of several materials: Steel, aluminium, Kevlar, and a ceramic blanket. On succeeding modules, they were made up of similar materials. But instead of steel, stainless steel was used as well as composite materials, aluminium alloys, and titanium [22]. We can take inspiration from this and compare these materials depending on our use cases.

Stainless steel was used as it has very good corrosion resistance. Although the habitat will be orbiting earth at 400km there is still a possibility of corrosion and so if say iron was used, that material would rust/corrode. Which is why stainless steel was used and/or corrosion resistant materials.

Aluminium and aluminium alloys (AA) are a good choice for a space habitat [23] as on Earth we have used them extensively for pressure vessels, so engineers are well aware of aluminium’s capabilities. It is strong, lightweight compared to stainless steel, easily machinable and non-corrosive and so would make a great choice for our primary structure. It is also, relatively inexpensive compared to titanium.

Table 2. Material properties [24]

Material	Youngs modulus (GPa)	Density (kg/m^3, 10^3)	Cost per kg(£)
Aluminium alloys	69-75	2.64-2.81	1.63-1.76
Titanium alloys	100-120	4.43-4.79	19.5-21.4
Stainless steel	190-210	7.61-7.87	2.17-2.32
High carbon steel	200-220	7.8	0.546-0.576
Low carbon steel	200-220	7.8-7.82	0.537-0.566
AA 6061	68-71.5	2.69-2.73	1.5-1.68

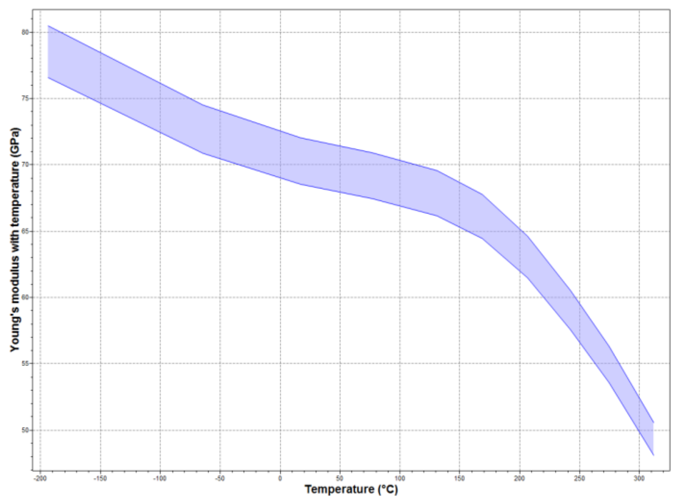

Figure 7. AA6061 young modulus distribution versus temperature [24]

5.2. Manufacturing process

For construction of such large parts there will need to be multiple processes to construct each module. One process could be hot/cold rolling. This process would form the main basis of the modules structure as the large circular tubes. They would then use welding processes like shielded arc welding/friction welding or other forms to weld the metals together and complete the pressure structures. For specific parts electroforming could be used as it provides the ability to replicates its mandrel counterpart very precisely. Other processes may be used to construct the habitat like milling, forging, amongst other for specific parts of the habitat.

6. Robotic construction

Considering the approach we have taken so far and the design points we have made so far, it is obvious to see that robotic construction will not be needed. However, the assistance of robots could be incredibly beneficial to our space habitat assembly over time and for maintenance work. It is in this use case that we would use a 6 degrees of freedom (DOF) robotic arm, this way we have maximum versatility. Then for the end/hand we would need a claw or large arm big enough to comfortably hold a module. However, if we chose to hold the entire module it would mean a hand size of 4.4 meters which is impractical to deploy. So, a claw idea would be best with enough strength to move modules. This would mean it would either have to be mounted to an existing module or a floating platform and if so, thrusters would need to be used to sustain its position in space.

7. Design and cost

7.1. Material cost per module

To calculate the material cost per module we must first calculate the total mass of each module. This will be based on aluminium being used and a hollow cylinder shape being used. The dimensions have been shown in *Figure 8* and *Figure 9*. Assuming the shape we can calculate the overall mass of each module using *Equation 13*.

$$M = \pi h(r_h^2 - (r_h - t)^2)\rho$$

Equation 13. Hollow cylinder mass equation

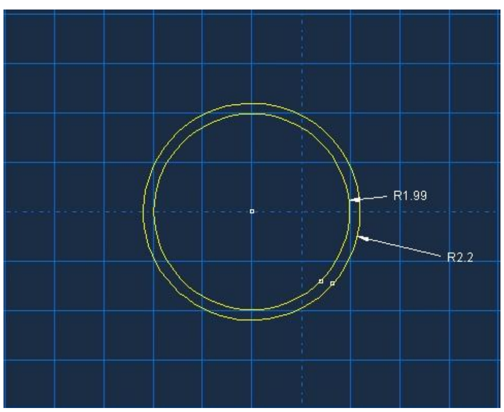

Figure 8. Space habitat module design (m)

Figure 9. Extruded habitat module view

From this we get the mass of each modules structure to be **122.11 tonnes**. This is only based on the primary and secondary structures being made up of aluminium and no front and end coupler/caps have been added as well as all the internal fittings. And so, these calculations are an incredibly approximate value. As we have not considered our Whipple shield which is comprised of various components as seen in chapter 4.5. However, the following calculations will provide an overall weight estimation.

We then must think about the various other components like all the systems and subsystems we will have, the various facilities and components that will be on this habitat and the weights these systems will have. Based on these mass estimations we can approximately calculate the material cost of the structure per module. If we take the values from *Table 2* AA6061 costs £1.58 – 1.68 per kg. This means for one module it would cost **£205,144.80** at a £1.68 per kg price. This cost only considers raw material cost and not manufacturing costs, labour costs amongst other costs. And I will repeat and say this cost is very approximate and only considers the module being made purely from aluminium.

7.2. Launch costs

Due to the use of Starship by SpaceX and its current progression it is difficult to estimate the cost of launch as it is still currently being tested and worked on. One thing we do know is that due to the reusability of the Starship this should bring down our overall launch costs. If we look at *Figure 10.* we can see that SpaceX, estimate that using the BFR, they will have the lowest cost per launch compared to other launch vehicles. Due to this we can estimate a total launch cost based on current launch vehicles of similar fairing size and capacity.

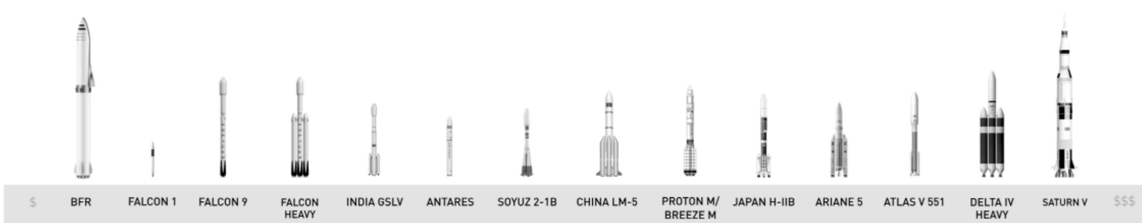

Figure 10. Launch cost comparison [25][1]

[1] BFR (big falcon rocket) is interchangeable with Starship

This paper by Jones et al [26] provides a great reference and comparison of most launch vehicles and their respective costs to launch. We can see that for the Falcon 9 and Falcon 9 heavy which have fairing sizes that are shorter but comparable in diameter, have a cost per launch of 62 and 90 million USD. With a cost per kilo at $2.72k and $1.41k respectively [27]. However, we must note that the performance is only up to 22.8 tonnes for the Falcon 9 and 63.8 tonnes on the Falcon heavy. Based on these figures above I would estimate the launch cost per kilo to be roughly $1k. This would mean the total cost of launch for the space habitat assuming just structures would be ***$122,110,000.*** This calculation doesn't consider various other costs that will be necessary like setup, propellant mass among other costs. Another thing to keep in mind is that currently SpaceX only launches from "Cape Canaveral space force station, Kennedy space centre and Vandenberg space force base" [28]. These sites are not near the equator and so for launches from these sites additional propellant will be needed to adjust inclination.

8. Computer simulations

8.1. Introduction of Orbit.M

In this chapter we will culminate all our design points together to form our space habitat. And with that, run orbital decay simulations to calculate the ΔV needed to sustain the orbit of our space habitat. For this we will be using the open-source program called Orbit.M [29]. It is an incredible tool that can be used for orbit maintenance and propulsion sizing. For this we will require a few parameters.

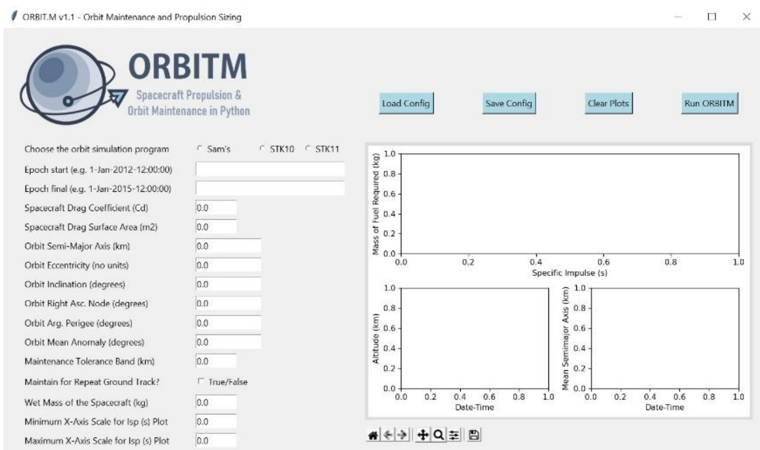

Figure 11. Orbit.M user interface

8.2. Parameters

As talked about previously we estimated the mass to 122 tonnes only considering the structure. Assuming the weight of the other systems, cargo, food, and water to be 50 tonnes extra this puts our **total spacecraft/module mass at 172 tonnes**. We must then consider how long we would like to run this simulation for. Initially we would have the first module for approximately 1 year then over time increase the habitat size with more modules.

We already know our orbit semi major axis, which will be 400km + the radius of the earth 6371km giving us an **orbit semi major axis of 6771 km**. As it is an equatorial near circular orbit our **eccentricity will be 0.0001** and **inclination angle at 0º**. Then we must approximate our drag surface area which can vary as it is the cross-sectional area based on the angle you are viewing it from not a simple summation of area. Meaning our cross-sectional area can vary, especially when considering the solar panels, we will have on our habitat. So, instead of viewing our habitat as a hollow cylinder module we can instead model it as a sphere at a maximum radius of half the length of the module. This way we overestimate and with future investigations this can be refined. This would approximate our **cross-sectional area at 804 $\boldsymbol{m^2}$** calculated using *Equation 14.*

$$A_{sphere} = 4\pi r^2$$

Equation 14. Area of a sphere

For the drag coefficient, this will be hard to say what value we will use as it does deviate throughout the year. This has been documented and discussed by Christopher L. Hassa [30]. Due to this we will run simulations at a range of C_D's. For our simulations we will have a tolerance band of 5 km meaning our orbit can vary from 395 – 405 km. We will allow for repeat ground track meaning the spacecraft will boost from a decayed orbit of 395 km to 405 km and then repeat once decay has taken place.

For these simulations we will be running the "Sam's" orbital simulation program. This program works quickly but very approximate as it makes some assumptions. Firstly, the program considers that the Earth is perfectly spherical and does not consider the oblateness of the earth. Secondly, for the atmospheric density model it uses a US standard atmosphere 1976 table whereas other programs like STK use better atmospheric density models. And finally, the "Sam's" program uses an approximated decay model.

In the default program a set of thrusters and respective ISP values are given. And so, fitting with our design requirements we chose a set of thrusters/engines listed in *Table 3.*

8.3. Results

In this section we will simply plug in all our design points and calculate how many burns we need, the total delta v as well as total impulse over the simulation period.

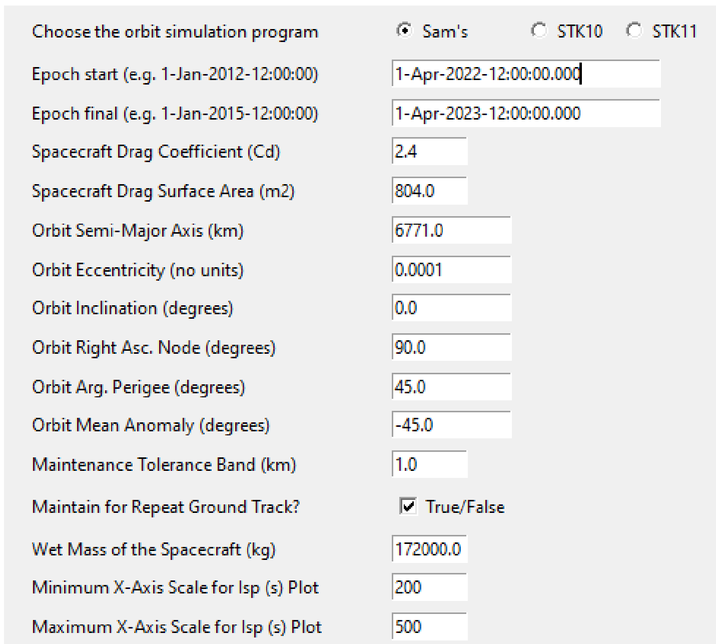

Figure 12. Parameters plugged into Orbit.M

Table 3. Thruster/engine values

Company	Model	ISP (s)	Fuel mass (kg)	Thrust (N)
SpaceX	SuperDraco	235	1500	73,000
Cygnus	BT-4	329	1500	500
Arianne	Vinci	457	1500	180,000
TsSkb	RD-0146	470	1500	68,600

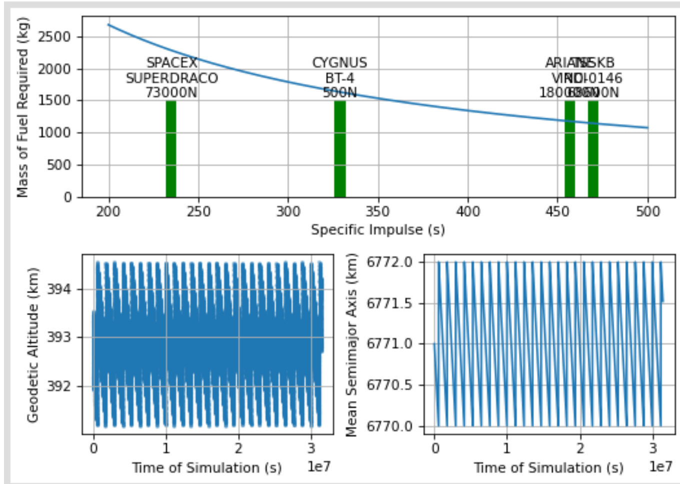

Figure 13. Simulation data at C_d = 2.2

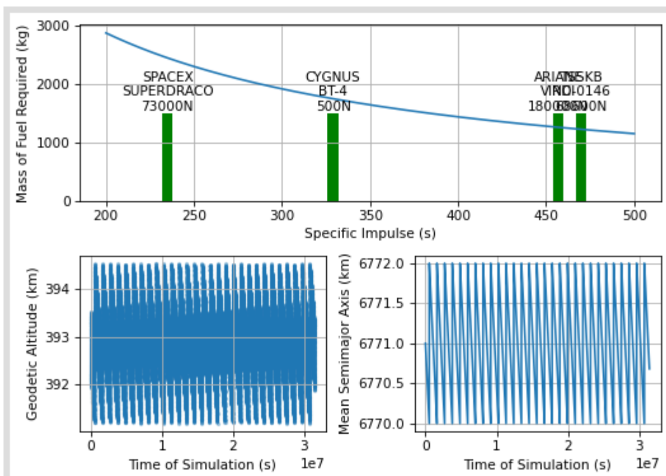

Figure 14. Simulation data at C_d = 2.4

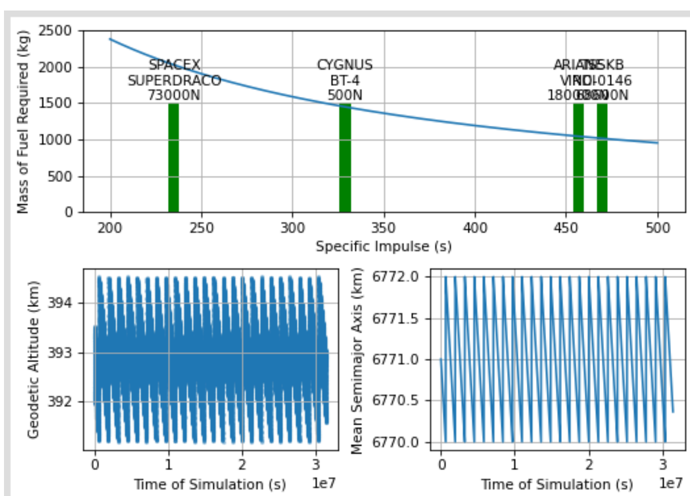

Figure 15. Simulation data at C_d = 2.0

Table 4. Parameters based on coefficient of drag

C_D	Lifetime decay date and time	No of orbits	Lifetime days	Total impulse (s)	Total ΔV
2.2	11/10/2031 17:00:00	54,229	3480	5,262,385.35	30.60
2.4	25/12/2030 17:00:00	49,710	3190	5,652,143.37	32.86
2.0	Doesn't decay in 10-year limit	-	-	4,677,621.55	27.20

The Hohman transfers are listed in the appendix 10.2 below.

From the above figures we can clearly see the effect of C_D on all of our parameters. Like how much mass of fuel is required for our burns, how often these burns will happen and at what time these will occur? From the top table in *Figure 13*, *Figure 14 and Figure 15* we can clearly see what engines would be best suited for our system. However, we must also consider each engine has a different set of parameters such as weight and size.

Overall, we can see that our space habitat will require many burns to sustain its orbit over its lifetime at approximately one burn every month. If we chose to change our tolerances, then less burns would need to be required but will have to be fired for a longer duration provided thrust stays the same.

9. Conclusion

In conclusion, in this report we have set out the basis for a potential space habitat. We have set the main design parameters required to make this habitat viable. Our final choice for the habitats main design points being: A low Earth equatorial orbit at 400km, a modular design primarily made from AA6061, 16 meters long with a diameter of 4.4 meters. We then went on to do some rough cost estimations. Found an approximate dry weight of one module being 122 tonnes, estimated the thickness of the habitat being 215mm, chose a 6 DOF robot with a claw hand for habitat maintenance and the estimated delta v values needed to sustain our habitat based on the about design points.

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10. Appendix

10.1. Derivation of orbital decay model

Below is the derivation of the orbital decay model. This takes into account both atmospheric drag as well as solar radiation drag. And is heavily reliant on Samuel et al formula [6].

$$\alpha_{drag} = -\frac{1}{2}\rho C_d\left(\frac{A}{m}\right)V^2$$

$$\alpha_{solar} = \frac{A(1+r)}{m} * P = 2.56 * 10^{-8}\ ms^{-2}$$

$$V^2 = GM\left(\frac{2}{R} - \frac{1}{a}\right) = \frac{GM}{R}$$

$$U = KE + GPE = \left(-\frac{GM_E m}{2R}\right)$$

$$\frac{dU}{dR} = \frac{GM_E m}{2R^2}$$

$$\alpha_0 = \alpha_{drag} + \alpha_{solar}$$

$$\frac{dU}{dt} = \frac{F.ds}{dt} = \frac{F * R * d\theta}{dt} = F * R * \omega$$

$$\omega = \frac{2\pi}{T} = \sqrt{\frac{GM_E}{R^3}}$$

$$\frac{dU}{dt} = m\alpha_o\sqrt{\frac{GM_E}{R}}$$

$$\frac{dR}{dt} = \left(\left(\frac{dU}{dR}\right)^{-1} . \frac{dU}{dt}\right) = 2\alpha_o\sqrt{\frac{R^3}{GM_E}} = \frac{\alpha_o T}{\pi}$$

$$\frac{dR}{dt} = \frac{\alpha_o(R).T(R)}{\pi}$$

10.2. Hohmann transfers

$C_D = 2.2$

1 Maintain.Hohmann 2022-04-08 06:00:00 1.1333120836439665
2 Maintain.Hohmann 2022-04-21 21:36:12 1.1331436618311828
3 Maintain.Hohmann 2022-05-05 13:12:24 1.1329920765138284
4 Maintain.Hohmann 2022-05-19 04:48:36 1.1332519441053668
5 Maintain.Hohmann 2022-06-01 20:24:48 1.1330552284119921
6 Maintain.Hohmann 2022-06-15 12:01:00 1.133318569505057
7 Maintain.Hohmann 2022-06-29 03:37:12 1.1331623314391615
8 Maintain.Hohmann 2022-07-12 19:13:24 1.132997921047148
9 Maintain.Hohmann 2022-07-26 10:49:36 1.133266775344128
10 Maintain.Hohmann 2022-08-09 02:25:48 1.1330708415150843
11 Maintain.Hohmann 2022-08-22 18:02:00 1.1333231042287397
12 Maintain.Hohmann 2022-09-05 09:38:12 1.1331809365083076
13 Maintain.Hohmann 2022-09-19 01:14:24 1.133005645412707
14 Maintain.Hohmann 2022-10-02 16:50:36 1.133280283087284
15 Maintain.Hohmann 2022-10-16 08:26:48 1.1330874742727057
16 Maintain.Hohmann 2022-10-30 00:03:00 1.1333256160069598
17 Maintain.Hohmann 2022-11-12 15:39:12 1.1331992499611423
18 Maintain.Hohmann 2022-11-26 07:15:24 1.1330151937368904
19 Maintain.Hohmann 2022-12-09 22:51:36 1.1332922792201887
20 Maintain.Hohmann 2022-12-23 14:27:48 1.1331049550929153
21 Maintain.Hohmann 2023-01-06 06:04:00 1.1329863429642664
22 Maintain.Hohmann 2023-01-19 21:40:12 1.133217031724456
23 Maintain.Hohmann 2023-02-02 13:16:24 1.133026469658423
24 Maintain.Hohmann 2023-02-16 04:52:36 1.1333026239707262
25 Maintain.Hohmann 2023-03-01 20:28:48 1.133123042512949
26 Maintain.Hohmann 2023-03-15 12:05:00 1.13298793768417
27 Maintain.Hohmann 2023-03-29 03:41:12 1.1332340660540363

$C_D = 2.4$

1 Maintain.Hohmann 2022-04-07 16:30:00 1.1331042783953935
2 Maintain.Hohmann 2022-04-20 04:56:12 1.1330496684922928
3 Maintain.Hohmann 2022-05-02 17:22:24 1.1330092153817963
4 Maintain.Hohmann 2022-05-15 05:48:36 1.1329884482984252
5 Maintain.Hohmann 2022-05-27 18:14:48 1.1333224902931849
6 Maintain.Hohmann 2022-06-09 06:41:00 1.1332985449278308
7 Maintain.Hohmann 2022-06-21 19:07:12 1.133255566024697
8 Maintain.Hohmann 2022-07-04 07:33:24 1.1331993093359205
9 Maintain.Hohmann 2022-07-16 19:59:36 1.133137308143095
10 Maintain.Hohmann 2022-07-29 08:25:48 1.1330778222720674
11 Maintain.Hohmann 2022-08-10 20:52:00 1.13302887318792
12 Maintain.Hohmann 2022-08-23 09:18:12 1.1329969738818715
13 Maintain.Hohmann 2022-09-04 21:44:24 1.1333262327165694
14 Maintain.Hohmann 2022-09-17 10:10:36 1.133314080186914

15 Maintain.Hohmann 2022-09-29 22:36:48 1.1332808178071079
16 Maintain.Hohmann 2022-10-12 11:03:00 1.1332308686462778
17 Maintain.Hohmann 2022-10-24 23:29:12 1.1331709559403556
18 Maintain.Hohmann 2022-11-06 11:55:24 1.1331090797446217
19 Maintain.Hohmann 2022-11-19 00:21:36 1.133053538659731
20 Maintain.Hohmann 2022-12-01 12:47:48 1.1330117304221732
21 Maintain.Hohmann 2022-12-14 01:14:00 1.1329892767153602
22 Maintain.Hohmann 2022-12-26 13:40:12 1.1333234488734965
23 Maintain.Hohmann 2023-01-08 02:06:24 1.1333011752661064
24 Maintain.Hohmann 2023-01-20 14:32:36 1.133259522022631
25 Maintain.Hohmann 2023-02-02 02:58:48 1.1332040548964926
26 Maintain.Hohmann 2023-02-14 15:25:00 1.1331421951907383
27 Maintain.Hohmann 2023-02-27 03:51:12 1.1330822224616526
28 Maintain.Hohmann 2023-03-11 16:17:24 1.1330321973072142
29 Maintain.Hohmann 2023-03-24 04:43:36 1.1329987470468854

$C_D = 2.0$
1 Maintain.Hohmann 2022-04-08 22:10:00 1.1333131549576128
2 Maintain.Hohmann 2022-04-23 22:26:12 1.1329897000994822
3 Maintain.Hohmann 2022-05-08 22:42:24 1.13303733289295
4 Maintain.Hohmann 2022-05-23 22:58:36 1.1331258019970285
5 Maintain.Hohmann 2022-06-07 23:14:48 1.1332247306817878
6 Maintain.Hohmann 2022-06-22 23:31:00 1.1333001070852005
7 Maintain.Hohmann 2022-07-07 23:47:12 1.132986364142955
8 Maintain.Hohmann 2022-07-23 00:03:24 1.1330187668487646
9 Maintain.Hohmann 2022-08-07 00:19:36 1.1330983729086823
10 Maintain.Hohmann 2022-08-22 00:35:48 1.1331978553143394
11 Maintain.Hohmann 2022-09-06 00:52:00 1.1332830385423136
12 Maintain.Hohmann 2022-09-21 01:08:12 1.1333246410217357
13 Maintain.Hohmann 2022-10-06 01:24:24 1.1330040364873146
14 Maintain.Hohmann 2022-10-21 01:40:36 1.1330725462146385
15 Maintain.Hohmann 2022-11-05 01:56:48 1.1331698196502769
16 Maintain.Hohmann 2022-11-20 02:13:00 1.1332624081266778
17 Maintain.Hohmann 2022-12-05 02:29:12 1.133318524147306
18 Maintain.Hohmann 2022-12-20 02:45:24 1.1329935658541153
19 Maintain.Hohmann 2023-01-04 03:01:36 1.1330490758535472
20 Maintain.Hohmann 2023-01-19 03:17:48 1.1331413923642506
21 Maintain.Hohmann 2023-02-03 03:34:00 1.1332388191134486
22 Maintain.Hohmann 2023-02-18 03:50:12 1.1333078504463963
23 Maintain.Hohmann 2023-03-05 04:06:24 1.1329876298305055
24 Maintain.Hohmann 2023-03-20 04:22:36 1.1330286012736224