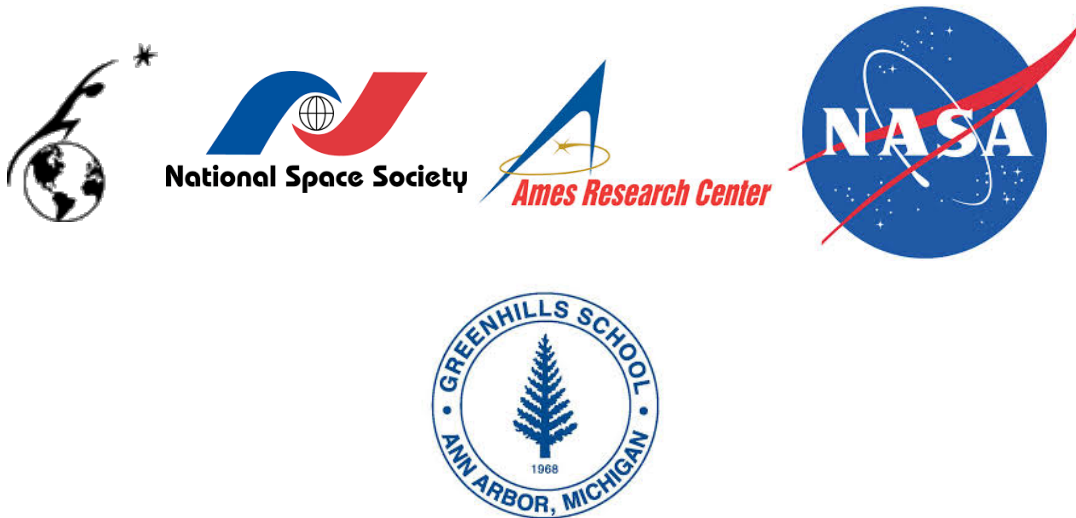# The Freyr Project

Alexander C. Reeves

2015

FREYR

This report is dedicated to Mr. Thomas Reeves, Jr., who taught me to be thorough and take it all seriously.

Contents

List of Figures

List of Tables

0.0 Abbreviations and Terminology

CCN - Closed-Cell Neoprene
COTS - Commercial Off-The-Shelf
EML(n) - Earth-Moon Lagrangian Point #n
ENE - Earth Normal Environment
ETV - Earth Transfer Vehicle
EVA - Extravehicular Activity
FDP - Freyr Docking Protocol
GSO - Geostationary Orbit
^{3}He - Helium-3, an Isotope of Helium
IGTS - Inertial Guidance and Tracking System
IIR - Isobutyl Isoprene Rubber
I_{sp} - Specific Impulse
ISRU - In Situ Resource Utilization
kPa - Kilopascals
LEO - Low Earth Orbit
LFTR - Liquid Fluorine Thorium Reactor
LLO - Low Lunar Orbit
LTV - Lunar Transfer Vehicle
MCP - Mechanical Counterpressure
MPa - Megapascals
NTR - Nuclear Thermal Rocket
OLS - Operational Lifespan
PAMAM - Polyamidoamine (Dendrimer Membrane)
PC - Polymer Concrete
PPM - Parts Per Million
RPF - Rigid Polyurethane Foam
RTG - Radioisotope Thermoelectric Generator
S-CO$_2$ - Supercritical Carbon Dioxide
SCWO - Supercritical Water Oxidation
SEL(n) - Sun-Earth Lagrangian Point #n
SLS - Space Launch System
TEI - Trans-Earth Injection
TLI - Trans-Lunar Injection
UHF - Ultra High Frequency
VASIMR - Variable Specific Impulse Magnetoplasma Rocket
VLF - Very Low Frequency

0.1 Executive Summary

Freyr is the orbital settlement that *The Freyr Project* describes. It provides a home and societal structure for 20,000 individuals and is designed to be part of a pseudo-modular system for long-term space settlement.

Freyr takes the form of a central cylindrical core surrounded by concentric tori that contain its various functions. The entire structure has a radius of 525 meters. Pseudogravity is provided by rotating the entire structure about its central axis; one section is left non-rotating.

Habitation is provided in the outermost torus, along with most of the life support equipment. Inside of this torus is the Storage torus, and the innermost torus is the Industrial torus, which contains the various industrial apparatus used by the settlement.

Industrial goals include the processing of metals, silicates, and other lunar materials into useful products, the extraction and processing of helium-3, and the manufacturing of spacecraft for expansion into the rest of the Solar System. These apparatus may include an interface with existing space agencies or private firms, especially entities already present in space.

Freyr's power is provided through a liquid fluorine thorium salt reactor attached to the Industrial torus. The power supplied allows Freyr's internal workings and keeps the interior temperature at a comfortable level; heat is radiated out to space to offset power generation.

The Freyr Project includes a description of Freyr's support systems, including various vehicles designed to ferry cargo and passengers as well as structures set up on the lunar surface. The purpose of these structures and vehicles is to support Freyr in its operations and keep the settlement supplied with raw materials.

Freyr's timeline suggests a 20 year construction period followed by at least 50 years of operation. Freyr could be built mainly using technology that exists today, so it is not a terribly far-fetched idea with the exception of obtaining the many billions of dollars of funding required for construction to begin.

In keeping with the principles of chaotic propagation, human elements of Freyr are not extensively discussed. It is assumed that Freyr's inhabitants will discover a system that works for them and work within that frame to obtain the best result. Despite the impossibility of predicting such things as population demographics accurately, an effort is made to model them reasonably accurately, and governmental agencies are sketched out in a very rough form. The predictions made - for they are predictions - simply reflect the author's opinion of solutions that are likely to work and could reasonably be adopted by the inhabitants of Freyr.

Freyr is the first space settlement built by humans, but it is not intended to be the last. Its location, mission, support structures and vehicles, and even societal structure serve as a test bed for future settlements and help to test new technologies that will make the next generation of space settlements more economical, more capable, and sturdier, with the eventual goal of developing interstellar capabilities. Freyr is only the first step in this dream, but it is a strong first step that paves the way for a second, a third, and eventually the entire thousand miles.

0.1.1 Report Structure

This report is divided into several partitions for clarity. Freyr itself is described in Chapter 1, support systems that help Freyr operate are described in Chapter 2, Freyr's construction and operations are described in Chapter 3, and a conclusion is given in Chapter 4. After Chapter 4, various appendices appear, describing important portions of the report and helping to clarify concepts used herein. Endnotes appear after these appendices and are referenced throughout the report by superscripted in-text citations.

That is to say, materials directly related to the settlement itself (industry, habitation areas, physical structure, etc.) are located in Chapter 1, while things such as the Earth Transfer Vehicles (ETVs) and Lunar Transfer Vehicles (LTVs) that shuttle cargo, the structure of ISRUs that provide Freyr with raw materials, and other supporting systems are located in Chapter 2, while Chapters 3 and 4 include, respectively, the overall timeline of Freyr's construction as well as its operational capabilities and a conclusion tying the report together. Please go to Chapter 4 for a summary of some of the workings of Freyr's structures for a further overview of the report; to get a very, very general idea, the Table of Contents is your friend.

Some mathematical and physical derivations are, by necessity, presented in Appendices A, B, and E. These help readers to understand the sources of equations used in the report and are not themselves a part of the description of Freyr. Appendices C and D, however, contain information vital to understanding Freyr and its support systems, and it is suggested that the reader peruse these appendices at appropriate times during their exploration of the report.

0.1.2 Acknowledgements

Thanks to Mr. Al Globus for organizing and putting together this competition, to all the other judges who have given their time to review submissions, and especially to the NASA Ames Research Center and the National Space Society for their support of passionate students. I would also personally like to thank Dr. Deano Smith, Mr. Thomas Reeves, and Mrs. Stephanie Reeves for supporting me as I wrote this report and for encouraging me when the going got rough.

I hope you enjoy reading about Freyr, humanity's first home among the stars.

Chapter 1

Freyr

1.1 Background

As humanity continues to develop our capabilities and explorations, it is inevitable that we will be forced to seek a home outside of Earth's atmosphere and gravity: either we will make Earth uninhabitable ourselves, or some natural disaster (e.g. super volcano, asteroid impact, etc.) will force us to abandon the planet. There is a certain potential for these needs to be met with outposts on other worlds, but such planetary settlements have several drawbacks. Specifically, launching out of a gravity well requires much greater fuel budgets, residence on a planetary surface requires costly measures against contamination by dust and other harmful substances, and construction on a planetary surface is significantly more difficult (especially since, whether construction is carried out in orbit or on a planetary surface, construction workers will need to wear protective atmospheric suits). It is possible, of course, that planets in other star systems may provide a home for humans, but these star systems are unreachable on human time scales and any ship that could visit one or more of them would have to function as a self-sustaining settlement in the vacuum of interstellar space for some thousands of years. While planetary bases will have applications in the exploration and settlement of space, then, the more optimal solution for our needs lies in free-flying space settlements.

Certainly, orbital settlements have their own drawbacks. They are harder to shield against radiation, must provide a form of artificial gravity, and have to be resupplied with critical materials on occasion. Compared to planet-based settlements, however, they are still far superior. To optimize the settlement design, we combine a primary orbital settlement with support and production facilities planetside, making use of the advantages of an orbital settlement while ensuring that the settlement is sustainable.

This report is intended to be a discussion of a space settlement that could be built using technologies little more advanced than today's. That is, unproven and outlandish concepts such as launch to LEO from massive electromagnetic cannons, the use of space elevators to lift payloads to orbit, 90% efficient solar panels, and cold nuclear fusion are not employed in the design. Additionally, the design strives to be as realistic as possible, making use of reasonable specifications and cost estimates. This report does not describe a fairy tale with kilometer-square mirrors to reflect sunlight; it is instead an examination of how an orbital space settlement could actually be built. The key philosophy behind Freyr has several points:

1. While technologies that are currently within our technological ability but are not currently under development may be used, it cannot be assumed that miraculous technological advances will be made.

2. A proposal for a space settlement should endeavor to be as realistic and accurate as possible.

3. A space settlement must have an economic reason for existence.

4. Design of the settlement should be carefully considered to maximize simplicity, efficiency, structural integrity, and utility.

Freyr's design, capabilities, and technologies are based on this philosophy, and all parts of Freyr's design seek to maximize practicality and functionality. It attempts to be a complete look at an orbital space settlement from a technical point of view: exploring all the major systems required for functionality, investigating how various subsystems are connected, devising strategies for industrial

and support mechanisms, and in general providing a comprehensive look at what a space settlement could actually be. Attention has been paid to every detail of the design, and every part of Freyr is designed with care and intent to be the most effective and most practical solution.

Freyr was built from the ground up with a common vision: simplicity. Freyr is designed to be a simple, yet functional, design that provides the services necessary of a space settlement without becoming extravagantly expensive or overly fancy. It is not a working camp or scientific outpost, but it is not a hotel either. Freyr is a place used by thousands of people every day and a hub of inter-orbital and interplanetary travel, and as such, it is functional in the extreme.

While it is true that it is very difficult or impossible to determine exactly what the structure of a settlement will be of what the economic modalities of a space settlement will require, it is nevertheless possible to make general statements about the economy, society, and physical structure of these settlements. For example, Freyr incorporates a large manufacturing capability, which will become useful in any of a number of possible developmental regimes. While the specific industries may vary, the large-scale structures are fairly constant - and the materials that will be processed are, by and large, much the same due to the limited number of available compounds on the lunar surface and elsewhere. With that said, many of the details of population dynamics, societal structure, and other factors related to the human aspects of the settlement are left unspecified beyond vague and general statements. This is not for lack of consideration, but rather for lack of knowledge about the evolving societal pressures and population shifts that may occur in the future. Even many of the engineering details of Freyr are dependent on technological developments, but it seems reasonable to make certain assumptions about development timescales and improvement schedules, which were used to lead to the technology used. Additionally, it stands to reason that if a particular structure is a good choice in the present, it will likely also be a good choice in the future; the laws of physics do not change in the same way that the laws of societal dynamics do.

Design Challenges

One of the problems with orbital settlements is population sustainability. The settlements cannot be too large before they break up under the centripetal forces required for artificial gravity, and population size is essential for continued health of the colony's residents, the long-term viability of the settlement, and the avoidance of genetic diseases: a direct conflict is set up between settlement size and population sustainability. There are two main solutions: extend a single space settlement along its axis of rotation, thereby keeping the rotational radius small and working around the material limitations on a large radius, or construct multiple settlements that are capable of cooperation and intermixing to achieve a large enough population size to be sustainable.

Other concerns are of a structural nature: the materials used must allow the station to generate artificial gravity (the only feasible method to do this is through rotation, which results in a centripetal acceleration that functions as gravity), withstand the harsh environment of space, provide adequate radiation shielding for residents, and perform all the other functions necessary for maintaining healthy life in the vacuum of space.

Furthermore, the psychological well-being of the residents presents several challenges. For extended

life in the settlement to be psychologically sustainable, multiple conditions must be met: spaces that simulate the outdoors, light spectra that mimic ambient light, areas for recreation and for exercise, and others. These spaces are difficult to construct in a rotating settlement, providing significant challenges to developing the settlement correctly.

Perhaps one of the most critical challenges lies in the economic situation of the settlement, for without economic justification there will never be support for the station's construction in the first place. The expected cost of any self-sustaining station cannot be less than some hundreds of billions of dollars with additional tens of billions in maintenance, and presenting the cost of such an investment up front is impossible due to public opinion, financial difficulty, and a range of other concerns, so it is essential that the settlement have a means of economically supporting itself. Marx would say that the ideological superstructure of a pace settlement must be built over an economic substructure in order to survive. This means must come in the form of either goods or services at the station, and must justify the cost of station construction and maintenance: thus the economy of the settlement must not simply break even, but actually provide a net income for the station. The preference for this economic justification is, of course, a quick return on investment and a large profit margin for further development.

A final concern is resupply of the settlement. Up until now, space stations have followed one basic paradigm: materials to sustain life are brought from Earth, some parts of the life support system are recycled on board, and the waste left over afterwards is jettisoned and allowed to burn up in the atmosphere. This has only been possible because these stations have existed solely in LEO, where it is possible to provide frequent resupply at acceptable cost. Any space settlement, on the other hand, will be far from LEO and have too large a population to import the same types of goods that are regularly delivered to the ISS or were delivered to stations like Mir and Skylab. Instead, the settlement has to be, for all intents and purposes, self-sufficient.

While the settlement is capable of manufacturing many of the materials it will require from raw materials, some items will need to be imported from Earth. Medical supplies, for example, especially drugs, are particularly difficult to manufacture in orbit - not due to the fact that they are being made in orbit, but because of the relatively small population size: manufacturing the wide range of medicines required to treat the set of illnesses that may be encountered requires large numbers of skilled technicians and equipment.

All of these concerns are addressed in the details of the settlement and supporting equipment.

Development of Freyr

Freyr, as proposed here, is not a finished product. Rather, it is the beginning of a whole set of new colonies that will spread humankind through the solar system and, eventually, through the stars. Nevertheless, Freyr is intended to be a full development plan, at least in terms of physical structure. This is because once Freyr has been set rotating, it will be nearly impossible to perform additional construction on it. While it would be possible to stop the rotation, perform construction work, and then resume Freyr's rotation, this results in months and years of lost gravitational time - which, given the size of Freyr and the economic-industrial processes that must be kept running

to keep it stable and in the black, translates to the Freyr's stagnation and death, not to mention the effect of years of microgravity on Freyr's inhabitants.

Thus, Freyr's physical structure is intended to remain relatively unchanged throughout its life cycle. To be sure, when Freyr is spun up the interior is not finished, and there may even be sections that are unpressurized, but the exterior structure is not significantly altered once Freyr is spun.

The one possible exception to this general statement is the addition of another rotating section at the other end of Freyr's central core. This would have the effect of doubling Freyr's population, industrial, and manufacturing capacity, leading to further profits and a more economically and culturally powerful Freyr. This development, however, would have to come after many years of operation and is not expected for quite some time.

As Freyr develops and becomes profitable, it may become desirable to construct additional settlements in orbit around the Moon. These may be similar to Freyr (or even identical, to save on R&D costs), or depending on technological advances and lessons learned from Freyr they may be quite different. It is not anticipated that these additional settlements will have any large impact on Freyr's existence apart from collision avoidance (which could easily be dealt with by placing them in a slightly different orbit). That's because while transportation between two such settlements is theoretically possible and would require little ΔV, the transport of large numbers of people is still relatively infeasible and so the populations as a whole are expected to remain fairly separate and autonomous. That said, multiple colonies would allow each individual settlement to focus on one or a few particular areas and simply trade with other settlements to get the rest of what they need, allowing better economies of scale.

1.1.1 Naming

As humanity looks to build its first space settlement, it wishes to express a feeling of hope and wonder at its new place in the heavens. The expectation is that this settlement will result in greater prosperity, great scientific bounty, new ways to explore space, and vast economic benefits. As such, humanity wishes to give the settlement a name that reflects the hope that goes into its completion. Many are considered, but the conclusion is made to call our orbiting home Freyr after a Norse deity.

Freyr is one of the most revered Norse gods, even being called "the foremost of the gods"[1]. His good will leads to wealth, power, fertility, and peace for those who honor him, much as the orbiting settlement would lead to a greater age of human exploration and life.

The Ynglinga saga writes of Freyr[2]:

> "Frey took the kingdom after Njord, and was called *drot* by the Swedes, and they paid taxes to him. He was, like his father, fortunate in friends and in good seasons. Frey built a great temple at Upsal, made it his chief seat, and gave it all his taxes, his land, and goods. Then began the Upsal domains, which have remained ever since. Then began in his days the Frode-peace; and then there were good seasons, in all the land, which the Swedes ascribed to Frey, so that he was more worshipped than the other gods,

as the people became much richer in his days by reason of the peace and good seasons. His wife was called Gerd, daughter of Gymis, and their son was called Fjolne. Frey was called by another name, Yngve; and this name Yngve was considered long after in his race as a name of honour, so that his descendants have since been called Ynglinger."

This paragraph embodies what Freyr represents as a space settlement: the beginning of an era of peace, yes, but also an era of prosperity, the beginning of an honorable legacy, and the enduring human conquest of space. When Freyr came to the Swedes, he provided the means for them to improve their situation by providing for them, helping the harvests to come, and providing a return on investment to the Swedes. In the same way, Freyr serves as a mechanism by which the human race is given the ability to each out into the stars and usher in a golden age of humankind.

1.1.2   Purpose

The most important question that a space settlement must answer is simply "why?". Without a reason why it should be built, a reason why it will result in a net benefit, there is no reason to build the settlement in the first place. After all, probes and robots can explore the solar system much more cheaply than we can: why should humans leave the Earth at all?

Freyr's answer to this is manyfold, with several factors playing towards the decision to construct the settlement. Chief among these is the fact that at some point, the Earth will become uninhabitable to humans. This may not happen until the Sun cools into a red giant in some billions of years, or it could happen tomorrow when a nuclear weapons accident causes global devastation through automatic retaliation protocols. In any case, the human race has two options: to be at least somewhat prepared to do without Earth, or to die on that day. Another reason for building Freyr is its economic justification, which provides a net profit back to Earth on a relatively short (25 years) timescale and provides new resources that Earth would not otherwise have access to. Freyr also provides a platform for exploration, both to find new places for humans to live and to bring back a wealth of valuable scientific data to Earthbound scientists for developing medical treatments, more advanced technology, and theories about the universe. To this end, Freyr has been given several missions, or purposes, detailed below.

0) Overview: Freyr allows a thorough study of how radiation and microgravity can best be handled in continuing human colonization, helping develop technologies to continue human exploration. It also provides an advanced base for launching interplanetary missions and fabrication of perfect crystals for technological applications.

1) Human habitation in space: a space settlement is an essential step towards fuller knowledge of how human anatomy reacts to being in space, which will allow for greater and further exploration of the solar system and will set guidelines for future settlements. The data provided by years of observation of thousands of people will also answer questions about the psychological effects of very long-term spaceflight and confinement in a relatively small habitat.

2) Microgravity industry and research: the environment of space is a prime location for manufacturing many components essential for further technological progress. An example of this is perfect crystals, which can only be grown in a μg environment such as the laboratory space Freyr provides.

While crystals grown in normal gravity have defects due to gravitational stress, crystals grown in μg can be flawless, leading to better semiconductor performance, and perfect crystals of proteins are invaluable to scientists studying their structure with crystallographic methods[3], leading to advances in fields from biotechnology to agriculture.

3) Solar System exploration and colonization: a third great benefit of an orbital settlement like Freyr is reduced ΔV to other astronomical bodies. Freyr is located only 0.09 km/s from Earth escape, a whole 12.52 km/s above the surface of the Earth[4]. Additionally, the lack of atmosphere and gravity at Freyr means that interplanetary probes and vehicles may be constructed in a way optimized for spaceflight, rather than a compromise between travel in atmosphere and in vacuum. Combined, these facts mean that Freyr can launch interplanetary missions at lower cost and with better ability to handle interplanetary flight. From Freyr, the solar system is within our reach. A consequence of this ability to easily reach solar system targets is that Freyr is a hub of the interplanetary spacecraft construction industry as the first established orbital colony. Freyr is capable of constructing and launching spacecraft at lower cost and higher efficiency than any Earth-bound counterpart, leading to faster, more reliable, and more thorough exploration of the solar system and providing another source of income for Freyr.

4) Economic self-sufficiency: perhaps the most important reason for Freyr's existence is its economic justification. As mentioned before, Freyr has a fantastic ability to launch spacecraft on interplanetary missions without the massive expense of launching a rocket from Earth. This allows Freyr to act as a contractor for space agencies: the agency requests a spacecraft built to certain specifications with certain capabilities and experiments, and Freyr builds and launches the craft. Freyr also contracts itself out to provide a μg experimental environment for testing human subjects or the behavior of objects in freefall. Freyr's most important economic item, however, is the production of valuable materials for use on Earth. From mining operations on the Moon, Freyr has access to cheap silicon, precious metals, and all other components needed to construct circuit boards. Since they are etched into nigh-perfect silicon crystals in an absolutely sterile environment, these integrated circuits and circuit boards are superior for high-power tasks and fast applications. Other materials, such as titanium, can be more efficiently produced in space, and it may eventually make economic sense to transport them back to Earth. Freyr also has the capability to provide access to vast stores of volatiles adsorbed to the lunar regolith, including helium, hydrogen, carbon dioxide, and methane, that alleviate its economic status and help it to be self-sufficient. For example, helium-3, an isotope of helium found in lunar regolith, can be sold for billions of dollars per ton, and it is currently estimated that a reasonable price would be \$5,700,000,000[5] per ton. Freyr could sell this and other materials to Earth to help provide its economic justification.

4.5) Tourism: one last economic benefit that Freyr can provide is a tourist service to the edge of Earth's influence. It is not difficult to move the mass of one person from LEO to Freyr in an Earth Transfer Vehicle (ETV), and such a trip would provide up to tens of millions of dollars in revenue for Freyr. Along similar lines, agencies and individuals could send up experiments to be run in microgravity, experiments that may take too long for testing in a parabolic airplane trajectory but that cannot be tested another way. Freyr provides a controlled microgravity environment for these experiments.

1.1.3 Positioning

Freyr's position was chosen to allow it to remain in close contact with the Earth, as it is humanity's first space settlement and therefore must be readily available for scientific, legal, and emergency purposes, among others, and to promote the economic viability of the settlement. Several locations were considered, based on potential resources and proximity to Earth (measured as communications time delay).

Table 1.1: Position Candidates

Position	Resources	Distance
LEO	None other than Earth	<<1 second
GSO	None other than Earth	<1 second
Lunar Orbit	Lunar minerals & ^{3}He	1.3 seconds
Earth-Moon L_4 Point	Lunar minerals & ^{3}He	1.3 seconds
Earth-Sun Lagrange Points	None other than a few asteroids	8.5 minutes
Venus Orbit	Venusian atmosphere	2.1 to 14 minutes
Mars Orbit	Martian minerals Deimos and Phobos	3 to 21 minutes
Asteroid Belt	Asteroids	ca. 30 minutes
Jupiter Orbit	^{3}He and minerals on the moons	33 to 53 minutes
Saturn Orbit	^{3}He and minerals on the moons	ca. 1.3 hours

Considering more carefully the various aspects of these orbits, other advantages and disadvantages become clear. Beyond Saturn, resources become too scarce and communication too difficult to consider settlement at this stage in humanity's development. LEO is unsustainable due to orbital decay, GSO is already crowded with communication satellites, and Jupiter's massive van Allen belts rule out any permanent orbit within several planetary radii. Additionally, it is clear that for any sort of timely communications to be kept up, Freyr must be at least within an hour of Earth, and preferably closer; this requirement restricts Freyr's location to somewhere in Venus orbit, Mars orbit, or the Earth-Moon system (the Earth-Sun Lagrange points are discounted because of low mineral availability). Venus orbit, however, is problematic for several reasons despite its relative proximity to Earth, for materials cannot be harvested from Venus itself with any known technique (Venus is a truly nasty place) and Venus has no moons, meaning that resources would be very scarce in Venusian orbit. Mars orbit is likewise troublesome, as there is a large ΔV budget involved in harvesting materials from the Martian surface and Deimos and Phobos are not resource-rich. Furthermore, these locations are simply too far away from Earth for an emergency evacuation operation. The two remaining options are the EML_4 and LLO, of which LLO is the better candidate. Lunar orbit does result in communication blackout for a small period of time on a regular basis, but this is easily avoidable with a lunar communications network that will already be necessary for operations on the dark side of the Moon. Additionally, lunar orbit provides the closest access to materials mined from and refined on the Moon's surface, while EML_4 requires a greater effort to lift materials to Freyr off of the Moon.

For these reasons, it was decided to locate Freyr in a near-polar lunar orbit. Aside from the benefits of a lunar orbit, this particular configuration provides several advantages, detailed below. Additional facilities are located on the surface of the Moon and in lunar orbit, including In-Situ Resource Utilization (ISRU) units, [3]He extractors, communications systems, and water production facilities. These are not part of the primary settlement, but help to sustain Freyr and provide an economic reason for its existence.

A near-polar lunar orbit was chosen for several reasons. First, Freyr is still relatively close to Earth, a positive factor in our early stages of space habitation. It is important to maintain this proximity because, especially when we are just stepping out of Earth's influence, there must be room for error as we learn how to deal with a hard space environment. Unlike a station in LEO or GSO, Freyr does not suffer from orbital decay due to the stability of lunar orbit: the International Space Station loses between 50 and 100 meters of altitude every day due to atmospheric drag[6], and satellites in GSO have to constantly use small amounts of xenon propellant to remain in the proper orbit[7]. Being in a polar lunar orbit means that Freyr's orbit will not decay due to atmospheric drag, and ensures that minor variations in the orbit are not catastrophic for timing and orbital configuration. Most crucially, a polar orbit passes over every part of the Moon's surface over a two-week period (half the Moon's orbital period, since the Moon is tidally locked to Earth). This means that *lunar mining, refining, and manufacturing facilities only need to launch into polar orbit, and do not need to equip their rockets for plane-change maneuvers*. This saves an incredible amount of ΔV and greatly reduces the cost of launching lunar materials to Freyr.

Despite the advantages of a purely polar lunar orbit, there are tremendous disadvantages associated with a lunar orbit with an inclination of 90°. The lunar gravitational field is not uniform even to the extent that Earth's is, and so-called mass concentrations, or mascons, dot the lunar surface. These mascons exert asymmetric gravitational forces on orbiting spacecraft and eventually cause it to be flung into the lunar surface; one subsatellite released by Apollo 16, PFS-2, lasted only 35 days in LLO[8]. These mascons produce a variation in gravity as strong as 0.5% of lunar gravity, providing a strong pull on spacecraft that knocks them out of orbit. Needless to say, it is incredibly important to ensure that Freyr is not, in fact, flung into the lunar surface. Fortunately, there do exist some "frozen" lunar orbits that are indefinitely stable and do not destroy satellites[9], and it is one of these orbits that Freyr is placed in. Frozen orbits exist at 27°, 50°, 76°, and 86°[10]: specifically, Freyr is placed in an orbit with inclination 86° to attain most of the benefits of a polar orbit while remaining in a stable orbital configuration.

To obtain the maximum benefit for lunar-based ISRU facilities and other launch-dependent facilities, Freyr is placed in a low orbit of 100 km. While this orbit does bring Freyr quite close to the lunar surface, an orbit at 86° is so stable that Freyr's orbit does not change due to mascon influence. Additionally, 100 km is distant enough to avoid excessive tidal forces on Freyr, which helps to stabilize the settlement, but near enough that launch to Freyr is not overly difficult and a small ΔV budget can be maintained. Based on these considerations, it was found that a circular lunar orbit at 100 km with an inclination of 86° is the optimal orbit for Freyr.
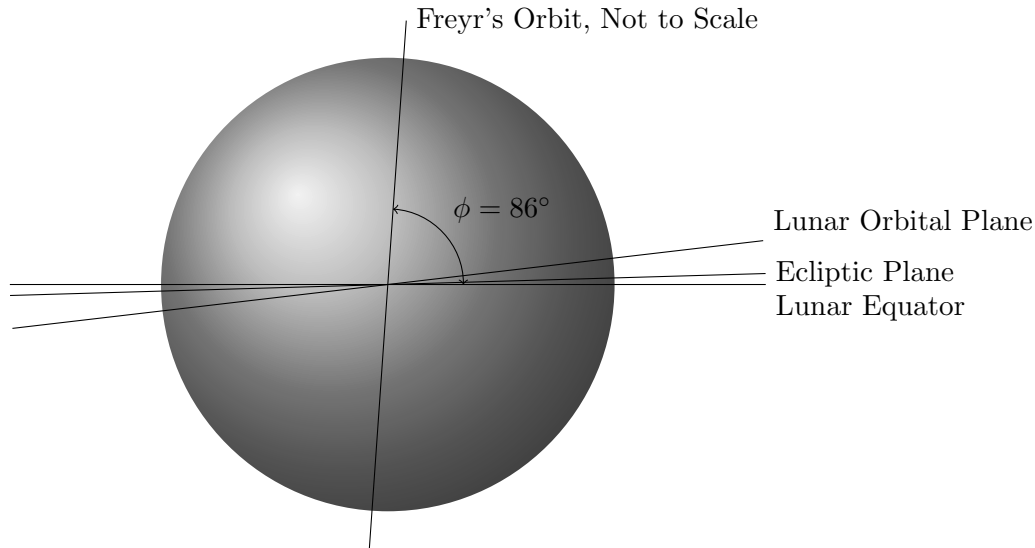
Figure 1.1: Freyr's Orbit

1.1.4 Power Supply

Freyr's power is provided by a liquid thorium salt breeder reactor. This choice makes the most sense when the drawbacks and advantages of various systems are considered. Of the energy technologies available to us on Earth, only a few are available in space. Any kind of fossil fuel is absolutely out of the picture, as are wind, geothermal, tidal, and (for our purposes, at least) biomass. The remaining possibilities are solar and some form of nuclear - fusion or fission, either using thermocouples or a typical turbine design. Table 2.2 provides a short comparison; details are discussed below.

Discussion

Solar is one of the worst options for Freyr. While solar panels have a fairly long lifespan and do not require any fuel to run since they convert sunlight directly into electron-hole pairs, they are expensive to produce and would have to be brought from Earth's surface because of how difficult they are to manufacture; Freyr might eventually have the capability, but not at first. Further disadvantages are Freyr's rotation along one axis and inertial motion along another axis, which mean together that the only reasonable orientation of Freyr is with one end facing the Sun - pointing the station that way is no simple task. What's more, on occasion Freyr is eclipsed by the Moon and/or the Earth, which would bring blackout to a settlement using solar power.

RTGs, radioisotope thermoelectric generators, are also not a very good choice. These power sources use the decay of radioisotopes to generate heat, which is applied to a thermoelectric diode to drive a voltage. Despite their long life span and extremely low maintenance levels, with space probes lasting for decades on RTGs with no maintenance whatsoever, RTGs are not practical for a station Freyr's size. First, these generators have a high mass to power ratio, with an average value being 3 watts per kilogram, making the mass of RTGs to produce just one megawatt well over 325 metric tons. Second, most of an RTG's energy production comes in the form of low-grade heat that must

Table 1.2: Freyr's Energy Source Possibilities

Energy Source	Advantages	Disadvantages
Solar	No fuel Low Maintenance Becoming more efficient	Must be lifted from Earth Only ca. 20% efficient Settlement rotation High cost Eclipses
RTG	Consistent Radioisotopes available Long life	Large mass Large heat/electricity ratio Waste very radioactive Difficult to scale up
Fusion	Large power output Clean waste Little fuel ^{3}He fuel in production	Large heat output Difficult to achieve Large support structure
Uranium Fission	Known to work Scalable Large electrical output Simple design	Lunar uranium is scarce[11] Large heat output One-time fuel use Produces actinide waste
Thorium Fission	Thorium is plentiful Breeds fissionable fuel Comparable power output Extracts nearly 100% of energy	Not extensively used currently Produces actinide waste Comparable heat output Fairly complex design and layout

be radiated out to space - typically about 10 times as much heat is generated as electricity. Finally, RTGs are very difficult to scale up to Freyr's size, and the end product of their life cycle is a metal casing full of radioactive metals that have to be carefully stored for centuries.

The only remaining choices are direct fusion and some form of fission. Fusion is a very attractive power source at first glance: it provides large amounts of power, Freyr is already producing ^{3}He fuel for use in Earthbound reactors, and fusion produces no radioactive waste that must be stored until it becomes inert. Looking deeper, however, it becomes clear why fusion is not the correct choice for Freyr. Existing fusion containment chambers, called Tokamaks, require massive support equipment, and need a large power source of their own to start up. On Earth, providing that energy boost to get over the critical temperature for fusion is not a huge problem, because other energy sources exist in close proximity. On Freyr, however, *there is no power source capable of starting a fusion reaction.* An entirely different power source would have to be brought in to start the fusion reaction going. An additional consideration is the cost of fuel. One metric ton of ^{3}He is valued at somewhere over $5.7 billion, meaning that every ton of ^{3}He used on Freyr is $5.7 billion that does not go towards Freyr's operations, limiting Freyr's economic capability; another concern is that until Freyr's $_3$He production gets underway, the settlement will have no reliable source of power.

The final option to consider is nuclear fission. Unfortunately, the amount of uranium on the Moon is not large enough for it to be used effectively as Freyr's main power source; the abundance of uranium in lunar regolith is never greater than 2.1 ppm[12]. This makes uranium fission a much less attractive prospect due to the larger uranium mining, separation, and purification facilities that would be required to obtain a usable amount of fissionable U-235. A more attractive option is thorium, but unfortunately thorium fission is not possible because it has no adequately fissionable isotopes. Therefore, thorium reactor designs must take the form of breeder reactors, which use neutrons generated in the fissioning of fissile U-233 or U-235 to convert thorium into fissionable uranium. One pathway is[13]:

$$^{232}\text{Th} +^1 n + \gamma \rightarrow^{233} \text{Th} \rightarrow^{233} \text{U} + 2\beta-$$
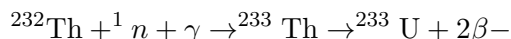
This conversion occurs when ^{232}Th is bombarded by thermal-grade neutrons, which can be supplied by the fission of ^{235}U, ^{233}U, or another fissionable isotope. In this way a reactor can synthesize more fuel for itself even as it burns fuel; any reactor with a production/use ratio, or breeding ratio, of 1 or greater is called a breeder reactor because it produces more fissionable fuel than it uses. A thorium-uranium reactor of this type would burn ^{233}U to transmute ^{232}Th into ^{233}U via neutron capture, which has a number of advantages.

1. Transuranic elements are generally not produced due to the large number of neutron captures required for transuranic production starting from ^{232}Th and the potential for fission at the ^{233}U stage and the ^{235}U stage.

2. The neutrons used for such a reactor are "slow" or "thermal" neutrons as opposed to "fast" neutrons, and having already been passed through a moderator are easier to control and shield against.

2. (b) Breeding of fuel in the reactor's jacket means that neutron flux is drastically reduced in favor of easily containable beta radiation.

3. Readily available thorium is converted into more energetically available uranium within the reactor itself, so there is no need for external uranium handling.

4. Once the reactor is started, the only fuel required is thorium and the only reaction products are fission products, which are typically much less radioactive than conventional nuclear waste.

5. Because the thorium/uranium salt can be molten, any leaks in the reactor will be contained as the salt solidifies upon exit.

Additionally, thorium is located in the same areas of the moon as iron, titanium, and other useful metals[14]. This makes it much more economically viable to separate thorium for use in Freyr's power supply.

Reactor

The specific reactor used in Freyr is a 215 MWt/100 MWe two-fluid liquid fluoride breeder reactor[1] (LFTR). This reactor has a breeding ratio of 1.07 and requires 200 kg of initial fissile material to begin the fission process[15]. The two-fluid specification refers to the separation of a ^{233}U core and a blanket of ^{232}Th salt, which increases the breeding ratio, reduces the amount of fissile ^{233}U required for the reactor, and helps to reduce the complexity of fuel processing by ensuring that the thorium to be separated from the fertile fuel is isolated from fission products that complicate the separation process.
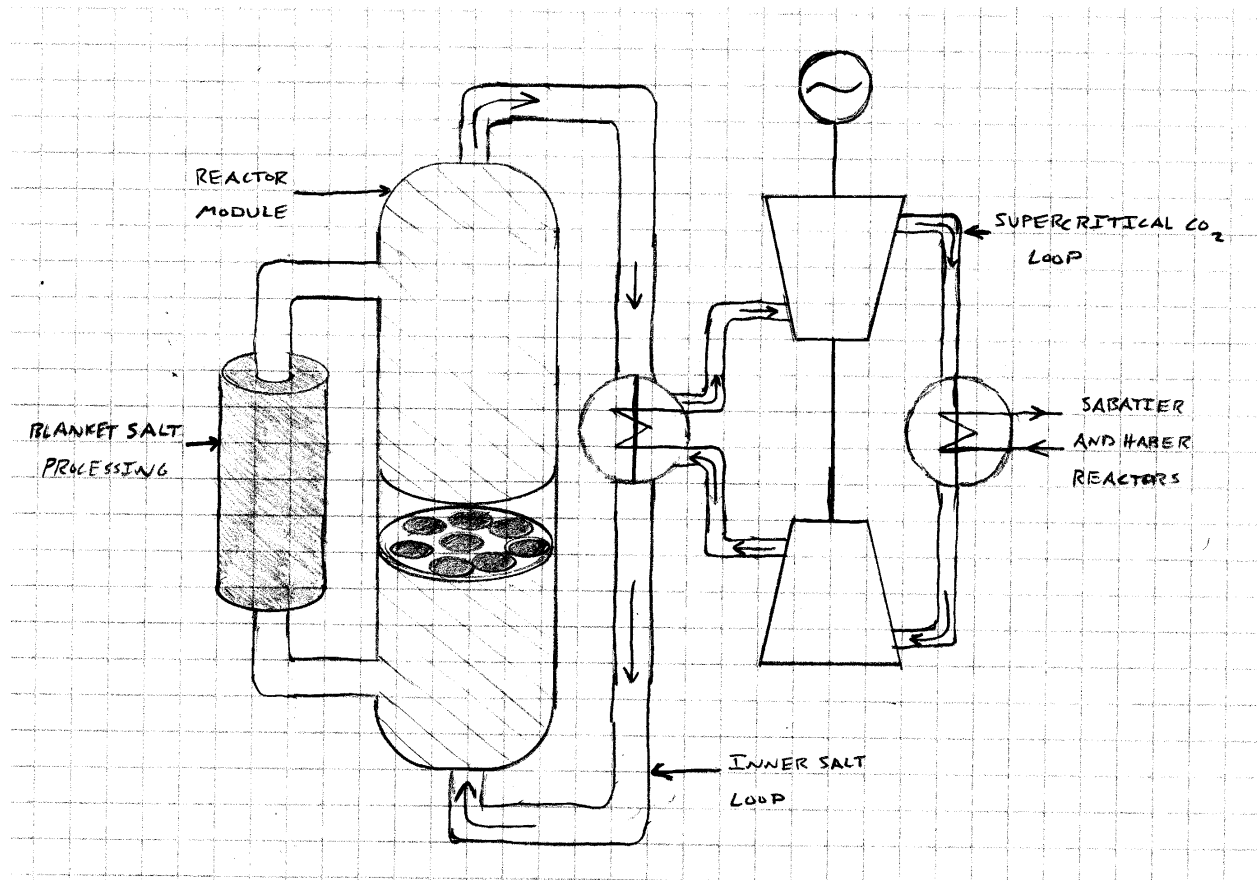
Figure 1.2: Diagram of the LFTR

The LFTR uses two salts in its operation, an inner salt and a blanket salt. The blanket salt is situated outside the reactor core and contains a fluoride of thorium-232, which captures neutrons released in the inner salt, thereby producing uranium-233 fuel and absorbing damaging neutrons, preventing neutron emission. The inner salt, by comparison, contains the fissile nuclear fuel and is itself the fuel used by the reactor. It flows through the center of the reactor, undergoing nuclear fission and generating heat. By using a two-fluid design instead of a one-fluid design, the reactor better prevents neutron flux out of the reactor, reducing emitted radiation and making the reactor safer.

---

[1]MWt = megawatt thermal; MWe = megawatt electrical

The inner salt is cycled through an exterior loop with a heat exchanger, coupled to an electrical generation system. This system is composed of two supercritical CO_2 (S-CO_2) working fluid cycles[16]. The heat exchanger runs the two cycles countercurrent to each other to produce maximum heat transfer between them and attain the maximum possible temperature for the S-CO_2. After heating in the heat exchanger, the S-CO_2 is passed through a closed Brayton cycle including an expansion turbine, a heat exchanger to draw off waste heat, and a compressor stage to re-compress the S-CO_2 to operating pressure. The two S-CO_2 cycles are in a complementary N+1 configuration to ensure that component failure or emergency shutdown of one cycle does not cut off the power to Freyr's systems or emergency facilities and so that during times of peak load, both cycles can be run to attain higher efficiency at high power output.

In general, the two S-CO_2 cycles are both run at 50% capacity, for several reasons. Having two active turbines means that if one goes offline, there is no power interruption to Freyr's essential computer, guidance, and control systems, while an increase in load can be easily responded to by increasing the power output from one or both turbines. Most importantly, keeping both turbines active at 50% of maximum load means that both turbines are being used and maintained, and will not develop problems during long idle periods, but also that neither turbine will experience intensive wear and tear, extending the useful life of both turbines.

The expansion turbine is coaxial with the compressor stage and with a 100 MWe static-coil generator. The generator is cooled by hydrogen harvested from the lunar regolith, allowing a smaller turbine and generator[17]. Note that because the Brayton cycle is closed, there is no loss of S-CO_2 working fluid, simplifying turbine operation.

The Brayton cycle, running at a working temperature of 727 °C (1000 K) and with a minimum pre-compression temperature of 33 °C (306 K)[18], has a theoretical Carnot efficiency of[19]:

$$1 - \frac{T_{min}}{T_{max}} = 1 - \frac{306}{1000} = 69.4\%$$

69.4% efficiency is, of course, unattainable in a real system with these operating parameters due to parasitic losses, increase in entropy, and other system losses. A reasonable reduction in efficiency is achieving 47% efficiency for the cycle, plus usable waste heat. 47% efficiency gives 101.05 MWe, matched to the generators Freyr uses for optimum generation efficiency.

Needless to say, the end result of this reactor's operation is that 215 MW must be stored or rejected through radiation. Much of the thermal energy output extracted from the S-CO_2 working fluid in the secondary heat exchanger is used for industrial processes (such as ammonia and methane production, via the Haber and Sabatier processes respectively), and remaining low-grade heat is used for heating the habitable portions of Freyr as energy is lost to the vacuum of space through radiative cooling. Electrical power is used for Freyr's operations, for lighting, for communication, and for spacecraft construction in the form of electron beam welding and other electrical processes. For a discussion of heat rejection, please see 1.2.4.

Waste Disposal

One of the only downsides to a nuclear fission reactor is the radioactive waste generated by the process of fissioning a heavy element like uranium. The fission products from the reaction remain radioactive for some time and must be dealt with in a manner that does not put humans at risk of a massive radiation dose or allow the problem to remain dangerous for successive generations of space colonists.

There are several criteria for effective disposal of nuclear waste. These include:

1. The waste must be placed in a location where it has no chance of coming into contact with humans,
2. Waste must not be impacted at high velocity in the vicinity of humans,
3. Waste storage locations must be reasonably energetically favorable,
4. Storage locations should be expected to remain stable for centuries or millennia, and
5. Storage mechanisms must be passive rather than active.

With these criteria in mind, several options for waste disposal can be ruled out. First, returning the waste to Earth is simply not an option. The only economically and energetically feasible way to do so would be allowing the spent fuel to disintegrate in the atmosphere upon re-entry, causing untold damage and irradiating large areas of the planet's surface. Disposal on the lunar surface is also inadvisable: either the waste is deliberately impacted into the surface, which could again irradiate a large part of the lunar surface, or it is soft-landed in a particular area, which would be a location of extremely concentrated radiation and therefore be very unhealthy for any humans who happened to venture near it.

The remaining option, which contains within it a large number of potential solutions, is disposal in a space environment. This environment could conceivably range from cislunar space (perhaps at one of the EML points) to ejection from the solar system entirely. When designing a mission to dispose of this waste, however, it is necessary to consider both the potential harm a piece of waste could do at a certain position and the energetic difficulty of getting it there. The first consideration rules out most areas in cislunar or near-Earth space, while the second makes it hideously impractical to send waste into the Sun or out of the solar system; just dropping the waste into the Sun would require some 27 km/s of ΔV[2], clearly not attainable using any reasonable means[3]. By a similar token, launching materials out of the Solar System requires a ΔV budget of about 12.4 km/s, which is much more reasonable but still a little high for routine disposal[4].

The final option is disposal in cislunar, inner solar system space (so that the waste would have to gain energy to return to Earth). It has been pointed out that placing the waste into an orbit where it could be retrieved for later use could be desirable[20], which suggests a stable orbit just inside Venus. This could be accomplished with little more than a Hohmann transfer to Venus and a gravity assist from that planet, reducing the one-way ΔV to barely 3 km/s, which accounts for an Earth escape burn and a TVI (trans-Venus injection) burn. After this second burn, the spacecraft

---

[2]See section 5.2.3; this calculation disregards the mass of Earth (which is, surprisingly, reasonable).

[3]See section 2.2.1; ETVs have just over 30 km/s of ΔV when loaded with only fuel as cargo.

[4]The derivation of this fact assumes that the final radius is simply infinity, a very good approximation because gravity is an inverse square law.

is on a Hohmann transfer towards Venus, where it will undergo a gravity assist by flying in front of and slightly offset from Venus in its orbit. This gravity assist slows down the spacecraft and puts it in an orbit near Venus by lowering its apoapsis. It also puts the waste on a trajectory slightly inclined with respect to the ecliptic, which does make recovery somewhat more difficult but also allows use of Venus at some point in the future without the worry of having radioactive waste in the same plane.

The much reduced ΔV requirements for such a disposal regime imply that an ETV could dispose of nearly 300 metric tons of waste at a time, which is the amount expected to be produced in over 1000 reactor-years of operation[21]; an important advantage of this disposal scheme is that the ETV can then easily return to Freyr, resulting in no loss of infrastructure for the settlement. Taking into account the irradiated components that may also need to be discarded, it is expected that one ETV flight for reactor waste disposal will be required every five to ten years. Note that due to the positioning of the reactors on the outside of the rotating structure, it is also possible to directly jettison nuclear waste in an emergency, although this is not recommended and would only be used in the event of a meltdown paradigm.

1.1.5   Propulsion

Freyr is equipped with some very slight maneuvering capability. It is not anticipated that Freyr will have to make any major course corrections, as lunar orbit is currently uncluttered and will be kept clear of debris. Keeping lunar orbit debris-free will not be difficult due to the reusable nature of Lunar Transport Vehicles (LTVs).

With that said, it is necessary that Freyr will have to correct or slightly change its orbit. It is not, however, feasible to provide Freyr with engines of its own, as this would add enormous complexity in routing fuel lines, would produce a system that would rarely be used, and would produce the problem of engine maintenance, compounding Freyr's not insignificant maintenance schedule. The solution that Freyr utilizes is the ETVs and LTVs: in the event that Freyr needs to boost its orbit, these craft dock to the non-rotating section of Freyr and use their engines to push Freyr into a different orbit. Thus Freyr has the capability to modify its orbit slightly, the problem of engine maintenance is solved because the ETVs and LTVs already maintain their engines for regular trips, and Freyr is moved with high efficiency due to the high I_{sp} of the ETV's and LTV's gas-core NTR engines (see 2.2.1 and 2.2.2). The ETV and LTV craft, combined, exert a total of 7362 kN of thrust against Freyr due to their combined 18 gas-core closed-cycle NTR engines.

Because of the large mass of Freyr, even with many ETV and LTV spacecraft exerting force Freyr will not accelerate at very high rates. There is no problem with having to secure items on board the station, and in fact many residents will likely be unaware that the operation is even occurring due to the small acceleration involved. This acceleration is on the scale of 10^{-4} g, depending on the exact layout of Freyr's internal structure and Freyr's precise mass at the time; a calculation assuming that Freyr's mass is 5E9 kg (see 1.3.9) says that the acceleration of Freyr will be 0.00147 meters per second squared.

1.2   Materials Analysis

Before design of Freyr was stated, the materials to construct the settlement were carefully considered. The choice of materials for applications on Freyr is crucial to the proper functioning of the settlement, in terms of both structural capability and safety. Obviously, the materials used must be capable of withstanding the stresses that will be placed on them, maintaining safety on the settlement, and they must provide adequate radiation protection for inhabitants and sensitive electronics.

Another consideration is the availability of materials to Freyr. Clearly, any materials lifted from Earth will be much more expensive than materials lifted from the Moon, so it is optimal to use lunar-derived materials in Freyr's construction. While this is not a huge problem, it does limit the materials permitted for Freyr: lifting only the mass of the ISS from Earth would cost Freyr some \$2 billion even with a large reduction in the cost of orbital insertion (disregarding construction costs, transportation to the Moon from LEO, etc.).

These considerations lead to some difficult choices in the design of Freyr, but on the whole they tend to support the general goals of Freyr well.

1.2.1   Structural

The structural integrity of Freyr is paramount. It is what keeps the population from dying a sudden death in the vacuum of outer space, what keeps materials from flying off the outside of the settlement, and what makes sure that Freyr stays in the sky.

It is extremely important to consider the structural loads on Freyr's components; if the materials chosen are incapable of bearing these stresses for long periods of time, the settlement will fail before it even begins. Structural loads can, of course, be alleviated by optimizing the structure of Freyr's load-bearing components and Freyr's overall shape, but ultimately the materials themselves must be up to the task.

For example, a long, 1 cm thick cylindrical shell of radius 100 m enclosing a pressurized gas at 101.3 kPa (Earth's sea-level pressure) holds a tensile stress of over 1 GPa, which is clearly untenable for all but the most advanced and expensive composite materials, and yet has a mass of 17 tons per meter of length[5]. To achieve a more reasonable stress of 100 MPa, the mass per length balloons up to 170 tons per meter.

It's clear that while some structural optimization can reduce the stress that Freyr's components must withstand, the materials chosen must still be very strong - there's simply no way around it. Additionally, because Freyr has to withstand frequent and potentially very large temperature variations, it is important that materials chosen must have good thermal properties.

It is clear that the best structural material here, in terms of tensile strength and density, is a composite carbon fiber material, but the expense of having these materials manufactured and shipped to orbit in large quantities makes carbon fiber a less attractive choice for Freyr's large

---

[5]The density of the material is assumed to be the same as that of aluminum.

Table 1.3: Comparison of Structural Materials

Material	Density	Young's Modulus	Tensile Strength	Availability
Aluminum[22]	2.7 g/cc	68.9 GPa	50 MPa	Lunar Processing
Titanium[23]	4.43 g/cc	120 GPa	950 MPa	Lunar Processing
Iron[24]	7.8 g/cc	211 GPa	690 MPa	Lunar Processing
Stainless Steel[25]	7.86 g/cc	193 GPa	986 MPa	Imported
Concrete[26]	2.4 g/cc	14-41 GPa	3-5 MPa	Imported
Polyethylene[27]	0.95 g/cc	700 MPa	20 MPa	Imported
Carbon Fiber[28]	1.60 g/cc	135 GPa	1.5 GPa	Imported

structural components. That said, it is put to use in smaller-scale applications such as ETV and LTV structures where smaller quantities are required and low mass is important.

Disregarding carbon fiber, two materials stand out for their poor properties: polyethylene and concrete. The low tensile strengths of these materials make them unsuitable for use on Freyr, and polyethylene particularly tends to deform when placed under a constant stress, leading to a gradual large-scale deformation and failure of Freyr's structure. Additionally, both of these materials must be imported from Earth (some of the concrete can be composed of native regolith on the Moon, but at least 15 mass % of the material must be shipped from Earth. The high cost of this import is another reason why these two materials are unsuitable for load-bearing structural components.

Stainless steel is attractive due to its high strength and corrosion resistance, but it too must be imported from Earth - at least, the coke and lime that are added to iron to produce the steel. Its density is also a problem at 7.86 g/cc.

The final three options are iron, titanium, and aluminum. Of these, titanium holds the most promise due to its corrosion resistance, high strength, and relatively low density. Aluminum is not strong enough for some applications with a tensile strength of just 50 MPa, and iron is dense at 7.8 g/cc. Titanium on its own could be a good structural material, but when combined with aluminum in an alloy called 6AL-4V Titanium[29], which has a tensile strength of 1034 MPa, but is no more dense than regular titanium and can be thermally treated and work hardened. Note that some vanadium is also added to the alloy; vanadium is available in the lunar regolith but can be forgone if necessary.

This 6AL-4V Titanium alloy is the workhorse of Freyr's structure, forming the primary hull and many other components, for all the reasons given above.

1.2.2   Radiation Shielding

Based on data from the Apollo missions on radiation exposure in lunar space, it is estimated that the unshielded radiation dose for Freyr residents would be a maximum of 46 rad per year[30], but that it could be as low as 8 rad per year. For safety, Freyr is built to shield from the highest

reasonable estimate based on available data, 46 rad per year. To provide effective shielding, it is necessary to choose the correct materials for the job.

Radiation shielding materials are varied in nature and in effectiveness. Generally, metals tend to have good resistance to radiation flux, but they have their own issues, while other materials can be better at absorbing or deflecting radiation but be lacking structurally. A thorough review of these materials was conducted before the design process and is summarized here. Note that properties of RXF-1 are not available because it is under proprietary development; numbers given here are reasonable estimates based on data. When looking at the data below, the optimum material has a low density, high Young's modulus and tensile strength, low thermal conductivity, and does not produce secondary radiation scatter.

Table 1.4: Comparison of Radiation Shielding Materials

Material	Density	Young's Modulus	Tensile Strength	Conductivity	Scatter
Aluminum[31]	2.7 g/cc	68.9 GPa	50 MPa	167 W/m-K	•
Titanium[32]	4.43 g/cc	120 GPa	950 MPa	6.7 W/m-K	•
Stainless Steel[33]	7.86 g/cc	193 GPa	986 MPa	16.2 W/m-K	•
Lead[34]	11.34 g/cc	16 GPa	12 MPa	35.3 W/m-K	•
Polyethylene[35]	0.95 g/cc	700 MPa	20 MPa	0.43 W/m-K	
RXF-1 (Estimated)	1.04 g/cc	Unknown	150 MPa	0.5 W/m-K	
Tantalum[36]	10.67 g/cc	186 GPa	650 MPa	57 W/m-K	•

On Freyr, it is imperative that radiation shielding be as light as possible to minimize the energy and monetary cost of lifting it into orbit, but the radiation protection capacity of the shield cannot be compromised. This encourages the use of low-density materials, which are also beneficial because they have a high probability of producing an atomic cross section that will interact with neutron flux, increasing the effectiveness of the shielding[37]. Low-density materials, however, are as a rule worse than high-density materials at protecting from gamma radiative flux and high-energy beta particles. High-atomic number materials tend to be best at protecting from these types of radiation, but they do produce secondary radiation upon impact, which can cause greater damage to tissue than the original radiation itself.

Another requirement is that the radiation shielding must be structural. If radiation shielding is not structural on Freyr, it only puts a greater strain on the structure: a few centimeters of lead isn't a big deal until it's all over the outside of a two-kilometer-diameter space habitat, at which point it becomes untenable and causes structural failure. As such, it is preferable to have a high ultimate tensile strength and Young's modulus, both measures of how well a material holds up under stress. A high Young's modulus is particularly important because it describes the relationship of stress to strain within a particular material, and so determines how much Freyr's structure will stretch under the load of rotation; a material with a Young's modulus of 100 GPa will experience a strain of 1% when subjected to a stress of 1 GPa, while a material with a Young's modulus of only 10 GPa would experience a strain of a whopping 10%. Thus Young's modulus is very important when considering how to construct the structural and radiation shielding portions of Freyr.

Although polyethylene-based components seem to be an attractive option for Freyr, with excellent radiation protection ability and low density, they are unsuitable for several reasons. First, polyethylene materials are too weak for the structural loads that Freyr will put on them; simply containing the atmosphere results in a stress of 236.3 MPa, far past the capabilities of polyethylene or aluminum, and other considerations only add to the stress. Additionally, polyethylene-based materials cannot be produced on the Moon due to the scarcity of carbon and would have to be imported at huge cost from Earth. Finally, as if these considerations were not enough, polyethylene has a low melting point of about 130 °C[38], is flammable, can be dissolved by many hydrocarbon solvents, and has a tendency to gradually deform under stress, leading to greater and greater strain until complete failure of the polyethylene.

Most metals fall prey to considerations just as devastating: lead, while excellent at blocking gamma radiation, is very poor at stopping neutron flux, and elements like tantalum are simply very rare and cannot be produced in appreciable enough quantities for use on Freyr.

The solution utilized by Freyr is a Graded-Z style radiation shield. This type of shield uses high-atomic number materials in the external layers, graduating in to lighter materials as it extends back. For example, tantalum is often used as the outermost layer in such a shield[39], while other materials like copper, steel, tin, and aluminum make up the inner layers. The arrangement chosen by Freyr involves thin, mostly non-structural layers of high-Z materials with a thick structural layer of titanium and some very light materials on the inside to absorb gamma rays. The layers are as follows:

- 0.5 mm tantalum,
- 0.2 mm tin,
- 0.2 mm copper,
- 0.5 mm low-carbon steel,
- 22. cm titanium-aluminum alloy,
- 1.0 cm aluminum,
- 2.0 mm polyethylene,
- 2.0 mm aluminum.

The layers graduate towards lower-Z materials as they get closer to the inside of Freyr, ending with a layer of aluminum to help protect the polyethylene. Because the outer layers are good at stopping protons, alphas particles, and beta particles, but produce secondary radiation in the form of gamma rays, and the inner layers are better at absorbing gamma rays and neutrons, the net result of this Graded-Z shield is that each layer helps mitigate the effects of the layer before it, resulting in up to a 60% performance boost over single-composition material of the same mass[39]. This shielding mechanism has several other benefits: be utilizing the same core as the main structure of Freyr, it provides structural support in addition to radiation protection, and it is still relatively low-mass: one square meter of shielding has a mass of 1.17 tons, of which all but 3.2 kg can be extracted from lunar regolith and lifted to Freyr at little expense.

This radiation shield protects against all types of damaging radiation and provides a protection factor of approximately 150, corresponding to an annual dose of 0.3 rad per year from ambient radiation, which is comparable to the 0.3 rad per year received from natural background radiation

on Earth[40]. While the habitation area is equipped with this shielding, other parts of Freyr may be less shielded in accordance with use.

To evaluate the effectiveness of this shielding and determine the radiation dose experienced by various individuals on Freyr, many of Freyr's inhabitants are given excitation-style radiation dosimeters. These dosimeters use excitation in a section of calcium oxide, readily available in lunar regolith, to count the number of energetic incident particles, which can then be used to determine the radiation dose incurred. The only downside to these counters is that they do not differentiate between highly energetic and moderately energetic particles, and so may not give an accurate measurement of the damage done to a human by that radiation. Several other radiation dosimeters are placed in locations around the settlement (for example, in the Life Support/Habitation torus, near the LFTR, in the central core, etc) to generate a map of safe areas on Freyr and determine how effective the settlement's shielding is at blocking radiation. The data collected from these dosimeters will then be used to evaluate the shielding, decide if more is needed, and keep track of the radiation dose incurred by people working different jobs on Freyr. A lifetime limit of radiation exposure is established based on the data collected and experience; NASA currently limits astronauts to about 1 rem, which varies depending on sex and mass, but this limit may be modified based on extended experience with a space environment.

1.2.3 Utility

Several of Freyr's components require extremely durable materials or must perform very particular tasks. For these applications, it is necessary to develop specialized materials that are capable of bearing the stresses involved, are long-lasting, are extremely heat-tolerant, or some combination thereof depending on the task.

Several types of materials are used for these applications. Because these materials are not intended to bear large loads, there is no overwhelming preference for light weight, cost effectiveness, or strength, although for obvious reasons these properties are preferable. As a result, the substances chosen for utility purposes include crystalline SiO_2 (either quartz or shocked quartz), metal-reinforced ceramics, some metals, and advanced composite materials. Because of the wide variety of utility tasks on Freyr, the specific materials used are not detailed here.

1.2.4 Heat Rejection

Clearly, because the LFTR generates a total of 215 MWt, Freyr has to reject 215 MWt of heat energy (a little less, actually, since it stores some energy in the dissociation of water or in forming chemical compounds, but not much less). A standard application of the Stefan-Boltzmann blackbody heat transfer equation[6] indicates that the exterior shell of Freyr will be a fairly chilly 197 K, which corresponds nicely to -75 degrees Celsius. That is, the exterior of Freyr will reach equilibrium with empty space and reach a temperature of 197 K.

---

[6] $\dot{Q} = \sigma A \left(T_1^4 - T_0^4 \right)$

It is, however, necessary to consider incident solar power. Based on the assumption that about a sixth of Freyr's area will be exposed to sunlight at any given time (A_e), and assuming an albedo, Φ, of 0.35 (similar to galvanized steel, this seems reasonable)[41], it is possible to calculate the incident power to Freyr by using the solar irradiance at Earth's location.

$$P = A_e(1 - \Phi)I_s$$

$$P = \frac{2493620 \, m^2}{6} * 0.65 * 1366 \, W/m^2 = 369 \, MW$$

The addition of 369 MW to Freyr's power to be radiated suggests that Freyr's outer skin will instead be at a more reasonable 253 K, just -20 degrees Celsius. Note that this assumes even heating of the exterior surface; this is reasonable due to Freyr's rotation and the relatively quick (2 hours) orbit around the Moon.

$$T^4 = \frac{\dot{Q}}{\sigma A} + T_0^4 = \frac{584014200}{5.67037 * 10^{-8} * 2493620} + 3^4 = 4130299200 \, K^4$$

$$T = 253.5 \, K$$

Of course, this only speaks about the exterior of Freyr's shell. Because of the insulating properties of the shell itself, the interior will be much warmer. Particularly, the distribution of exterior heat flux varies over Freyr's surface, depending on the exact position on the surface and the processes going on inside that particular section.

Life Support/Habitation

It is shown later that about 50 MWe is required to light the Life Support/Habitation torus. A small additional amount of power is required to run life support systems, on the order of less than 5 MWe. Thus the Life Support/Habitation torus must reject approximately 55 MW of heat. This leads to an external shell temperature of 155 K, again by calculating the result from the Stefan-Boltzmann law. Incorporation of the incident energy from solar radiation increases this temperature to 237.6 K, still unacceptable for inhabitants. Note, however, that the Life Support/Habitation torus has a particularly thick shell (see 1.3.6) and incorporates a layer of polyethylene, which both contribute a modicum of thermal insulation that helps maintain the Life Support/Habitation torus at a higher temperature.

Analysis of the shell of the Life Support/Habitation torus shows that it has a total R-value of 1.775 (because R-values of components in series are additive), which indicates that the change in temperature over the shell is given by:

$$\Delta T = R * \dot{Q}_A = 1.775 * \frac{55000000 \, W}{1680000 \, m^2} = 58.1 \, K$$

Because the interior of the shell is therefore 58.1 degrees warmer than the exterior, we can add 58.1 to the previous value of 237.6 K to obtain an interior temperature of 295.7 K, a balmy 22.6 degrees Celsius (72.5 degrees Fahrenheit). This ought to be a comfortable temperature for the interior of the Life Support/Habitation torus, and a slight adjustment of power consumption will only change the value slightly due to the fact that the power rejected is proportional to the fourth power of the temperature of the exterior surface.

Other Parts of Freyr

The allocation of 55 MW for the Life Support/Habitation torus leaves 160 MW for the rest of Freyr. Additionally, the incident absorbed energy from solar radiation is given by:

$$P = \frac{1}{6}A(1 - \Phi)I_s = \frac{1}{6}1026920(0.65) * 1366$$

$$P = 151967045\,W$$

That is, the total amount of heat to be rejected is 312 MW. Applying the Stefan-Boltzmann law, it can be found that:

$$T^4 = \frac{\dot{Q}}{\sigma\,A} = \frac{312000000}{5.67037 * 10^{-8} * 1026920}$$

$$T = 270.6\,K$$

The exterior temperature is therefore 270.6 K, just under the freezing point of water. This is a little cold for human workers, but taking into account the insulating properties of the shell itself, which is typically about 4.5 cm thick, it can be found that the interior temperature is actually quite a bit higher. The R-value of the shell is low, at just 0.0238, but this nevertheless gives some increase in temperature.

$$\Delta T = R * \dot{Q}_A = 0.0238 * \frac{312000000}{1026920} = 7.23\,K$$

That is, the interior of the shell is fully 7.23 degrees warmer than the exterior, giving an interior temperature of 277.8 K, or 4.6 degrees Celsius (40.4 degrees Fahrenheit). This is still on the cool side, but nothing that sufficiently dressed humans cannot handle. This does not account for the possibility of additional heat sources within the Industrial torus - for example, some of the processes may be run on their own power so that they are not as much of a drain on Freyr's primary power supply. With these enhancements, the interior temperature could be as high as 12 degrees Celsius (54 degrees Fahrenheit). It is also possible that heat could be transferred from the Life Support/Habitation torus to the other volumes of Freyr; considering that the volume of this torus is 83.9 million cubic meters, or 61.8% of the total volume of Freyr (1.3.9), a reduction of

the Life Support/Habitation torus's temperature to 18.5 degrees Celsius (65.3 degrees Fahrenheit) would increase the temperature of the other portions of Freyr by 6.1 degrees Celsius, raising the internal temperature to fully 15 degrees Celsius (59 degrees Fahrenheit).

It is inescapable that, with its power supply, Freyr will be slightly on the cool side. It is, however, likely that the effect of solar heating has been underestimated and that, therefore, the actual interior temperature of Freyr will be higher. It is also possible that Freyr will increase its power output after some time, for example by running another of its LFTRs full-time, which would allow the interior temperature to be raised further. For now, however, there appears to be a relatively happy balance between interior temperature and power output from Freyr.

1.3   Design Characteristics

Freyr's design is constrained in several ways. First, it must be capable of housing 20,000 individuals in decent comfort. Second, it must be able to provide rotational pseudogravity (See 1.3.1) for its inhabitants while maintaining structural integrity. Third, it must provide protection from the vacuum of space in every reasonable way. Finally, it must create the illusion of open spaces for the psychological well-being of inhabitants.

Clearly, Freyr must have a rotating section. This section should be circular to evenly distribute stresses along the structure, and can also be used to provide structural strength for the settlement. Because of the proximity of lunar resources to Freyr by means of ISRU refineries and LTVs that can refine minerals in the lunar regolith and launch them up to Freyr as construction materials. Specifically, large amounts of titanium, iron, aluminum, and other useful metals are readily available in the lunar maria and highlands. Processing these materials is an excellent way of producing the materials for construction on Freyr, and in fact Freyr's internal and external construction details are based on what materials are available from the Moon.

Just as clear as the necessity of a rotating portion of Freyr is the necessity of a non-rotating portion. This part of Freyr is used for docking procedures, microgravity research and industry, and limited microgravity recreation. Having a non-rotating region of the settlement for docking results in easier and less dangerous docking procedures, simplified cargo handling after docking, more manageable vehicle maintenance, and a host of other benefits; having an area for microgravity industry allows for the manufacture of parts or products without the stress of gravity, allowing simpler and more functional processes better suited to a microgravity or vacuum environment.

Freyr make use of a series of concentric tori that contain different functional parts of the settlement. This approach provides several benefits, but also has drawbacks.

The overall structure of Freyr is composed of the rotating tori connected to a central core that extends beyond the rotational plane of the disk. This central core contains both a rotating portion, coincident with the plane of the tori, and a non-rotating portion that extends beyond the disk's plane. Docking facilities are only located on one end of the core to minimize technical difficulties associated with differences in rotational speed between parts of the settlement.

1.3.1   Settlement Shapes Analysis

Clearly, it is desirable to have a settlement that requires the least amount of material for a given enclosed volume - and, specifically, usable volume. While several shapes for the settlement are possible, circular cross-section tori stand above the rest.

Several settlement designs are explored below to justify the choice of a torus.

Sphere

A sphere has the highest surface area to volume ratio, but it is undesirable for other reasons.

First, the stress in a large sphere (such as would be used for a space settlement) is given by the equation

$$T = \frac{\Delta P\, r}{2h}$$

For a derivation, see Appendix E and get a little creative with the derivation for the torus. Because the radius of the space colony is larger than, say, 750 meters, and the internal pressure is higher than, say, 75 kPa, the stress in a wall that is fully half a meter thick is at the very least 56.3 MPa - and such an enclosure would require 3.5 million cubic meters of shell material, for a mass of some ten to fifteen billion kilograms while only providing 1.7 billion cubic meters of space and providing just a small fraction of that volume as human-habitable volume. A huge amount of empty space at the center of the structure would be wasted, and gravity would change as one walked around the floor of the settlement.

Dumbbell

A dumbbell shape is promising because it provides the surface to volume ratio of a sphere while reducing the radius of said spheres, alleviating structural concerns. A dumbbell also allows easier sealing between the two habitable portions of the settlement in case of an accident.

The dumbbell shape does, however, have several disadvantages, not the least of which is more confined and separated living areas, which can feel claustrophobic after long periods of time. Also, the dumbbell shape makes it inherently difficult to support a large enough population, and the connecting structures between dumbbell structures decreases structural efficiency.

Cylinder

A cylinder seems like a good idea, until one realizes that the radius of curvature of the atmosphere containment hull is quite large - and that the end walls would have to be heavily reinforced or deliberately bowed outward. A cylinder is also less efficient with materials than many other structural choices.

A cylinder does have the advantage of long lines of sight, but these same lines are provided by a torus as well, and when inside a torus one cannot see the "ceiling" above you looking up at you on the opposite side of the structure, reducing disorientation.

Torus

A torus has the advantages of a relatively easily contained atmosphere, good structural integrity, high structural efficiency, long lines of sight, and highly habitable volume.

While tori can be constructed with practically any cross-section, it is advisable to stick to a circular cross-section to avoid failure modes and stress points in the resulting structure, such as sharp corners or larger radii of curvature. While other shapes provide a flatter base for construction, use of the

curved base for utilities eliminates the necessity for a flattened base section and therefore a circular cross-section is not a problem.

Based on these considerations, it was decided that Freyr should be primarily constructed of tori (the exception is the central hub, for good reason). The construction style adopted allows Freyr to be built in sections, each being pressurized in turn while not holding up construction of the rest of Freyr's systems. It also reduces the structural requirements by eliminating most empty space, thereby also marginally reducing heat loss and keeping the structural maintenance of Freyr as easy as possible. This construction method is explained in section 1.3.9.

1.3.2 Central Hub

The central hub of Freyr is where the backup LFTR, some processing facilities, and staging facilities are located. It forms a tube around the axis of rotation of the main disk and contains separate life support systems from the tori to provide emergency life support for a large number of people or long-term life support for the settlement inhabitants who work in the central hub or microgravity areas.

Because the central hub is so close to the axis of rotation, the effect of Freyr's rotation is much smaller here and loads can be moved and handled much more easily. This makes the central hub a favorable location for heavy materials processing, construction for export, and processing of any materials that do not remain within Freyr, but rather are exported to Earth, lunar colonies, or other locations. While the hub itself is too small for all of these processes, access from the hub to the inner tori is quite easy and the hub can act as a staging area.

The central hub also contains Freyr's computer mainframe, command and control (C&C) center, and communications equipment.

Dimensions

The central core has a length of 100 meters and a diameter of 50 meters. It is capped on one end by the non-rotating section of Freyr, and on the other end by a hemispherical shell. It takes the shape of a cylindrical shell with a thickness of 5 cm, giving a total shell volume of 785 cubic meters when the core is complete; the endcap has a thickness of 2.5 cm. When the endcap is added (not yet accounting for the non-rotating section), this volume becomes 883.5 cubic meters. The volume of the core itself is 229000 cubic meters, and the flat floor area is 15700 square meters, providing ample space for organization, processing, and command facilities.

The tension in a ring with the density of titanium that has a radius of 25 meters and is rotating at the same rate as Freyr (0.0967 rad/s) is given by[7] the formula:

$$F_T = A\rho\omega^2 r^2 = A * 4100 * 0.0967^2 * 25^2$$

In the above, the density ρ is in kilograms per cubic meter and A is the cross-sectional area. The stress in the ring is simply the tension divided by the area, meaning that the stress in the ring is

---

[7]See Appendix E for the derivation.

24.0 kPa, far below titanium's ultimate tensile strength of more than 400 MPa[42]. This leaves a lot of room for expansion and allows Freyr's government and inhabitants to install further equipment and machinery in the central core without concern for its structural integrity.

Under the expected load of another one and a half tons effective per square meter, the stress T on the titanium shell is given by:

$$T = \frac{\left(A\rho + \frac{m}{dl}\right)\omega^2 r^2}{A}$$

$$T = (4100 + 30000) * 0.0967^2 * 25^2 = 199\,\text{kPa}$$

This is still far below titanium's ultimate tensile strength, but due to the potential pressure-induced stress in the shell, the tensile stress jumps up to 45.2 MPa[8], and making the shell much thinner only increases this stress, so much so that even a small decrease in thickness doubles the tensile stress. Another reason for keeping the shell fairly thick is that it allows more even handling of uneven loads across the interior of the shell, reducing point stresses and helping to eliminate failure modes in the shell.

Based on the shell volume of the core and the density of aluminum-titanium alloy, the core's shell has a mass of 3623 tons. Its moment of inertia[9] is 2.264E8 kg-m^2.

Materials

The central core is constructed of titanium, a metal present on the Moon that can be processed into a pure metal with good physical properties. Although high-carbon steel is also a good material for structural purposes, carbon is relatively scarce on the Moon[43] and the infrastructure for alloying iron with carbon or other elements must be developed before steel can be manufactured. Keeping in mind that the central core contains the LFTR and many other vital systems, it is in Freyr's best interest to construct it as soon as possible, making readily available titanium processing the best choice for Freyr's early development.

Titanium is combined with aluminum (90%/10%) to make construction of the core faster and easier while retaining titanium's good strength properties. Using this alloy means that due to the ease of refining aluminum, the central core can be finished much more easily than it would be if it were composed entirely of titanium.

Facilities

The central core contains many of Freyr's vital systems. It houses the command and control systems and areas, as stated above, and it contains auxiliary life support. It also contains the backup LFTR and power generation systems and Freyr's flight control systems, as well as a large staging area for materials destined for the non-rotating section, for transport to one of the tori, or for storage. Note that the backup LFTR is normally kept in cold shutdown and is never expected to be used, but could be started moderately quickly in the event of primary and secondary reactor loss.

---

[8] $T = \rho\omega^2 r^2 + \frac{m}{Adl}\omega^2 r^2 + \frac{\Delta P\, r}{h}$

[9] $I = mr^2$

The central core, in short, is the nerve center of Freyr. The computer core and much of Freyr's storage capacity is located here, and the vital systems of Freyr can all be controlled from the core.

1.3.3 Tori

Freyr's tori contain the industrial, storage, life support, and habitation areas that keep the settlement running and allow it to operate at a high level of functionality. These processes are separated into several tori to prevent a single event from depressurizing all of Freyr, and other precautions are taken to ensure that the inhabitants of Freyr are kept safe no matter what the pressurization state of any torus is.

The tori are linked all along their circumference by bolts driven during construction, but are also joined at several points spaced equally about the structure. These joining points utilize the sealing and compartmentalization mechanism described in section 1.4.6 to ensure that the tori can be easily separated if need be, and allow the transfer of cargo and personnel between tori. Joining configurations are given below.

• The core is joined to the industrial torus by eight access points, each 3m by 3m.
• The industrial torus is joined to the storage torus by six access points, each 3m by 3m.
• The storage torus is joined to the life support/habitation torus by three access points, each 2.5m by 2.5m.

Additionally, a column sealed at both ends proceeds from the life support/habitation torus directly to the core, and is used for evacuation in the case of some massive system failure. It is 3m in diameter with a 2 cm wall.

The individual tori are themselves detailed in sections 1.3.3 to 1.3.5.

1.3.4 Industrial Torus

The industrial torus is the closest one to the core and therefore has the lowest gravity. This lower gravity is advantageous because it allows near-weightless materials processing, which eases the complications involved in Freyr's industry.

This torus contains the various metal processing, refining, and synthesis operations on Freyr. It deals with processing the raw materials brought in on LTV vessels, making those materials into useful commodities, and eventually providing processing services to minor space-based industries and firms.

The industrial sections of this torus are divided into several areas: refining/smelting, construction, materials handling, machining, and control systems. Each of these plays a specific role and then passes its product along to the nest stage, enabling the clustering of related processes, compaction of related systems, and ultimately an increase in efficiency.

Dimensions

The industrial torus is located just outside the core. It has a major radius of 150 meters and a minor radius of 125 meters, resulting in a shell area of 740220 square meters[10] and an enclosed volume of 46.3 million cubic meters[11]. The volume of material required for the shell is calculated below.

Because the industrial torus is used for - as the name suggests - industrial processes, it is not necessary to pressurize it as would be required for a space to be inhabited by humans. Reducing the pressure in the industrial torus does, of course, mean that any workers in this area must be equipped with breathing masks to supply oxygen, but otherwise should not produce any ill effects. Humans can live in low-pressure environments for long amounts of time, as evidenced early Apollo tests, which used a pure oxygen atmosphere at only 5 psia. To reduce the risk of fire in the industrial torus, the atmosphere is composed of nitrogen and helium, both by-products of lunar volatiles extraction, at just 30 kPa.

An internal pressure of 30 kPa means that the stress on the torus is given by

$$T = \frac{3\Delta P \, r}{2h} = \frac{3 * 30000 * 125}{2 * h}$$

Given that an acceptable stress is approximately 65 MPa, the required thickness of the shell must be at least 0.069 meters:

$$65000000 \geq \frac{3 * 30000 * 125}{2h}$$

$$h \geq \frac{9}{130} = 0.069 \, \text{m}$$

Because 65 MPa already builds in a good safety margin, this shell is only thickened a little, for a thickness of 7.5 cm. This means that the total shell volume is equal to the product of the thickness and the surface area:

$$V_{shell} = 740220 * 0.075 = 55517 \, \text{m}^3$$

Given the density of titanium-aluminum alloy, this means that the mass of the pressure containment shell is fully 227,600 tons, plainly a huge endeavor.

The outside edge of the industrial torus is slightly thicker than the interior edge - 8.5 cm. This helps to account for the force applied by the centrifugal force experienced by the rotating machinery inside. While it is not possible to calculate these stresses precisely, a thickness of 8.5 cm gives the potential for up to 37 tons equivalent per meter of length, or a total of 50000 tons equivalent across the structure. This can be increased by moving the equipment closer to the axis of rotation, which can increase the allowable load to 5 times, for a maximum equipment mass of 250000 tons, or 250 million kilograms.

At an atmosphere of 88.6 mass % helium and 11.4 mass % nitrogen, which corresponds to the ratio in which these are available in the lunar regolith, and a pressure of 30 kPa, the atmosphere

---

[10] $S = 4\pi^2 \, r_{min} \, r_{maj}$

[11] $V = 2\pi^2 \, r_{min}^2 \, r_{maj}$

is composed of:

$$\frac{0.886\,\text{g} - \text{He/g} - \text{atm}}{4\,\text{g} - \text{He/mol}} = 0.2215\,\text{mol} - \text{He/g} - \text{atm}$$

$$\frac{0.114\,\text{g} - \text{N}_2/\text{g} - \text{atm}}{28\,\text{g} - \text{N}_2/\text{mol}} = 0.00407\,\text{mol} - \text{N}_2/\text{g} - \text{atm}$$

$$\frac{0.2215\,\text{mol} - \text{He/g} - \text{atm}}{0.00407\,\text{mol} - \text{N}_2/\text{g} - \text{atm}} = 54.423\,\text{mol} - \text{He/mol} - \text{N}_2$$

Based on these calculations, it is clear that the atmosphere is, by molarity, 98.2% helium and 1.8% nitrogen gas. The partial pressures of each gas, then, are 29.46 kPa helium and 0.54 kPa nitrogen. Because of the ideal gas law, $PV = nRT$, it is possible to calculate the density of this atmosphere by finding the number of moles per cubic meter of each gas and summing the resulting densities: given that $R = 0.008314$ cubic meter-kilopascals per mole Kelvin,

$$\frac{n - He}{V} = \frac{P}{RT} = \frac{29.46}{0.008314 * 298} = 11.89$$

$$\frac{n - N_2}{V} = \frac{P}{RT} = \frac{0.54}{0.008314 * 298} = 0.2180$$

Each result is in moles per cubic meter. Multiplying by the molar mass of each gas and summing the results, it is easily found that the density is

$$D = 11.89 * 4 + 0.2180 * 28 = 47.56 + 6.014 = 53.664\,\text{g/m}^3$$

The atmospheric density is 53.66 grams per cubic meter, meaning that the total mass of atmosphere contained is 2490 tons, the amount of gas released as a by-product of 0.71 tons of extracted helium-3 (see 1.7.4). This amount of atmosphere could easily be extracted within two years.

The moment of inertia[12] of the industrial torus is 7.789E12 kg-m^2.

Materials

The shell of the industrial torus is constructed of the same aluminum-titanium alloy as the core. This alloy is lightweight but strong, and is available in lunar regolith.

Interior structures are constructed of whatever materials are necessary for the particular application - probably aluminum, titanium, or in some cases composite materials or ceramics. The interior specifications are not completely discoverable without a much more in-depth study.

The atmosphere of the torus is composed mostly of helium for several reasons: first, helium is produced as a by-product of Freyr's economic operations, second, helium is not a heavy gas and therefore is a low-mass alternative to a mostly nitrogen or oxygen environment, third, helium is so light that any fumes released (except hydrogen gas) will sink to the floor, allowing for easier separation, and finally, helium is incredibly non-reactive, making for a safer operational environment. Helium, in fact, is stable as a gas all the way down to 4 K, where it liquifies, and does not react whatsoever at any achievable temperatures, making it a great choice for the potentially dangerous environment of the industrial torus.

---

[12]$I = (r_{maj}^2 + 0.75 r_{min}^2)m$

Facilities

The industrial torus contains the facilities for most of Freyr's processing and industrial activities. Please see section 1.7 for more information on the specific capacities of these facilities.

This torus also contains some command and control functions, emergency oxygen supplies for workers, and decompression shelters for anyone trapped in the torus while a decompression event occurred. These decompression shelters are located at 300 m intervals around the rim of the torus and can each contain up to 100 people in an emergency, albeit in discomfort. These are not intended as long-term residences, but instead merely as a refuge from the depressurized conditions outside; each person only has 10 square feet of space at maximum occupancy. The shelters contain enough oxygen for three days, which comes out to 240 kg of pressurized oxygen, and are equipped with chemical carbon dioxide scrubbers to keep CO_2 levels non-toxic.

Power Generation   The Industrial torus also contains Freyr's primary and secondary power generation facilities, in the form of two LFTR facilities attached to the exterior of the torus.

These facilities are placed on the Industrial torus for several reasons. First, because most of Freyr's electricity consumption is accounted for by that torus, the reactors are kept closer to where their power is needed; this reduces losses in the system and makes maintenance of power lines easier. Second, placing the reactors on the outside of this particular torus makes them safer radiologically: the thick shell of the Industrial torus helps to shield from radiation produced by the reactor without requiring expensive and heavy additional shielding. Finally, placing the reactors on the very exterior of a rotating structure provides a final level of defense against catastrophe in the event of a meltdown, which is always possible with a fission reaction. If the LFTR begins to go into a meltdown paradigm, it can be cut loose quickly from the main part of Freyr, and due to its instantaneous linear velocity will be flung away from the settlement, thus physically removing the danger of a reactor undergoing meltdown. Note that this does not completely remove the danger, because the reactor will still be in an orbit very similar to Freyr's, but a relative velocity of 77+ meters per second in lunar orbit should produce a significant change in orbital parameters that allows adequate time (on the scale of days) to deal with the problem before it comes near Freyr again.

This last consideration is expected to never be an issue, but it's reassuring nonetheless.

Power generation facilities are provided by two LFTR units arranged diametrically on the exterior edge of the Industrial torus. Typically, only one of these units is needed at a time, although both could be used in times of extremely high power demand. These two units are constructed to the same parameters as the back-up unit described in section 1.1.4, simplifying maintenance by establishing a standard for parts and design across all of Freyr's reactors.

1.3.5   Storage Torus

The storage torus has several purposes. It is intended to store the products of Freyr's industrial processes if they are not immediately needed, which helps to reduce crowding in the core, and

to store excess life support supplies when they are overproduced, for long-term storage, accident recovery, or shipment to other colonies. Because these functions do not require as much space, the storage torus is smaller than either the industrial or life support/habitation tori, but its purpose is just as important.

While the Storage torus does contain the same atmosphere as the Industrial torus, and the vast majority of its traffic consists of transition between these two tori, it makes sense logistically to instead have a single, slightly larger torus that combines the facilities of the Industrial torus and the Storage torus. The Storage torus, however, becomes important to Freyr during the earlier stages of construction. Please see section 3.1.2 for more information about this stage in Freyr's development.

Dimensions

The storage torus has a major radius of 295 meters and a minor radius of 20 meters, making it the smallest of Freyr's tori. It has a shell area of 237000 square meters and a volume of 2.37 million cubic meters, giving it 0.32 times the surface area of the industrial torus and just 0.05 times the volume - volume increases faster than surface area with increasing minor radius.

The storage torus is also pressurized to 30 kPa of 88.6% He and 11.4% N_2. The identical nature of the atmospheres of the Storage torus and the Industrial torus makes it easy to transfer materials between the tori while maintaining an inert, stable, and readily available atmosphere in both tori.

Because the atmospheric pressure and minor radius of the storage torus are so small, it is easy to fulfill the structural requirements of the torus. The pressure stress on the torus is given by

$$T = \frac{3\Delta P\, r}{2h} = \frac{3*30000*20}{2*h}$$

Again solving for the acceptable stress of 65 MPa, it becomes clear that the storage torus can actually be quite thin-walled:

$$65000000 \geq \frac{3*30000*20}{2*h}$$

$$h \geq \frac{18}{1300} = 0.014\,\mathrm{m}$$

To add some safety, the shell is made 1.6 cm thick, resulting in a shell volume of:

$$237000*0.016 = 3318\,\mathrm{m}^3$$

This volume, when multiplied by the density of aluminum-titanium alloy, gives a shell mass of 13600 tons, or 0.060 times the mass of the industrial torus shell.

Within the storage torus, gravity is somewhat greater than in the industrial torus, and when an additional 0.4 cm of structural mass is added to the outside edge of the torus to help support additional load, about 20 tons per meter of length, or 37700 tons around the whole structure, can be placed on the outside of the torus. This allows for large storage containers and tanks that can be distributed around the structure - and again, if these are moved to the inside edge of the torus,

the maximum allowable load increases to fully 45000 tons. This also allows a fairly large safety margin in several places, so more mass than this could be added if desired.

The moment of inertia of the storage torus is 1.228E12 kg-m^2.

Materials

The storage torus is constructed mainly of the same materials as the industrial torus. It uses the same titanium-aluminum alloy for the shell, but because there are not extreme industrial processes going on inside the storage torus, it is acceptable to use aluminum for virtually all of the internal fixtures. This reduces construction difficulty and refining difficulty while not resulting in unacceptable strength losses. Aluminum is also more readily available than titanium in the lunar regolith, and is only not used for the structural shells of Freyr because it is structurally insufficient.

Aluminum is also a good material for storage containers because it naturally forms a protective oxide coating when exposed to oxygen for even short periods of time, which protects against many acids and otherwise reactive materials. Aluminum can also be shaped and machined easily, making construction and maintenance of storage containers and tanks much easier.

Facilities

The storage torus contains much of Freyr's materials storage capacity, including gas, liquid, and solid storage.

Some of its most important facilities are the gas storage tanks, which store compressed gases in large cylindrical tanks for future use. These tanks are attached to the ceiling of the torus, which has several benefits: it offsets some of the tension in the torus's shell, frees up floor space for cargo that cannot be attached to the ceiling, and makes good use of the curvature of the ceiling. The tanks are shaped to match the ceiling and are welded to the ceiling; they are three meters tall and 16 meters wide, stretching across the arc of the ceiling, with a storage capacity of 114000 L per meter of length. They can be pressurized to about 1.5 atm because of their 1 cm aluminum skin, and are each 20 meters long, which gives a total capacity of 3.42 million liter-atmospheres of gas. Various tanks hold different gases, from carbon dioxide to oxygen to hydrogen or organics. Rules similar to those used for handling gas cylinders are followed when determining the placement of these tanks relative to one another: oxidizers are never placed near reducing agents, inert gases are placed around hazardous ones, etc. Each tank is fitted with two pressure release valves, which activate if the internal pressure exceeds 1.75 atmospheres, at which pressure the tanks are nearing their failure point. Two gases not stored in these tanks are helium and nitrogen, which are stored in the atmosphere itself.

Other materials are stored on shelves or in tanks on the walls, according to the needs of the particular material. Liquids are typically kept on the wall in an attempt to elevate them somewhat above the floor and decrease the load on the torus, while solids tend to be stored on the floor or on shelves. Typically, materials stored in the storage torus are unfinished products and do not

require their own packaging - for example, sheet metals and bulk materials as opposed to specialized fittings or components. Such finished products tend to be kept in individual storage areas closer to where they will be used (each department can keep a small cache of vital components nearby for routine maintenance). When dealing with solids and liquids, the same rules are followed as for gases: reducing agents are separated from oxidizers, dangerous liquids are kept near inert ones, and etc.

The maximum load of 20 tons per meter of length means that a truly massive amount of cargo can be stored here; a total of 45000 tons is the same mass as the entire blueberry crop of the state of Washington in 2014[44].

1.3.6   Life Support/Habitation Torus

The Life Support/Habitation torus is where humans live on board Freyr. It houses the human habitation areas, life support systems, recreation facilities, and many of the workspaces of Freyr's inhabitants and is the outermost of Freyr's tori.

This torus is the most important of Freyr's three tori. Without it, Freyr cannot support human life at all, and is simply an automated processing station - certainly also interesting, but nowhere near as dependable, useful, or worthwhile.

Dimensions

The life support and habitation torus has a major radius of 415 meters and a minor radius of 100 meters. These dimensions give it a shell area of 1.68 million square meters and an enclosed volume of 83.9 million cubic meters.

Because this torus must house the human inhabitants, it is pressurized to 90 kPa and the atmosphere consists of 79% N_2 and 21% O_2 (for more information on the atmosphere, see section 1.4.1). These are not mass percentages, but rather volume percentages, and are therefore the same as the molar fraction of each of the gases in the atmosphere. These mole fractions indicate that because the atmosphere consists of 36.3 moles of gas per cubic meter ($\frac{n}{V} = \frac{P}{RT}$), there are 28.70 moles of nitrogen per cubic meter and 7.63 moles of oxygen gas per cubic meter. Multiplying by the molar mass of each of these and summing the products, it is found that the density of the atmosphere is therefore

$$D = 28.70 * 28.0 + 7.63 * 32.0 = 1047.76 \, \text{g/m}^3$$

This corresponds to 1.048 kg per cubic meter, for a total of 87,900 tons of gas in the atmosphere.

Based on requirements for radiation shielding of the life support/habitation torus (see section 1.2.2), the shell of this torus is 23.54 cm thick, of which 22.0 cm consists of titanium-aluminum alloy. This is assumed to be the only load-bearing part of the shell. Based on a minor radius of 100 meters, the stress in the torus is

$$T = \frac{3\Delta P r}{2h} = \frac{3 * 90000 * 100}{2 * 0.22} = 67.5 \, \text{MPa}$$

This coincides perfectly with the thickness needed for radiation shielding, making a nice overlap between structural and physiological concerns. Note that while 67.5 MPa is a little higher than the 65 MPa assumed for calculations of the other tori, it is still far below titanium-aluminum alloy's ultimate tensile strength of 1034 MPa. In fact, pushing the materials used in Freyr's structure to the limit could reduce weight significantly, at the cost of radiation protection, structural stability under irregular loads, and ultimately the safety of Freyr's residents.

The downside of having such a thick shell is the mass. The total volume encompassed by the shell alone is 395000 cubic meters, and at a mass of 1.17 tons per square meter, the mass of the shell is 1.62 million tons. Clearly, this is a massive project: that is the same mass as the entire Sri Lankan rice crop, basis milled, in the 2012-2013 growing year[45]. On a more serious note, producing 1.62 million tons of titanium-aluminum alloy requires processing 16.2 million tons of lunar regolith. For this reason, it was decided to use a quantity of quartz glass in this structure as well. Casting the titanium alloy around woven quartz glass reduces the demand for titanium and replaces it with quartz, which is formed from the silica that makes up about 45% of the Moon. Because this substitution could be made, the materials requirements for the shell were cut by about 70%, down to just 4.86 million tons of lunar regolith to be processed. Another advantage of using quartz glass woven into the shell is that it increases the tensile strength of the material, up to as much as 1500 MPa, reducing structural concerns and dealing better with irregular loads due to its greater strength.

This material was not used for the other tori because its manufacture is very strenuous, and requires extensive manufacturing and industrial equipment already in place on site. Because these facilities were not available until the industrial and storage tori were complete, the material could not be produced for those structures. Due to their smaller mass requirements, however, this was not as big a deal as finishing the shell of the life support/habitation torus.

The moment of inertia of the Life Support/Habitation torus is 3.050E14 kg-m^2.

Materials

Just as the other tori, the life support/habitation torus is constructed primarily of titanium-aluminum alloy, and the structure of the torus's shell is described in 1.2.2. The alloy, however, is reinforced with quartz glass in this case, which reduces materials requirements and increases strength at the cost of a somewhat more complicated construction process. Interior furnishings are composed of more complicated materials due to the lack of structural concerns and the desire for variety in the habitation areas.

Facilities

The life support/habitation torus contains several different areas for human habitation and support of human life. These facilities are located at different points in the torus to make the best use of the available volume; a cross-sectional view is shown below.
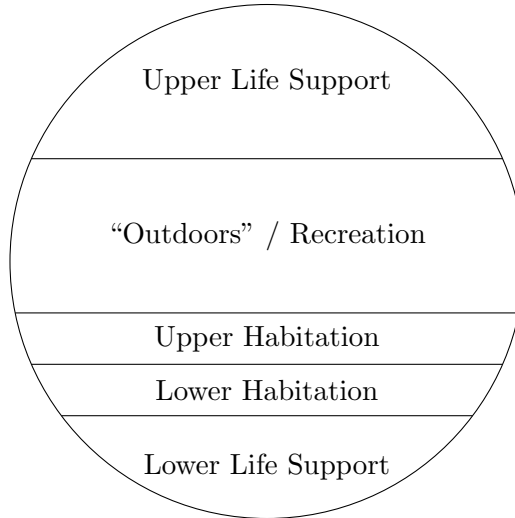
Figure 1.3: Cross-Section of Life Support/Habitation Torus

The life support areas are divided into two main groups, one above the habitation quarters and one below. This allows the torus's shape to be maximally exploited and for its volume to be most efficiently used by reserving the easy-to-use spaces for the human inhabitants while reserving harder-to-use spaces for machinery, which can use the smaller spaces for pipes, wires, small units, etc. By keeping the cross-section of the torus circular, the most efficient use of materials is maintained, and the shell stress is kept more evenly distributed.

The habitation areas are divided into three decks, as is clear from the diagram. Houses, community spaces, and some recreation areas are located on the lower decks, while the upper deck is reserved for a more open space. Consequently, the outdoors deck is fully 40 meters taller than either of the lower decks, and provides in this way more open space and less of a feeling of entrapment.

The high ceilings also allow better illumination, with more diffuse light reaching the ground and less of a feeling of artificial light.

Clearly, it is a challenge to correctly support the floors of each of these levels. Support is accomplished with a combination of titanium-aluminum cables and supports connecting the floors to the walls of the torus. The upper habitation area is kept free of these supports to emphasize the idea of being in an outdoors area; supports for its floor and ceiling are routed through the other levels. This is very feasible because the only area above this section is the upper life support bay, while the areas immediately below are the actual habitation areas, which can support their ceiling with various structures. Loads are also diverted to the outer shell by means of angled supports that conform to the shell and evenly transfer the load from the floor to the shell.

Upper Life Support   This life support section is located at the "top" of the life support/habitation torus. It contains most of the aeroponic facilities for growing food.

This section has a floor area of over 221000 square meters and experiences gravity of 8.4 meters per second squared. Its total volume is 17.94 million cubic meters, and about 15 million cubic

meters can be used for growing crops, allowing growing rotation, extra space for aeration, and less crowding. The maximum ceiling height is 60 meters.

"Outdoors" Deck   This deck is directly below the Upper Life Support Deck. It contains a simulated outdoors area for colonists to enjoy and recreate.

This deck has a floor area of nearly 274000 square meters and experiences gravity of 9.7 meters per second squared. Its total volume is 30.68 million cubic meters, of which nearly 100% can be used for various activities if desired. The maximum ceiling height is 60 meters, and the walls are almost uniform in width, ranging from 200 meters between them to 186 meters between them over the height of the deck.

Upper Habitation Deck   This deck is directly below the Outdoors Deck. It is one of two decks containing living quarters and community areas for Freyr's inhabitants.

This deck has a floor area of almost 268000 square meters and experiences gravity of 10.1 meters per second squared. Its total volume is 10.88 million cubic meters, nearly all of which can be used for habitation, recreation, sporting, community activities, and other purposes. The maximum ceiling height is 20 meters, allowing high population density while reserving space for life support and the outdoors deck.

Lower Habitation Deck   This deck is directly below the Upper Habitation Deck. It is the second of two decks containing living quarters and community areas for Freyr's inhabitants.

This deck has a floor area of almost 244000 square meters and experiences gravity of 10.6 meters per second squared. Its total volume is 10.30 million cubic meters, most of which can be used for various purposes. The maximum ceiling height is 20 meters, which helps to keep living areas relatively compact.

Lower Life Support   This deck is on the outside edge of the life support/habitation torus, which is the "bottom" when the torus is rotating. It contains water reprocessing facilities, atmospheric maintenance through the algae tanks, some storage areas, and if necessary some food production areas. Power systems for the torus are also located here.

This deck has a curved floor, with an area of about 735000 square meters, and gravity ranges from 10.6 meters per second squared to 11.4 meters per second squared. Its total volume is 14.09 million cubic meters, providing plenty of space for life support systems.

1.3.7   Rotational "Gravity"

The illusion of gravity is provided on Freyr by rotating the station. The centripetal acceleration involved in rotation causes residents to perceive a sensation of gravity due to Newton's third law.
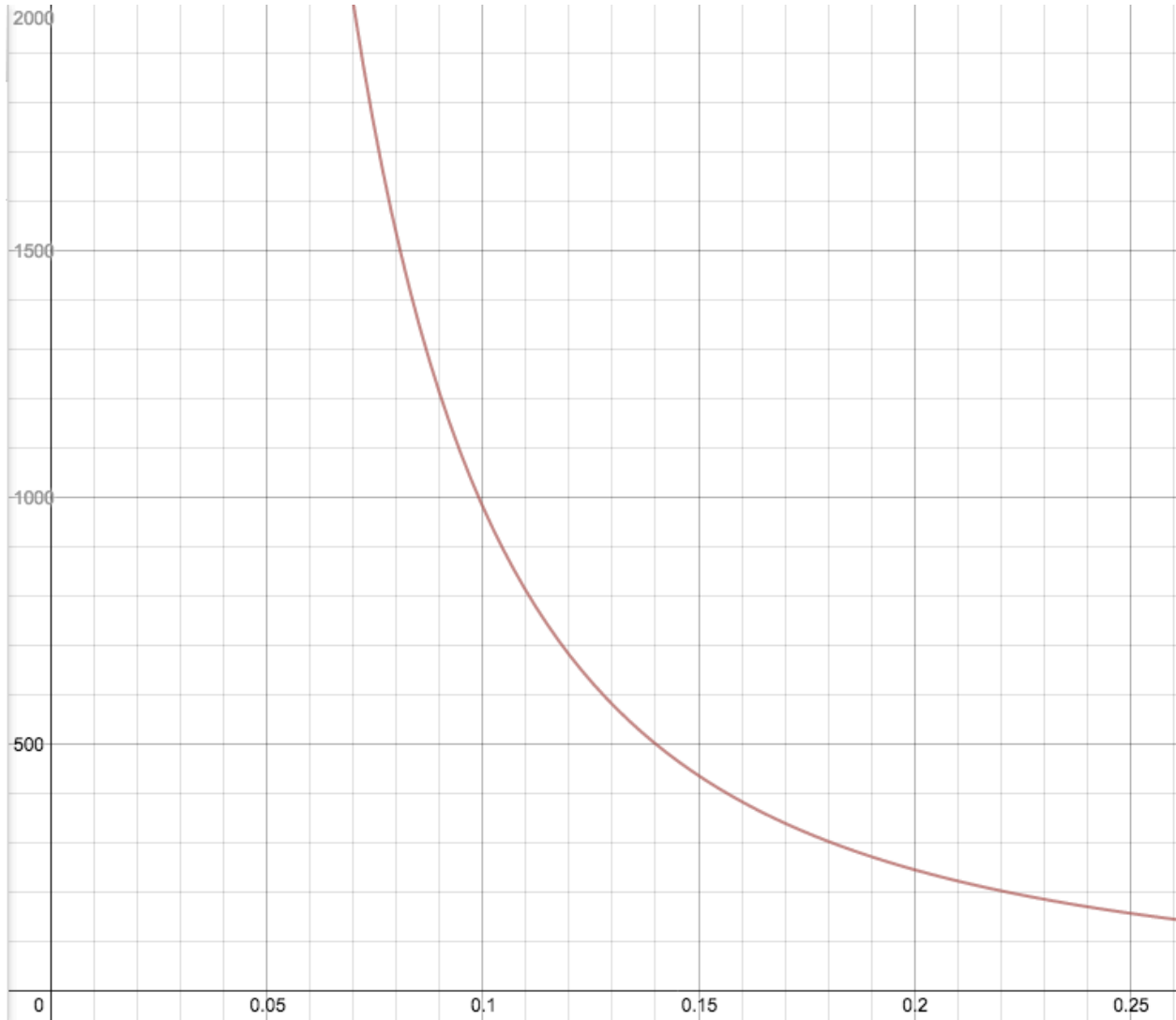
Figure 1.4: Plot of Radius Versus Angular Velocity for 9.81 m/s^2

While this does put extra stress on the station's framework, it is preferable by far to a microgravity environment, which is known to result in rapid muscle atrophy and bone decalcification[46].

Freyr rotates along its entire length, that is, the entire settlement rotates except for a microgravity workspace for EVA prep, spacecraft construction, μg research, and some industrial applications. Pseudogravity is useful for many applications, and often a microgravity environment can be detrimental: for example, NASA had to develop special zero-torque tools for use in space because normal tools caused astronauts to counter-rotate as they exerted force[47]. The use of rotational motion to generate artificial gravity on Freyr helps alleviate these concerns and provides a much more Earth-like environment that facilitates better quality of life and lower physiological stress on board Freyr.

Rotation also provides several advantages in low-gravity sections of the station. Because the effective gravitational effect is proportional to the radius from the center of rotation, areas of Freyr

closer to the central axis have lower gravity environments, conducive to industrial work, heavy loads, and construction. The lower effective gravity at these points in the station helps to ease the strain on equipment and makes it much easier to carry out tasks that would be very strenuous in higher gravity environments. A plot is provided above of the radius required to obtain 9.81 meters per second squared for a given angular velocity; for a given angular velocity, the gravitational effect scales linearly with displacement from the center of rotation.

Research suggests that the human body can typically adapt to angular velocities of less than 2 rpm (0.209 rad/s), while angular velocities of 3 rpm (0.314 rad/s) can be enough for some people to never adapt, so Freyr chose to place its limit at 1.5 rpm (0.1575 rad/s) to ensure the long-term comfort of residents. Calculations show that:

$$(0.1575 \, rad/s)^2 * r = 9.81 \, m/s^2$$

$$r = \frac{9.81}{0.1575^2} = 395 \, m$$

This constrains Freyr's radius to be greater than 395 meters to generate a centripetal acceleration of 9.81 m/s^2. Based on requisite population size and industrial capacity for a reasonable self-sustaining settlement, Freyr's radius is set at 510 meters; some of the habitation module, however, is as close to the center of rotation as 445 meters. To generate full gravity at a radius of 450 meters, Freyr has to rotate at:

$$\omega^2 * 450 = 9.8$$

$$\omega = 0.1476 \, rad/s$$

This gives an angular velocity of 0.1476 rad/s, or 1.409 rpm. This is sufficiently low to ensure eventual adjustment to the rotating reference frame while providing high gravity in the habitable areas of Freyr, with some habitation areas experiencing up to 10.1 meters per second squared, and the edge of the settlement experiencing 11.4 meters per second squared. The industrial areas, by contrast, are close enough to the center of rotation that they only experience up to 6.0 meters per second squared, and some industrial areas only experience 0.54 meters per second squared, or 0.056 g.

1.3.8   Non-Rotating Module

The non-rotating portion of Freyr is essential for several reasons. Although the construction of Freyr is complicated by having a rotating joint between the central core and the non-rotating module, the absence of rotation in part of Freyr makes it much easier to carry out many functions of Freyr's operation.

For example, docking is accomplished along the non-rotating portion of Freyr, allowing for much less difficult and dangerous docking maneuvers and vastly reducing fuel consumption. While ships could dock to one end of the central axis of a rotating module, such a docking induces very slight gravitation in the ship itself, leading to complications with cargo transfer, the Coriolis forces involved in such a small rotating area would be non-negligible, and difficulties are created as the spin of the spacecraft has to be exactly matched to Freyr's spin before docking. Docking to a non-rotating module alleviates all of these difficulties.

Another application for Freyr's non-rotating section is construction of spacecraft components, structural members, and crystals in microgravity. Even a slight gravitational or pseudogravitational effect can destroy the monocrystalline growth of the crystals fabricated, and the fabrication of large components in microgravity helps to keep them structurally sound and alleviates the need for bracing or heavy components to resist stresses that will never be felt in the vacuum of space. The ability to move even the largest of components easily also helps in cargo transfer as heavy modules and machines can be transferred easily from one location to the other. It's hard enough to move cargo around inside Freyr and to transfer it from transports without the effects of a rotating reference frame.

The non-rotating module is often called the Spaceport because of its utilities relating to transfer between Freyr and open space and because of the directly space-related industries located there.

Rotational Juncture

Rotation is hard to control in vacuum. Obviously, any seal between the central core and the non-rotating module must be hermetic, but most hermetic seals work through direct contact with both sections, and thereby result in massive amounts of friction between the non-rotating and rotating portions. While these seals work just fine for partial rotation or zero rotation, when placed on a joint that is continuously rotating, they quickly degrade and cause damage to both sections as well as to the seal itself. This presents some unique difficulties for a rotational to non-rotational joint in vacuum, one which is solved by the use of a compound mechanical-magnetic system.

The rotational joint that connects the non-rotating section of Freyr to the central core consists of several stages of interface. At each end of the joint, a set of ball bearings keeps the two shells precisely positioned and minimizes both shifting between the two sections and drag between them, which would otherwise accelerate the non-rotating section to higher rotational velocities even as it slowed down the primary disk. Between these sets of ball bearings, several stages of ferrofluidic seals step down the pressure from Freyr internal pressure to hard vacuum, resulting in low stress across each stage and minimizing leakage. Ferrofluids are ideal for this application because they have a low vapor pressure, very low friction due to no direct contact between rotating and non-rotating components, and very low maintenance requirements[48].

Freyr uses a nine-step ferrofluid step-down system, in which nine separate stages of ferrofluid each decrease the pressure contained by 10 kPa to ensure low leak levels and highly effective hermetic sealing. One major benefit of this seal strategy is that at each stage in the pressure step-down, gases that have diffused beyond the previous layer(s) can be recovered by pumping up across the pressure differential.

The ferrofluid seal is maintained by permanent magnets embedded in the walls of the rotating and non-rotating sections that are joined by the seal. This ensures low friction because the fluids are not mechanically restrained, but rather held in place magnetically. Because lunar meteorites contain up to several times as much neodymium and other rare earth elements as the Earth's upper crust[49], it is reasonable to expect that lunar mining operations will result in large enough amounts of vital rare earth elements to service these magnets and replace them when necessary, but
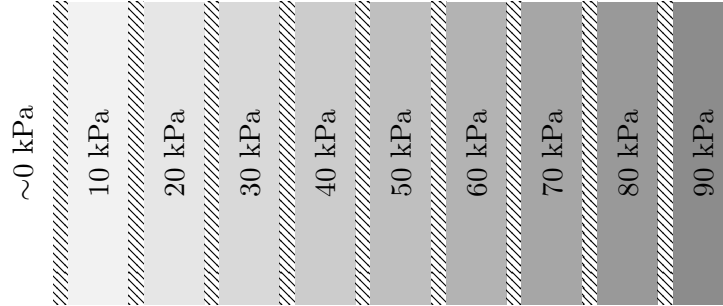
Figure 1.5: Diagram of Pressure Step-Down in Rotational Seal

the initial magnets used in construction of Freyr will be imported from Earth due to insufficient manufacturing capability at the time on Freyr or the Moon.

The overall structure of the seal contains two sets of roller bearings as well, which are not pressure-sealing and serve only a structural purpose in keeping the two sections properly aligned. These bearings are a double-row 3 cm design with a 1.49 cm raceway on either section[50]. This results in a high-conformity fit and holds the two sections in close and unshifting alignment, which is essential for smooth rotation and low vibration in the bearings. Having one set of bearings on each end of the sealing mechanism ensures that the sections are held in alignment with a two-point fit.
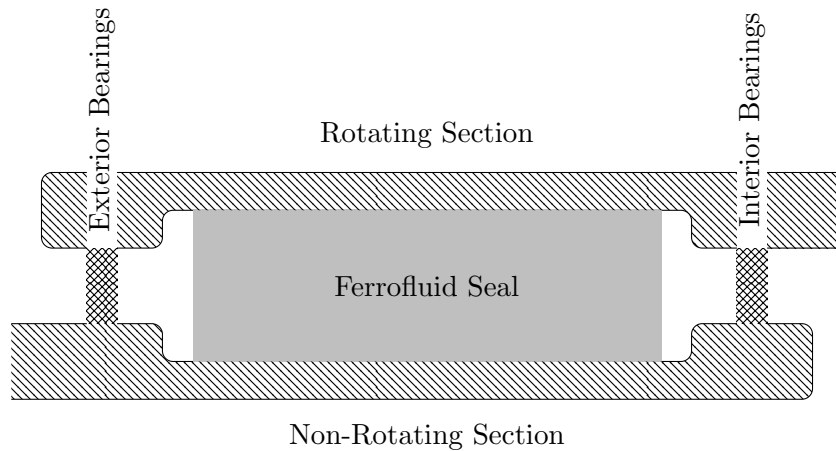
Figure 1.6: Rotating Joint Diagram

The total thickness of the rotating joint is 4.0 cm at the bearings and 8.0 cm for the ferrofluid and the magnetic components not housed in the sections themselves. In reality, the sections are somewhat thicker than shown in the diagram.

Rotational Maintenance As a matter of course, Freyr's rotation will gradually slow. This is due to one main factor: parasitic losses in the rotating bearing is one small influence, but the greatest influence on Freyr's rotational velocity is the addition of mass to the outlying regions of the settlement. Moving mass outwards from the center of rotation results in Freyr's moment of inertia increasing, which decreases its angular velocity because $\dot{L} = 0$. As the interior areas are

furnished or materials are stored in the storage torus, therefore, Freyr's rotation will slow.

To maintain reasonable levels of comfort within Freyr for inhabitants, the angular velocity of the settlement must be kept above 0.1422 radians per second, or 1.35 rpm. This corresponds to multiplying the moment of inertia by a factor of only 1.044, meaning that Freyr is faced with a problem of having to almost constantly rejuvenate its rotation.

The solution to this problem is electric thrusters fixed to the outside of Freyr's hull. These thrusters are positioned at a radius of 535 meters, meaning that for every newton of thrust they evolve, 535 newton-meters of torque are exerted on Freyr.

Current analysis of VASIMR-style engines (variable specific impulse magnetoplasma rocket) suggests that they have a maximum specific impulse of around 50,000 seconds, although current models top out at about 13,000 seconds[51]. At a power-to-thrust conversion rate of 20 kW per newton, a twofold increase over current technology that is reasonable given the fast rate of progress on VASIMR-style engines, allocating an excess 5 MWe for rotational stabilization allows a total thrust of 250 N, yielding a torque of 133,750 N-m.

The production of this much thrust can be used to calculate the fuel flow rate into these engines:

$$F_T = \dot{m} I_{sp} g_0$$

$$250 = \dot{m} * 13000 * 9.81 \Rightarrow \dot{m} = 0.00196 \, \text{kg/s}$$

The rate of fuel consumption is almost 2 grams per second. This means that a metric ton of fuel is used up every 510000 seconds, which is 141.7 hours. Thus, one metric ton of fuel can increase Freyr's moment of inertia (for an angular velocity of 0.1476 radians per second) by 4.6E11 kilogram meters squared, which is equivalent to the addition of 2,283 metric tons at a radius of 450 meters.

Based on the premise of adding mass to a point at a radius of 450 meters, 133,750 newton-meters of torque allows the addition of 4.47 kilograms per second, or a metric ton every 3 minutes and 43 seconds. This is clearly plenty of capacity for adding mass; Freyr is almost entirely a closed-loop system and maintains its distribution of mass very nicely.

When simply acting as a counterbalancing force for the torque caused by parasitic losses in the rotating ferrofluidic bearing between the Spaceport and the rest of Freyr, this amount of torque corresponds to 5350 newtons of force at the radius of the bearing. This is more than enough to compensate for the losses generated. Of course, a similar system is required on the Spaceport to produce diametrically opposed forces and cancel out the effects of the parasitic losses on the Spaceport itself, but this system can be much smaller (hundreds of kW) and is not extensively discussed here[13].

---

[13]It is also possible that visiting ETVs or LTVs could provide a momentary thrust to return the Spaceport to a state of zero rotation.

Dimensions

The Spaceport has a diameter of 100 meters and a length of 150 meters. Its diameter narrows to match that of the central core at the ferrofluid seal and thus allows an easy adaptation from core size to Spaceport size while making possible the exchange of large cargo containers and the construction of a large open area. The shape of the Spaceport is a cylinder capped at one end by the main disk of Freyr and at the other end by a semi-ellipsoid that has semi-axes of 50 m, 50 m, and 30 m.

The walls of the Spaceport are constructed of titanium layered with Graded-Z shielding, but the main titanium layer is somewhat thinner than it is on most other portions of Freyr because there is no rotationally induced stress. The shell does not need to deal with rotational stresses or pseudogravitational loads, so the only stress on the shell is provided by containing the internal atmospheric pressure. This stress is given by

$$T = \rho\omega^2 r^2 + \frac{\Delta P r}{h}$$

$$T = 4100 * 0.0967^2 * 50^2 + \frac{90000 * 50}{h}$$

In these equations, h is the thickness of the titanium shell. Solving for an acceptable stress of 150 MPa, it is easily found that

$$150000000 = 95847 + 4500000\frac{1}{h}$$

$$h = 0.030\,\mathrm{m}$$

Multiplying by 1.5 for reasonable loading, it becomes clear that the necessary thickness is 4.5 cm. This gives a total shell volume of approximately 3639 cubic meters of titanium. Of course, this leads to poorer radiation protection, but it is well worth the savings in materials and the greater ease of construction for this crucial initial section. Given these dimensions, the mass of the pressure shell is 14350 tons.

These dimensions give the Spaceport a surface area (interior surface of the constraining walls) of just under 34000 square meters and a volume of 707 thousand cubic meters (See Appendix D). While there are no large internal divisions, the volume of the Spaceport is roughly divided into four distinct areas: a Docking and Cargo Processing area, a Transport Channel from the Airlock Complex down the center of the Spaceport, a Spacecraft Manufacturing area, and a Microgravity Industry area.

The Spaceport's moment of inertia is $3.588\mathrm{E}10$ kg-m^2, but since it is non-rotating this is not included in the calculation of Freyr's moment of inertia.

Materials

The Spaceport is constructed primarily of titanium alloy, with an exterior of thin Graded-Z shielding and an interior that contains various machinery and components. Titanium was chosen for

the Spaceport because of its high strength, relatively low density, and availability in lunar regolith.

As in other applications on Freyr, titanium forms the backbone of the Spaceport's operations. Not only is the shell constructed of the metal, but much of the interior machinery is also composed of titanium due to its corrosion resistance, strength, and fairly high heat tolerance.

As in the central core, titanium for the Spaceport is alloyed with 10% aluminum to decrease build complication and time while maintaining good strength in the containing walls.

Facilities

Clearly, the Spaceport is a microgravity environment, and so transportation within the Spaceport is accomplished with a network of small cables for workers to grab onto or attach cargo to with slacklines. This network prevents loss of control and inability to move usefully throughout the space while still maximizing motility and minimizing obstruction, as compared to setting up a series of small compartments within the larger space, which would also allow motion control. While RCS systems would also provide these advantages, they have the disadvantage of spewing typically toxic gases into the environment they are used in - not a problem in the vacuum of space, but certainly a problem in an inhabited area. RCS thrusters could also damage equipment or structural members inside the Spaceport. Because these cables are not stressed very highly, they are aluminum cabling; this reduces expense while providing adequate strength for the job required. When moving along these lines, a double-line configuration is used to prevent accidents: while transitioning from one line to another, the user first transfers one line to the new cable, then the other, so that they are always connected to at least one of the lines.

The Spaceport contains all of Freyr's microgravity functions, which is why it is larger in both diameter and length than the central core.

At the far end of the Spaceport is the Airlock complex. This consists of one major airlock that has dimensions 10 m in length by 20 m width and 20 m height, allowing the passage of all but the largest components in one piece. This airlock is joined by four secondary or support airlocks that are intended for a single human occupant; these airlocks bracket the major airlock and allow the rapid transfer of personnel even when there is a slow transfer of equipment making use of the major airlock.

The airlocks are controlled by a double panel of isolated human operators, each of which has the power to shut down the entire operation if an unsafe situation develops. At any point, either operator may hit a kill switch on their panel, which will close all sets of doors not immediately obstructed and default to a fail-safe position. The actual airlock mechanism is a coupled oil diffusion/turbomolecular pump system with a standard starter pump to drop the initial pressure. This combination of pumps results in a quick reduction of pressure to 10^{-3} torr and then a slower reduction to 10^{-12} torr, which ensures that a) a small volume of gas is vented to space when the airlock is opened, and b) any and all pressure suits can be tested for leaks inside the vacuum chamber rather than in space.

The Spaceport is home to an additional six docking ports located closer to the rotating section of Freyr. These are used for maintenance activities, standard entrance/egress activities, and docking of ETVs and LTVs to the Spaceport. Located at these docking ports are clusters of the Spaceport's aluminum cabling network, allowing easy access just after disembarking to any of the important parts of the Spaceport or to the transition point to the rotating section of Freyr's structure. These docking ports are built based on the International Docking System Standard and can therefore be docked to by any spacecraft from Earth; Freyr's craft are equipped with an implementation of IDSS called FDS (Freyr Docking System), which is especially conducive to docking large crafts such as an ETV or LTV to the port. To accommodate several different types of ports, Freyr is capable of using different docking adapter scales within the IDSS implementation, which lets both small capsules and large cargo craft dock to the same docking port (although the procedures are different and the docking port's full capability is not used for these smaller craft).

1.3.9   Overall Structure and Diagrams

A summary table of some of Freyr's structural characteristics is located below. Note that the angular velocity is given as +0.1476 rad/s because the angular velocity pseudovector points along the direction of the Spaceport[14].

Table 1.5: Freyr Structural Statistics

Property	Value	Unit
Radius	525	m
Diameter	1050	m
Height	325	m
Angular Velocity	+0.1476	rad/s
Rim Velocity	77.5	m/s
Structural Mass	1.88E9	kg
Total Mass	3.76E9 - 5.64E9	kg
Moment of Inertia	3.140E14	kg-m^2
Loaded Moment of Inertia	6.281E14 - 9.421E14	kg-m^2
Habitable Volume	5.186E7	m^3
Habitable Floor Area	7.86E5	m^2
Population Capacity	24000	persons
Life Support Capacity	25000	persons
Recommended Population	20000	persons

The tori and the central hub are all coplanar and are arranged so that they surround each other, as in Figure 1.7.

The dashed lines represent stays that are used to hold Freyr's tori in the correct positions during acceleration and deceleration of the settlement. The industrial torus is also firmly connected to the

---

[14]Counter-clockwise rotation is defined as positive in a right-handed coordinate system.

central hub at its attachment points.
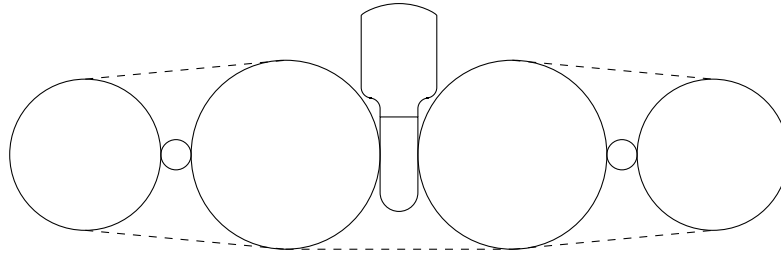
Figure 1.7: Cross-Section View of Freyr's Structure
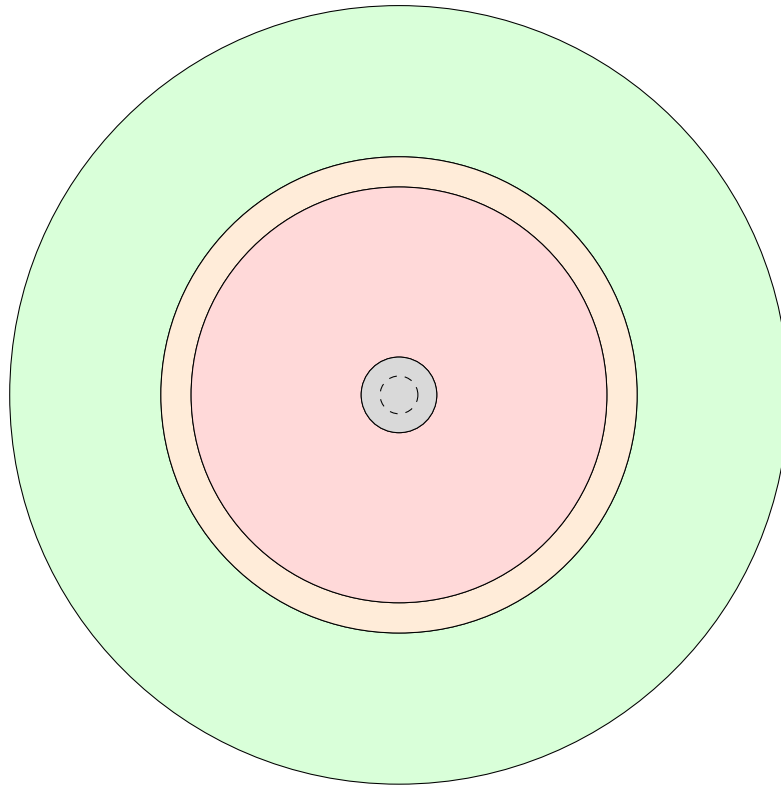
Figure 1.8: Top-Down View of Freyr's Structure

In Figure 1.8, green represents the Life Support/Habitation torus, orange represents the Storage torus, red represents the Industrial torus, and grey represents the central core. The dashed line represents the point where the Industrial torus and the central core meet, which is obscured by the Spaceport.

The views given so far do not adequately represent Freyr's structure; a pseudo-isometric view (Figure 1.9) shows Freyr's structure much more clearly.

In this image, it is difficult to see the storage torus, and it is clear that the habitation and life support torus takes up far more volume than the industrial torus does. This picture gives a much clearer representation of Freyr's structure and should clarify your image of the settlement.
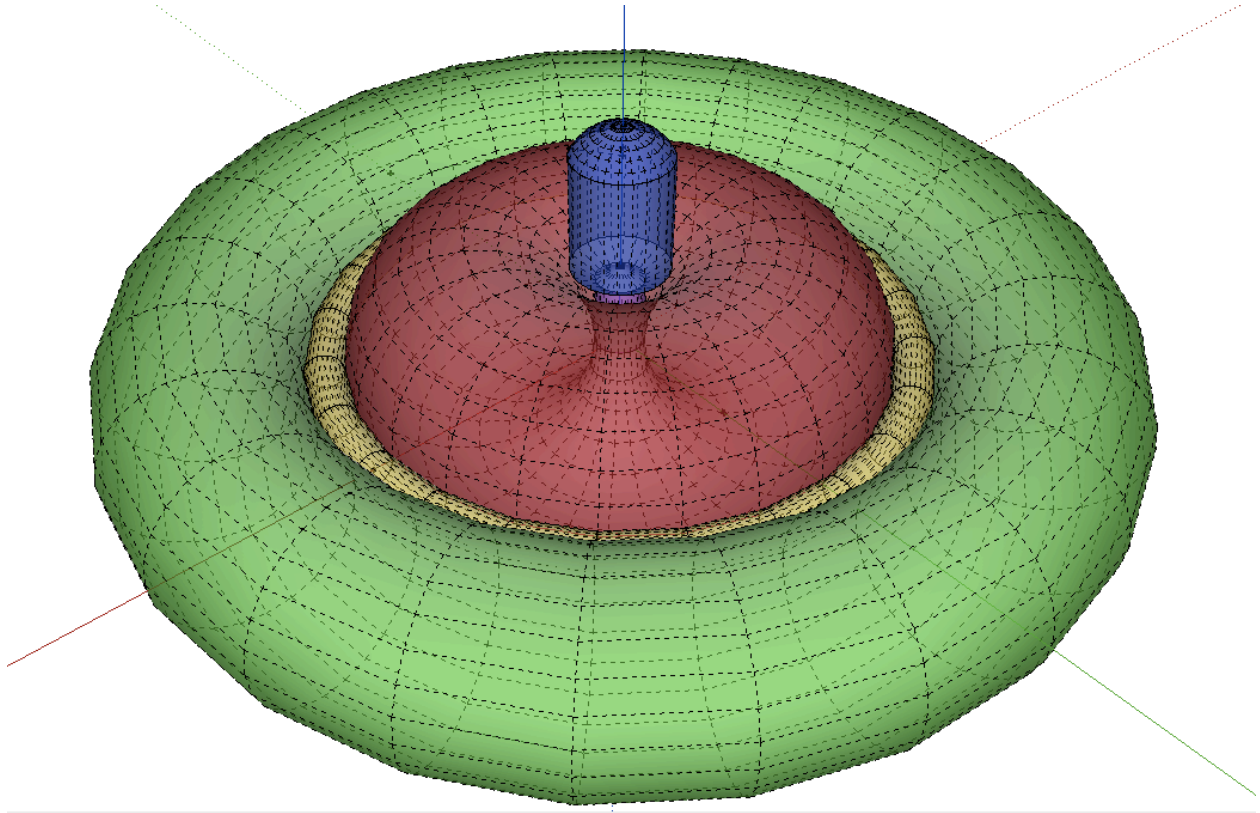
Figure 1.9: Perspective View of Freyr's Structure

While Freyr's structure may look strange from this angle, it is in fact very compact and efficient. The primary advantage over other proposed designs is that Freyr's rotating sections are co-axial and not offset, which means that less material is required for the central shaft. This makes it far easier to construct the initial parts of Freyr and then gain on-site manufacturing capability without the need to continue importing finished products to be joined together.

1.4   Habitation

This describes the habitation accommodations on board Freyr. As such, the information in this section pertains mainly to the life support/habitation torus, though some of it may also be applicable to the Spaceport and core. Included here is a discussion of the places in Freyr where humans live, the life support systems that make these places habitable, the safety features that keep Freyr's inhabitants safe, and the procedures Freyr follows when those systems break down.

Freyr provides support for a human population of 20,000. This includes radiation shielding, living quarters, community spaces, public services, "outdoor" areas, and all the other areas necessary for life. Human habitation is located in the rim of Freyr.

Freyr's habitation areas are rudimentary except for the outdoor areas that are eventually developed. Facilities are not elaborate, living quarters are smaller than they could be on Earth, and enclosed spaces are the rule rather than the exception. This is a natural consequence of life in an orbiting settlement and cannot be overcome without sacrificing operational capability, population size (and therefore workforce), or those open spaces that Freyr does provide for recreation.

Despite these drawbacks, Freyr is not simply a place to work. Businesses, entertainment venues, "open-air" parks, and community centers help to keep the Freyr community bound together. Freyr is a home, albeit one that is completely self-contained, has a population of just 20,000, and is isolated from all other communities. Luxuries are sacrificed, but the essentials remain.

1.4.1   Earth Normal

The environment in the human living quarters aims to mimic Earth normal conditions to reduce the stress on colonists and interfere as little as possible with human life. This leads to several requirements on the environmental controls within the living quarters to ensure that Freyr is suitable for long-term habitation. Some of these constraints are fairly easy to meet, while others are quite difficult.

It is absolutely imperative that Freyr provides as close an environment to Earth as possible. This is for the long-term health of residents and allows for research on human reactions to the environment of space over years without danger of catastrophic settlement failure due to a foreign atmosphere.

Atmosphere

Earth's atmosphere has an ambient pressure at sea level of 101.3 kPa. It is composed of 78.1% N_2, 20.9% O_2, 0.9% Ar, 350 ppm CO_2, and trace amounts of other gases. On Freyr, Ar and trace gases are neglected in favor of a N_2-O_2 atmosphere with low levels of CO_2.

Keeping in mind the facts that a concentration of oxygen above 23% in atmosphere constitutes an "extreme fire and explosion hazard"[52] and that the partial pressure of oxygen should remain at or above 17.6 kPa to ensure proper cognitive, neural, and respiratory function[53], the conclusion is that

the atmosphere of Freyr ought to be 79% N_2 and 21% O_2, with a total pressure of 90 kPa. This gives a partial pressure of oxygen of 18.9 kPa and a partial pressure of nitrogen of 71.1 kPa. This atmosphere meets oxygen limits and forestalls the possibility of explosion by keeping the % O_2 well below 23% and yet keeping the partial pressure of O_2 at the level recommended for humans. It is important to note that this atmosphere is about 90% as dense as Earth's at sea level and contains slightly less oxygen, although it is actually more rich in oxygen than Earth's atmosphere. This carries the possibility of reduced ability to function as compared to the environment at sea level, but according to the atmospheric scale height equation[54]:

$$P(h) = P_0 * e^{-\frac{h}{h_0}}$$

If we assume an air temperature of 273 K, a little colder than Freyr's interior temperature, Earth's atmosphere has a scale height (h_0) of 8.0 km, meaning that 90% of atmospheric pressure corresponds to conditions at just 850 m of altitude above sea level, clearly acceptable for human habitation. A far more pressing concern is the removal of carbon dioxide, which acts as a poison to humans if present in high enough concentrations.

There are two established methods for dealing with CO_2 buildup in atmosphere. One is mechanical and relies on canisters of chemicals such as LiOH (lithium hydroxide), which react with CO_2 and trap the carbon, releasing oxygen according to the equation

$$2LiOH + CO_2 \rightarrow Li_2CO_3 + H_2O$$
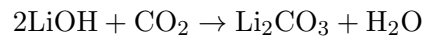
The other is biological and makes use of photosynthesis to remove CO_2 and H_2O to produce glucose and O_2 according to the equation

$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$
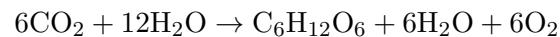
When considering the scale of the CO_2 conversion on board Freyr, and the indefinite length of time for which our chosen system must operate, the only reasonable choice is a biological treatment system. As an example, each Apollo mission carried about thirty 4 kg LiOH canisters[55], for a total mass of 120 kg for three astronauts for less than 10 days in space. Scaled up to Freyr's population, this translates to 80 tons of LiOH canisters per day, clearly an unacceptable amount. LiOH canisters are therefore absolutely impossible to scale up for 20,000 people and years of time.

A biological treatment system is therefore used on Freyr. It is desirable to optimize this system for oxygen production, carbon dioxide processing, low mass, and biological production; some photosynthetic organisms are better than others at carbon dioxide uptake. Additionally, trees and shrubs are not desirable due to large organism size, nutrient, and soil requirements; the optimal organisms are photosynthetic bacteria that can be suspended in aqueous solution and bubbled with carbon dioxide. To avoid the difficulties involved with a central air processing unit, several smaller stations are located at intervals around Freyr's central disk, near the human habitation areas. More details on this algae system are provided in 1.4.3.

Gravity

Earth has a gravitational field of 9.807 m/s^2, on average, at the surface. While it may not be necessary to exactly recreate this acceleration, it is generally understood that human tolerance, until it is better understood, should be assumed to be fairly small ($\pm 10\%$)[56]. This 10% margin indicates that the pseudogravity on Freyr should be between 8.826 m/s^2 and 10.788 m/s^2.

There are several proposed methods for the generation of artificial gravity. Such concepts as "gravity generators" and diamagnetic gravity simulation are obviously inapplicable to this station, gravity generators because there is no basis to suggest that they will be available in the near future or, indeed, are possible at all, and diamagnetism because it requires "either expensive cryogenics to keep [the magnets] superconductive, or...several megawatts of power"[57] to apply force to even small objects, let alone an entire settlement. That leaves two possible methods of generating artificial gravity, linear acceleration and rotation.

Linear acceleration provides a pseudoforce that simulates gravity by placing the occupant inside a non-inertial reference frame. This can be envisioned, essentially, as a platform accelerating upwards at 1g, generating the illusion of weight for anyone standing on the platform. There are several problems with this approach: accelerating in a linear direction requires that the entire settlement be accelerated at 1g, requiring massive amounts of fuel and expense. Additionally, the speeds such a scheme would involve are prohibitively fast for any kind of near-Earth settlement. These problems are exacerbated as the linear accelerator is left running for months or years and spirals out of control. With this said, linear acceleration may be a useful way to provide some artificial gravity in transit to Freyr or another solar system destination, but not on the scale of 1g for reasons that must be all too clear.

The only reasonable option left to consider is rotating Freyr. From the design, it must have already been clear that the settlement is designed to be rotated. Rotation makes use of centripetal acceleration:

$$a_c = \frac{v^2}{r} = r\omega^2$$

This produces the illusion of gravity inside the settlement. One consideration of note when dealing with rotating coordinate systems is phantom forces. One of the most significant of these is the Coriolis force, which arises from moving towards or away from the axis of rotation. On Earth, the Coriolis force is responsible for the directional rotation of the ocean gyres and hurricanes[58]; on Freyr a slightly different case arises. Because the rotation of Freyr is itself responsible for the "gravity" felt by residents, the Coriolis effect comes into play when an object moves "vertically" within Freyr. Due to the relatively low angular velocity of Freyr, only 0.1476 rad/s, the Coriolis effect is nearly negligible, as shown below.

$$\vec{F}_C = -2m(\vec{\omega} \times \vec{v})$$

Since the angular velocity vector is normal to the plane of rotation, and the velocity we are concerned with is "vertical" (towards the axis of rotation), we can replace $\vec{v}$ with $\vec{v}_r$, the radial velocity. Then the perceived Coriolis force is:

$$F_C = -2m(\omega v_r)$$

For a typical case of a human, say, climbing a ladder, the force is:

$$F_C = -2(70\,kg)(0.1476\,rad/s * 0.5m/s) = -10.332\,N$$

That is a practically negligible force, and further analysis shows that even for elevators traveling at several meters per second there is not an overly troublesome Coriolis force. These calculations indicate that a radius of 525 meters and angular velocity of 0.1476 rad/s provides sufficient conditions for human function and health (a little more than 1g on the habitation decks) while not causing debilitating Coriolis forces on objects and individuals moving vertically inside Freyr.

An interesting object of note is that there is an interesting critical vertical speed:

$$v_c = \frac{\omega r}{2}$$

At this speed, the Coriolis force becomes more important than the centrifugal force felt by an object, and above this speed it is easier to stand on a wall than on the floor. At a radius of 465 meters, right between the habitation decks, this speed is $v_c = 34.3$ meters per second, clearly unobtainable in the vertical direction, but near the center (say, at a radius of 25 meters), the critical speed is only $v_c = 1.85$ meters per second, easily attainable. The implications are interesting: they mandate slower movements with industrial machinery and have strange consequences for low-gravity recreation.

Radiation

On Earth's surface, the average yearly dose of radiation is 3600 μSv, of which about 10% (280 μSv) comes from cosmic radiation[59]. Freyr, outside Earth's protective atmosphere, will receive many times more radiation, including high-energy "Galactic Cosmic Rays," which are usually shielded by Earth's magnetosphere and atmosphere[60]. While Freyr's orbit keeps it inside Earth's magnetosphere approximately one third of the time[61], for the remaining two thirds of the time it must have some protection against ionizing radiation.

There are two types of shielding that may be employed: passive and active. Passive shielding uses a mass between the source of radiation and the item to be protected to reduce the amount of radiation experienced by the target, while active shielding uses an electrostatic or magnetic shield to deflect charged particles and prevent them from impacting the settlement at all.

Freyr uses passive shielding of a design detailed in section 1.2.2. This shielding also forms the hull of Freyr, and reduces incident radiation to levels acceptable for all of Freyr's inhabitants, including pregnant women and young children.

The decision not to use an active shielding mechanism was quite easy: although it is touted as a protection system for relatively small torus-shaped spacecraft, when scaled up to the size of Freyr the power requirement increases as the radius squared because of the vastly larger and more difficult

to maintain superconducting systems required for the shielding to be effective. Additionally, because Freyr's habitable areas already require a structural shell at least 20 cm in thickness[15], it is very simple to increase the thickness a little and provide additional shielding with thin layers of native lunar elements (which further helps to reinforce Freyr's structure). Bringing in the equipment for an active shield on top of already having a 20 cm wall would simply be excessive and is not worth the effort or the expense.

1.4.2 Human Living Quarters

On Freyr, humans can only inhabit the outer 100 to 200 meters for extended periods of time, and all residences are located within this range to minimize the harmful effects of low gravity. Specifically, the two Habitation decks are located between 485 and 445 meters from the center of rotation, with outdoor areas above them between 445 and 385 meters.

Homes for Freyr's inhabitants are provided in the Life Support/Habitation torus and are arranged as single-family houses. Each person on Freyr requires at least 400 cubic meters of space for continued psychological function, which sets the habitable volume requirement at more than 8 million cubic meters - clearly not a problem, given the size of the habitation decks. This includes interior and private areas as well as some "outdoor" and community space. Based on an assumption of 50 square meters (540 square feet) of indoor space at 3 meters of height, each person then accounts for 250 cubic meters of "outdoor" volume in the habitation decks. In order to reduce feelings of containment on Freyr, these decks have a ceiling of 20 meters, meaning that each individual accounts for 12.5 square meters of "outdoor" floor space, equal to 135 square feet. With 20000 people, the total "outdoor" area comes out to 250000 square meters, or 2.69 million square feet, the size of 35 regulation soccer fields. Within each habitation torus, some space is used for mechanical, maintenance, etc. purposes, but even so about half the available volume is not used by these volume requirements. This extra volume allows thorough study of the conditions for optimal psychological well-being and minimal space usage to maximize the efficiency of the settlement.

Houses are arranged along the side walls of the habitation decks to allow for a large open space in the center. Within each level, houses are stacked four high, with staircases leading to the higher houses; all houses are a single floor. This allows maximum use of volume while not compromising the ability to have relatively tall-ceilinged open spaces for recreation. The houses are designed for three inhabitants, but can house up to four comfortably. They are not, in general, capable of housing more than five terribly comfortably (although it is definitely possible), which helps to provide a non-invasive population control system. With the target occupancy of four individuals, the house has a footprint of fully 150 square meters (1610 square feet), which is ample room and provides much-needed private space. Without a large amount of truly extra room, houses both reduce volume usage and encourage inhabitants to utilize outdoor spaces, which promotes community.

The house has an adjustable floor plan and features moveable walls so that inhabitants can customize their house to a degree; this helps with individual expression and makes the arrangement

---

[15]Because of the stress in an inflated torus. See Appendix D.

less stifling. The walls are designed so that they are not easy to unfasten, but moving them to another part of the house is fairly easy. They employ a bracing system with locking pins to keep the walls immobile except when they are intended to be moved, but they are lightweight and can therefore be relocated easily once unfastened. The light weight of the walls is accomplished with metal foam, which is structurally sturdy but is also sound-muffling, which helps the space to seem not quite so small. The walls are constructed of 2.5 cm of this metal foam sandwiched between two 3 mm aluminum sheets, providing a low-mass construction (12 kg per square meter of wall) that is still very strong and muffles sound. Due to metal foam's high crush strength, these walls are even used as structural supports.

To help even the load on Freyr's electrical system, the two habitation decks are kept on separate day/night cycles. When the upper habitation deck is marking 1200 on their clocks, it is 0000 on the lower habitation deck. This also helps to even out the distribution of Freyr's workforce around the clock by ensuring that there is no point in time at which Freyr's inhabitants are all or even mostly asleep. The transfer between day and night is graduated to effect a gradual dimming or brightening, in line with Earth morning or evening, which also helps to even out the electrical load. This is made possible by the LEDs that illuminate the habitation decks (see 1.4.3).

Family Structure

On Freyr, the generally espoused family structure is two married adults with whatever children they may have had. Other family configurations are possible, but this is the most common and the easiest to fit into Freyr's houses comfortably.

Marriage per se is not, however, continued in the same way on Freyr as it has been here on Earth. It is allowed to gradually lapse by Freyr's administrative sectors, though it may well still be maintained by organizations on board the settlement. Marriage is still, of course, a useful institution, but it is also an aging one and Freyr's inhabitants will be allowed to decide for themselves whether marriage as an institution still makes sense on an orbital settlement.

That said, Freyr has no restrictions on who can get married aside from those required by simple decency. For example, children younger than 18 cannot cohabit or get married. Other than these common sense restrictions, Freyr does not discriminate against anyone who wants to get married, regardless of gender identity or sexual orientation. The caveat to this rule is that any individual may only be married to one other person at a time. Divorce is a possibility on Freyr, but polygamy is not sanctioned.

It is anticipated that each couple will have an average of two children. Some may have one or zero, and some may have three or four, but the average is expected to be two. This allows for population maintenance. Of course, while Freyr is building up its population, adults are encouraged to have more children, which helps with population growth.

1.4.3   Power

Freyr's LFTR is capable of generating 100+ MWe. By increasing reactor power output and running both S-CO_2 cycles at a greater percentage of their capacity, Freyr could conceivably generate 150 MWe if absolutely necessary. At nominal power usage, 100 MWe is generated, but this can be increased or decreased slightly as required.

100 MWe is quite a bit of power. This is absolutely true. Most of Freyr's power consumption is due to lighting. To provide an experience on Freyr that is conducive to long-term psychological well-being, Freyr must present an environment that is as Earth-like as possible, and that includes providing a simulation of sunlight. Here on Earth we don't think about sunlight as being a large power draw, but the power incident to the Earth due to sunlight is on the order of one hundred petawatts.

Illumination

Illuminating Freyr's habitable areas takes a lot of power. To help alleviate these power demands, as mentioned above, the two habitation levels are kept on opposite day/night cycles. Additionally, the "outdoors" deck can be powered down if necessary. Still, the total area to be illuminated is, at a reasonable estimate, about 518000 square meters. One way to do this, of course, is with mirrors to harvest natural sunlight, but consider that glass has an ultimate tensile strength of just 33 MPa (this is high-quality glass, too!) and that the points where windows joined the metal of the torus's shell would be very weak failure modes. Additionally, constructing a mirror hundreds of meters across - possibly up to kilometers across - and then keeping it out of the way of everything else, positioning it precisely, and ensuring that it was constantly in view of the Sun is not an engineering project that humans are currently able to undertake, and it is not likely that it will be within our capabilities within the near future.

As is clear from the table of typical schedules, these schedules are not universal. For example, some people work later in their day and have free time earlier, or are naturally on a different sleep schedule. In general, however, the residents of the two habitation decks are split into these two schedules by deck. During the local time of 2200 - 0600, the lights are very dim, and during the time between 1000 and 1800 they are at full brightness. In the remaining times they scale linearly between the two according to the direction of transition. This helps to ease the transition between day and night while keeping power usage constant.

The remaining option is to use artificial illumination to provide a simulation of sunlight within the habitable decks. There are certain problems with this, chief among them power usage. Fortunately, LEDs can be made with lunar materials, so Freyr can harvest what it needs to construct large-scale, energy-efficient lighting. These LEDs are dimmable, an advantage over compact fluorescent lightbulbs (which are also energy efficient) because it allows Freyr's control systems to reduce the lighting level if required while not damaging the lights themselves.

Assuming an illuminance of 10000 lux, comparable to a sunny morning, and an LED that generates 100 lumens per watt, reasonable with modest technological advances, the power requirement for

Table 1.6: Typical Schedule for Each Habitation Deck

Time	Upper Level	Lower Level
0000	Sleep	Lunch Break
0100	Sleep	Work
0200	Sleep	Work
0300	Sleep	Work
0400	Sleep	Work
0500	Sleep	Free Time
0600	Wake Up	Free Time
0700	Morning Activity	Free Time
0800	Work	Free TIme
0900	Work	Free TIme
1000	Work	Sleep
1100	Work	Sleep
1200	Lunch Break	Sleep
1300	Work	Sleep
1400	Work	Sleep
1500	Work	Sleep
1600	Work	Sleep
1700	Free TIme	Sleep
1800	Free TIme	Wake Up
1900	Free TIme	Morning Activity
2000	Free TIme	Work
2100	Free TIme	Work
2200	Sleep	Work
2300	Sleep	Work

illuminating such a large surface is calculated below:

$$\text{Illuminance} * \text{Area} * \text{LuminousEfficiency} = \text{Power}$$

$$10000\,\text{lux} * \frac{1\,\text{lumen}}{\text{m}^2\,\text{lux}} * 518000\,\text{m}^2 * \frac{1\,\text{W}}{100.\,\text{lumens}} = 51800000\,\text{W} = 51.8\,\text{MW}$$

The power requirement to light 518000 square meters at 10000 lux with these LEDs is 51.8 MWe, a little over half the nominal power Freyr has at its disposal. This provides a very Earth-like environment and ensures that Freyr actually feels like home to its inhabitants.

Areas other than the habitable sections of Freyr are sparsely illuminated to avoid excessive energy consumption. Workers carry flashlights and/or headlamps, and of course any dangerous locations are illuminated, but the average illumination in other parts of Freyr is closer to 10 lux, brighter than twilight but far dimmer than a living room.

When power consumption needs to be reduced, illumination in the habitable areas can be reduced to 1000 lux, more like an overcast day. This cuts power consumption to under 10 MWe.

Life Support

The life support system requires power to operate. Due to efficient operation protocols and some self-sustaining cycles (such as the SCWO waste destruction cycle), the life support system can under nominal conditions be powered with under 5 MWe.

Of the power consumption required by the life support system, some of the biggest drains are: ventilation systems, water pumps, and plant illumination.

Facilities

Freyr must provide power to several facilities. The central core needs about 1 MWe, various systems within the habitation torus require up to another 1 or 2 MWe, and communications and external lighting systems require up to 500 kWe.

These facilities include domestic lighting (about 0.5 kWe per home), appliances, charging electrical devices, communications and radar systems, external signal lights, computer systems (servers), cable elevators, and a few other systems.

Industry

Industry on Freyr uses the remaining 40.2 MWe, as well as some of the 115 MWt of waste heat from the reactor (concentrated into high-grade heat for chemical reactions), to run its processes.

Electricity is somewhat more handy than thermal energy because it can be applied in a variety of ways. For example, electricity can be used to either heat or cool a material, provide an arc for welding, provide an electro-potential for redox reactions, and in many other applications as well, while thermal energy can really only heat stuff up.

The industry uses all of the remaining electrical power and then finds a use for thermal energy as it can. Electrical loads can be started or discontinued based on electrical availability, making it possible to continuously keep Freyr at its electrical capacity by varying its industrial output of certain products.

Thermal energy can be used in several ways. Sufficiently high-grade heat can be used to bring reactions above their critical temperature, while lower-grade heat can preheat the reactants or materials for a certain process. The waste heat for which no use can be found is either radiated to space using radiators at the bottom of the central core or is passed into a thermocouple that uses the temperature difference between the waste heat and space to generate a little extra electricity. These thermocouples are not efficient, getting maybe 5% of the energy contained within waste heat, but they help to reclaim usable energy from waste and reduce energy production, generating as much as 2.5 MWe (although a more typical output might be 200 kWe). Freyr's thermocouples are

particularly inefficient because of their large size to reject a large amount of heat, which necessitates that they be built exclusively from lunar materials that do not typically make good thermocouples due to their similar Seebeck coefficients.

1.4.4 Air

As the residents of Freyr breathe and carry out cellular respiration, they use up oxygen and sugar while expelling carbon dioxide and water vapor. Water can be relatively easily condensed from the atmosphere and used for agriculture or, once processed, for drinking, but carbon dioxide is a bigger problem. Once concentration of carbon dioxide in the atmosphere reaches about 1000 ppm, or 0.1%, people begin to feel "generally drowsy," and levels of more than 2500 ppm (0.25%) can lead to large-scale health effects.

To deal with the carbon dioxide problem, as stated previously, Freyr relies on a biological conversion system (BCS) utilizing Spirulina algae bubbled with carbon dioxide-rich gas.

Oxygen production is increased by feeding nearly pure CO_2 through the algae tank system. We achieve this by use of a system of hydroxyl modified polyamidoamine (PAMAM) dendrimer membranes, which show a selectivity of $\sim$4000 for CO_2 over N_2 and O_2[62]. The membranes are set up as shown below.
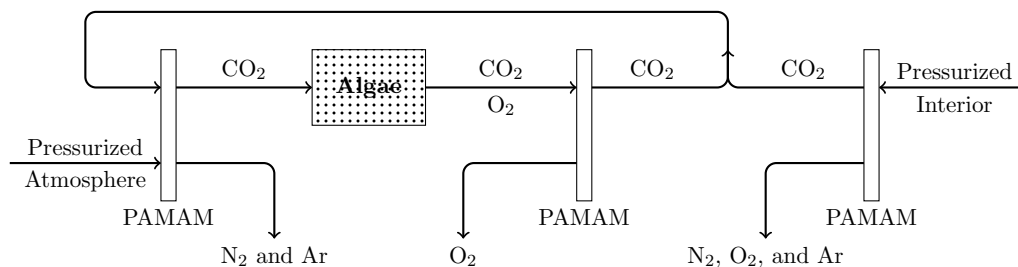
Figure 1.10: PAMAM Membrane System for CO_2 Selection

This system does several things for us. It produces nearly pure CO_2 to run through our algae, it filters CO_2 out of our breathing air, and it produces (when exterior atmosphere is used) a mixture of N_2 and Ar, which can be separated to yield the individual gases, and whenever it is used it produces oxygen that we can store. This oxygen can be pressurized, released to the base's atmosphere, or even liquified to perform a variety of applications. It is important to note that the gases produced here are not entirely pure - our oxygen has some carbon dioxide in it, and vice versa - but that the selectivity of the membrane indicates that these impurities should be less than one part in 500 (<0.2%). Even if the membrane does not work as well as projected, the impurities in the gases produced are acceptable, as we are not using the gases produced by this mechanism for high-performance scientific work.

Studies indicate that Spirulina cyanobacteria are capable of producing at least 7 L of oxygen per 1 L of packed cell volume (about 50 L of culture volume) per hour under light irradiation[63]. Higher rates of oxygen production are possible in laboratory, but are infeasible on such a large scale.

NASA estimates that a human requires 0.835 kg of oxygen per day to survive[64], which under our conditions translates to about 25 L O_2 per hour. Thus, we need 175 L of algae culture per person[16], for a total of 3.5E6 L of algae culture. We have 4.0E6 L of algae culture in operation so that (a) we have an excess of oxygen to store, (b) the algae can be rotated in and out if need be, (c) the algae growth can be harvested for food, and (d) extra oxygen can be converted into useful fuel or materials. Algae production can be throttled down if need be, to provide the required amount of oxygen but avoid excess production to prevent storage difficulties. This algae volume reduction would also result in a large quantity of algae to be processed into food.

To help ensure proper atmospheric mixing, carbon dioxide extraction and oxygen introduction are carried out at several places around Freyr's hull. Additionally, the air stripped of carbon dioxide and infused with oxygen is re-introduced in different locations, which helps to set up circulation patterns inside Freyr's habitation areas. Intake and outlet ducts run through all habitable levels and are used to help with air mixing. Stagnation points are very difficult to predict for Freyr without extensive modeling, so Freyr's inhabitants will have to test areas for CO_2 concentration to determine where stagnation occurs, then take steps to prevent it (perhaps by installing strategically placed fans or intake/outlet ducts).

If 25 L/hour of oxygen are required per person, and 20000 people must be supplied with oxygen, then an hourly throughput of 500000 liters of oxygen is required. Removing not more than 800 ppm of carbon dioxide from the atmosphere means that 500000 liters per hour is not more than 800 ppm of the total throughput per hour, which makes it necessary to circulate at least 625 million liters, or 625000 cubic meters, of atmosphere per hour through the air processing system (carbon dioxide removed and oxygen generated are in a 1:1 ratio). This corresponds to 18.4 cfm (cubic feet per minute) per occupant, just under the recommendation for office spaces and restaurants given by ASHRAE standard 62-1989[65]. Because a typical carbon dioxide removal level is closer to 400 ppm, a little over the atmospheric concentration on Earth, typical throughput is on the order of 1.25 billion liters (1.25 million cubic meters), which is 36.8 cfm per occupant, exceeding even the standards for hospitals. This large throughput of air through the processing system indicates that Freyr's atmosphere will feel much like Earth's and does not become stale.

1.4.5   Water

On Freyr, water is generally fairly clean, but unlike on Earth all of it must be recycled (or at least very nearly all). This makes it necessary to recycle not just water used for industrial purposes and greywater, but also blackwater and all waste products. While existing water treatment plants here on Earth are good at processing large amounts of water, they tend to use large amounts of toxic chemicals not readily available on the Moon, which makes them hideously impractical for Freyr's use. Additionally, the effluent from wastewater treatment plants is not considered safe for human consumption.

The solution, which provides clean water and breaks up organic compounds in waste, consists of a supercritical water oxidation system (SCWO) in conjunction with a maceration facility and UV

---

[16]See Appendix D

irradiation.

The maceration stage breaks down large waste particles (food waste, fecal matter, large particulate) and turns the influx of dirty water into a dilute slurry of organics in water, by adding more water if necessary, to obtain a waste concentration between 1% and 5% by volume. This slurry has approximately the consistency of water but is still considered a biohazard, hazardous material, or other classification based on the original constituents.

This slurry is then fed into the SCWO itself, which uses a combination of pressure and temperature to oxidize the wastes into small, typically non-toxic, molecules. At waste concentrations of over 1% the SCWO process is self-sustaining because the heat from waste decomposition provides the heat for decomposition of more waste[66], leading to small power requirements for the system. In all, an SCWO can achieve 99.99% or better destruction of waste products, and the result of SCWO treatment is mostly water, carbon dioxide, nitrogen, and some acids that can be precipitated out of solution or stored for industrial use. Carbon dioxide produced in this system is sent to the air processing units, while nitrogen is allowed to escape into the atmosphere and water is sent on.

Note that there are some waste sources that do not require processing in an SCWO. These include shower drains, sink drains (mostly), and a few other sources of wastewater. Instead of being funneled to the SCWO, these sources of water are either irradiated with UV light, used to dilute waste products traveling to the SCWO, or reused for processes such as flushing toilets. Note that while this water does not contain large amounts of toxic substances, it is still not safe for human consumption and therefore cannot be used for drinking, food preparation, or general human use without being treated.

To maintain a large amount of safe water for use and provide an emergency buffer in case of purification system failure, Freyr maintains a supply of 6.0 million liters (6000 tons) of water on board.

Water Use

To calculate the required capability of water processing facilities, it is first necessary to determine water usage by Freyr's population.

Each person requires approximately 2 liters of drinking water per day, plus 2 liters for food preparation. Using low-flow faucets and shower heads and assuming total usage (for an average resident of Freyr) of five minutes of faucet time per day and ten minutes of shower time per day, each inhabitant of Freyr uses 14.2 L/day for hand-washing and 50 L/day for showering[67].

Additionally, assuming four toilet flushes per inhabitant per day, about 18 L/day are used per person for toilet flushing. Using greywater from showering time, however, reduces this usage to zero. Dishwashers, the other main use of water, also use reclaimed greywater in their initial cycles, cleaning food residue off of utensils and dishes without using additional water. A steam cycle is then used to sterilize the dishwasher's contents, leading to water use of about 5 L/load, or 1.2 L/day per inhabitant.

Other water use (aeroponics, recreation, etc) could add up to 25 L/day per inhabitant (estimated). In total, then, each resident of Freyr uses approximately 95 liters of water. This means that Freyr's water processing systems must be capable of processing 1.89 million liters of water per day; fortunately, because the two habitation decks are on opposite day/night schedules, this load can be spread out over all 24 hours and there aren't times of true peak use.

Processing Unit Capabilities

SCWO units can be built to handle as much as 10 kg/min of waste products, or 0.6 tph, quite easily. Assuming that these wastes are 5% of the feed slurry, each SCWO can then process 12 tph of waste slurry, of which 11.4 tph is water. Each SCWO can therefore process some 273.6 cubic meters of water in 24 hours, meaning that to process the entire 1.89 million liters per day (1890 cubic meters per day), 7 SCWO units are required.

Since an SCWO has a mass of only several tons, this system is very feasible and provides an excellent method for purification and reuse of Freyr's water supply.

Placement

To maximize distribution and minimize travel distance to the SCWO units, SCWOs are placed in the Lower Life Support deck of the Life Support-Habitation torus and are spaced at 450 meter intervals at a radial distance of 501 meters. This places them near the top of the Lower Life Support deck and reduces the energy expended to raise the water back to the habitation decks.

Other tori have their own processing systems. The Industrial torus has a set of SCWO facilities that are used to break down waste products of its reactions; these waste products are then disposed of in various ways depending on their composition. Additionally, the core has an SCWO system capable of limited reprocessing (not much water is typically used in the core).

Safety Margin

If an SCWO fails, it will take time to repair the mechanism. During this time, some water restrictions will be in place. Specifically, showers will be limited to five minutes, reducing water consumption greatly while causing a slight inconvenience to Freyr's population. This reduction in water use allows Freyr to function with just six or even five SCWO units operational; further reductions of shower time could be necessary if more units were damaged.

1.4.6   Food

Food on Freyr is nearly as essential as water. Without food, Freyr will cease to function within days as people become unable to complete their jobs properly. For this reason, it is essential to ensure a supply of food sufficient for Freyr's inhabitants, preferably while placing as little stress as possible on the settlement's resources.

To reduce the energetic requirement of growing food, all food on Freyr is vegetarian; no animals are raised to be used for food. The elimination of a trophic level from the food chain, moving humans one step closer to primary productivity, increases the effective yield of energy input tenfold[17]. This greatly reduces the amount of energy necessary to produce the food that feeds Freyr's inhabitants and eliminates the mess and hassle of livestock.

Food Supply

Food on Freyr is provided by culturing several varieties of plants. These include soybeans, beets, Khorasan grain, potatoes, and blue-green algae. The first four species will help to supply many of the trace minerals required for the human body[68], while the fifth serves several purposes. Note, however, that while these form the core of Freyr's food supply, other produce varieties are available in smaller quantities for flavor, trace nutrients, and relief from monotony.

The yield of all of these plants is relatively high. Khorasan grain produces about 1.3 tons per hectare, soybeans produce about 50 bushels per acre[69], and beets have multiple harvests (beet greens and the beet itself) while providing substantial amounts of trace minerals. Potatoes are one of the crops recommended after thorough study for their productivity at room temperature, ability to keep without degradation for some time, carbohydrate content, and digestibility[70]. Nevertheless, these crops (and a few others) are intended to provide supplement and taste to the astronauts' diet.

Algae   The main food source for astronauts on our base is blue-green algae, specifically Spirulina and AFA[71]. These varieties of algae have high protein content, high antioxidant levels, and contains large amounts of calcium and magnesium, along with vitamins A, C, E, B6, and B12. In addition, algae grow very rapidly in the presence of nitrogen and phosphorous, especially if the air has a high carbon dioxide content[72]. As mentioned before, we will use blue-green algae to maintain atmospheric O_2 - these same glue-green algae are harvested to prevent overgrowth and processed into foodstuffs.

It's clear that there are some concerns that will need to be addressed regarding the nutritional profile of this algae. For example, it is high in sodium and low in Vitamin D, Vitamin A, β-carotene, and carbohydrates. Additionally, some other sources of lipids will be required. However, these nutrients can be removed from the algae (in the case of sodium) or provided by other foodstuffs, and blue-green algae provides almost everything else required by the human body. 100 grams of algae contains 290 calories[73].

To encourage algal growth, we bubble nearly pure CO_2 through the algae tanks at relatively low flow rates (so as not to disturb the water overly much). Additionally, wastewater and ground solid waste are recycled through the algae tanks and farm areas to provide greater nutrient levels. This system leads to faster algal growth and ensures a plentiful supply of food.

Our growth system makes use of two types of lights. We use LEDs for all lighting because of their

---

[17] Assuming that each trophic level has 10% efficiency, a good estimate.

high efficiency. The LEDs are optimized for two different wavelengths of light, 450 nm and 650 nm, to optimize photosynthetic efficiency[74]. This helps us to avoid wasting energy while ensuring that the light we are providing is sufficient for photosynthesis.

Nutrition Information

All values in the following tables are given for 100. grams of the food. Note: an exception is the data for potatoes, which indicate the values for one medium potato (ca. 148 grams).

It is clear that a variety of foods are required for proper function, and that a large array of foods must be produced on Freyr.

Table 1.7: Nutrient Content of Blue-Green Algae.

Nutrient	Quantity	Nutrient	Quantity
Carbohydrates	23.9 g	B_5	3.48 mg
Sugars	3.1 g	B_6	0.364 mg
Fiber	3.6 g	B_9	94 μg
Lipids	7.72 g	Choline	66 mg
Saturated	2.65 g	Vitamin C	10.1 mg
Monounsaturated	0.675 g	Vitamin E	5 mg
Polyunsaturated	2.08 g	Vitamin K	25.5 μg
Protein	57.47 g	Calcium	120 mg
Vitamins and Minerals		Iron	28.5 mg
Vitamin A	29 μg	Magnesium	195 mg
β-carotene	342 μg	Phosphorous	118 mg
B_1	2.38 mg	Potassium	1363 mg
B_2	3.67 mg	Sodium	1048 mg
B_3	12.82 mg	Zinc	2 mg

Table 1.8: Nutrition Content of Soybeans

Nutrient	Quantity	Nutrient	Quantity
Carbohydrates	11.1 g	B_6	0.1 mg
Sugars	6.9 g	Vitamin C	17 mg
Fiber	4.2 g	Calcium	145 mg
Lipids	6.4 g	Iron	2.5 mg
Saturated	0.7 g	Magnesium	60.0 mg
Monounsaturated	1.2 g	Phosphorous	158 mg
Polyunsaturated	3.0 g	Potassium	539 mg
Protein	12.3 g	Sodium	250 mg
Vitamins and Minerals		Zinc	0.9 mg
Vitamin A	156 IU		

Table 1.9: Nutrient Content of Khorasan Grain.

Nutrient	Quantity	Nutrient	Quantity
Carbohydrates	60.02 g	Choline	66 mg
Starch	57.5 g	Vitamin C	< 1 μg
Fiber	11.3 g	Vitamin E	8.03 μg
Lipids	1.99 g	Vitamin H	0.06 μg
Saturated	0.43 g	Silicon	826 μg
Monounsaturated	0.38 g	Boron	1.57 μg
Polyunsaturated	1.18 g	Calcium	202 μg
Protein	14.64 g	Iron	37.3 μg
Vitamins and Minerals		Magnesium	1.38 mg
Vitamin A	0.8 μg	Phosphorous	3.09 mg
B_1	3.94 μg	Potassium	4.15 mg
B_2	0.82 μg	Sodium	52.7 μg
B_6	1.1 μg	Zinc	30.9 μg

Table 1.10: Nutrition Content of Beets

Nutrient	Quantity	Nutrient	Quantity
Carbohydrates	9.6 g	B_6	0.1 mg
Sugars	6.8 g	Vitamin C	4.9 mg
Fiber	2.8 g	Calcium	16 mg
Lipids	0.2 g	Iron	0.8 mg
Saturated	< 0.1 g	Magnesium	23.0 mg
Monounsaturated	< 0.1 g	Phosphorous	40.0 mg
Polyunsaturated	0.1 g	Potassium	325 mg
Protein	1.6 g	Sodium	78.0 mg
Vitamins and Minerals		Zinc	0.4 mg
Vitamin A	33 IU		

When values are given in %, this number indicates the percent of the recommended daily allowance contained within the serving size analyzed.

Based on these nutritional profiles, Freyr primarily makes use of blue-green algae to feed its inhabitants, providing them with a high-quality and high-quantity protein source, and supplements this nutrient with sources of carbohydrates and some fats. Unfortunately, none of these major foods that can be grown easily contain much fat; perhaps methods will be developed to grow nuts and harvest them for their fat and protein content.

As stated above, these foods are merely the staples of Freyr's food supply; many other foods supplement them for variety. For example, fruits are grown in limited supply, and leafy vegetables are available for individual families to grow small plots. As part of the reality of living on board a space settlement, however, these foods must take a backseat to more easily produced crops such

Table 1.11: Nutrition Content of Potatoes

Nutrient	Quantity	Nutrient	Quantity
Carbohydrates	26 g	Vitamin A	0%
Sugars	1 g	Vitamin C	45%
Fiber	2 g	Calcium	2%
Lipids	0 g	Iron	6%
Saturated	0 g	Magnesium	6%
Monounsaturated	0 g	Phosphorous	6%
Polyunsaturated	0 g	Potassium	620 mg
Protein	3 g	Sodium	0 mg
Vitamins and Minerals		Zinc	2%

as those detailed above. Ensuring that Freyr's inhabitants have enough food to survive is more important than growing a large variety of foods to avoid monotony.

Per Capita Food Supply

Considering a daily protein intake of more than 90 grams per person, which is a reasonable target for most, and a daily allowance of typically between 2000 and 2500 calories, with an average of 2250, the following quantities of food are needed to supply adequate food for Freyr's population.

- 300 g low-sodium dried Spirulina algae (870 kcal)
- 200 g soybeans (280 kcal)
- 200 g Khorasan grain (660 kcal)
- 300 g potatoes (220 kcal)

This, plus some choices from available fruits, vegetables, beets, and specialized foods, provides 2250 calories of food per day. This is assumed to be the breakdown of Freyr's typical food supply. Note that this distribution could be changed from day to day depending on availability and preference, and to balance a person's diet over the long term.

Some preliminary nutritional information for the combination of foods outlined above is given here.

Table 1.12: Per Capita Food Supply Nutrition Information

Nutrient	Amount	% DV
Lipids	40 g	60%
Carbohydrates	266 g	93%
Sugars	25 g	
Fiber	46 g	172%
Protein	232 g	

This does not quite line up with governmental specifications for a daily nutrition profile, but an excess of protein helps to compensate for the lack of fats in the foods available on Freyr, and extra fiber can help to slow absorption of nutrients and spread out fullness across the day. A high protein content also helps with this.

The low sugar content displayed here is partially due to a lack of beets in this particular combination of foods, but an even more prominent reason is that without truly refined sugar on Freyr, diets are much lower in sugar. The replacement of sugar with slower-digesting carbohydrates may help to promote healthy weight control on Freyr.

Once again, while the diet laid out here may seem boring and monotonous, variety is provided by the small amounts of other foods that the diet is supplemented with. Obviously, on a space settlement not all the foods that are available here on Earth will still be available: many foods are difficult to produce without a large infrastructure, which precludes their inclusion in Freyr's design. Later-generation space stations, working with advanced composite materials and with an extensive manufacturing base already in existence in space, may provide some of these foods, but Freyr does not pretend to have this capability.

Aeroponics

Food on Freyr is primarily grown via an aeroponic system. This is a type of growing system that uses a nutrient-rich mist to directly contact plant roots. There are many advantages to using aeroponic methods, including:

1) As little as 2% the water use of soil-based methods;
2) Increased crop yield per square foot;
3) As little as 40% the fertilized use of soil-based methods;
4) A full growth cycle in as little as 20 days;
5) Half the nutrients required for soil-based systems; and
6) Longer shelf life than other methods.

To date, the major limitation of large-scale aeroponic systems has been the expense of the required machinery. Because Freyr controls the lunar resources it makes all its components from, however, it can simply make the parts for itself and take a little longer. Once the initial costs have been paid, aeroponics can help make a life support system a closed loop.

One of the biggest advantages of aeroponics for Freyr is the short growth time. Some aeroponic systems claim complete crop growth times of as little as 12 days[75], but for Freyr's foods these times will likely be closer to 20 days. Still, a crop time (from harvest to harvest) of only 20 days means that each aeroponic unit can grow up to 18 crops per year, resulting in a per-square-meter productivity of nearly 200 kg[75].

While alternatives to aeroponics are available, they are inferior for Freyr's purposes. All of those systems use more water and result in a shorter shelf life for produce, especially soil-based methods, and both aquaponics and hydroponics are more difficult to maintain than aeroponics. Additionally,

the extra trophic level involved in an aquaponic system reduces the amount of energy available to Freyr's inhabitants.

Food Quantity

Clearly, enough food must be produced on a daily basis to feed Freyr's entire population. Aeroponic systems, described above, are used to ensure that this is possible. They greatly reduce the arable space required to feed Freyr's population.

Nevertheless, to feed Freyr's entire population of 20000 (excluding food provided by algal harvest), up to 1 kg per person per day, or 20 tons per day for the entire population, is required. This translates to 7,305 tons of food per year, and at 200 kg per square meter per year, Freyr needs to have 36,525 square meters of aeroponic farms under cultivation. This amount fits easily inside the upper life support deck of the Life Support/Habitation torus, allowing some extra space for additional food production and plenty of room for processing, storage, and nutrient infusion operations. Additionally, more area than this (on the order of 40,000 square meters) is kept under aeroponic cultivation to produce extra food supplies in case of emergency. This extra food can be freeze-dried or otherwise preserved to provide a stockpile of food for Freyr's inhabitants, to be used if the primary food production suffers a failure. It can also be shipped to other stations or settlements, or be packed as provisions for ETV/LTV missions or to keep astronauts alive on long-term missions until their food production systems are online.

Distribution

Freyr's inhabitants are encouraged to cook at home or in groups, and there are not common cafeteria areas. All houses have a small range and oven for cooking, which lets families cook at home, but another option is for several families to get together and cook their food in one location. This has several advantages, including fostering community interactions.

Food can be picked up from a central distribution area on each habitation deck in packages of one day to two weeks. In all likelihood, most inhabitants will choose to pick up groceries on a roughly weekly basis. In addition to the basic food goods that are provided for each inhabitant, these central distribution areas stock other food goods in smaller quantities, such as fresh fruits, fresh vegetables, spices, and some other products.

Any food that is grown on the Outdoors deck is available to the community, and can be harvested at request by any of Freyr's inhabitants.

1.4.7 Compartmentalization

The interior of Freyr is divided into compartments, each of which is normally sealed and airtight. In the event of a massive hull breach, all compartments except the one directly affected will remain airtight and available for habitation, increasing catastrophic event survivability and providing extra security for Freyr's inhabitants.

Compartments are formed naturally by the separation of Freyr's component tori. Each torus, then, can be sealed off from the others and kept airtight with no ill effects. Additionally, the central core module is sealed off from the tori. Sealing mechanisms are typically an airlock method, although certain divisions between interior components of tori are formed by a sealed negative-pressure volume that prevents contamination.
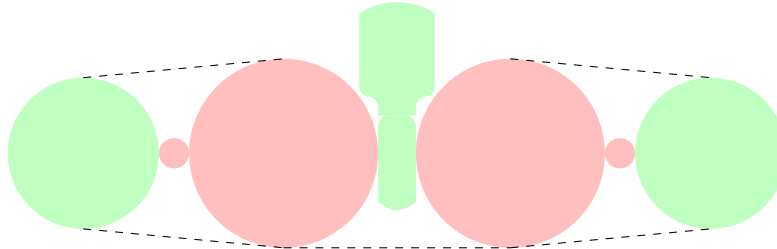
Figure 1.11: Compartmentalization of Freyr

In the above figure, green represents a nitrogen/oxygen atmosphere at 90 kPa and red represents a carbon dioxide atmosphere at 30 kPa. At the points where the tori touch each other, there are containment airlocks that separate the atmospheres but nonetheless allow passage between them.

All compartments utilize hermetically sealed doors of varying size. The doors are composed of 1 cm titanium to resist vacuum pressure and are not intended to resist vacuum for long durations, though they provide complete vacuum protection when engaged. Most compartmentalization doors are 2.5x2.5 meters, allowing for human, small vehicle, and equipment passage while not becoming too large to hold pressure against vacuum. Doors smaller than 2.5x2.5 meters restrict access through the passage, especially for larger pieces of machinery or large numbers of people, while larger doors become physically unsustainable if the light weight is maintained. Note, however, that some compartmentalization doors are larger than this and some are smaller. Larger doors may be thicker than 2.5 cm or may divide low-pressure areas used for industry or spacecraft construction.

The hermetic seal around the doors is provided by a nitrile rubber[76] O-ring style seal between the door and its housing, which forms a non-brittle seal and allows the door to be sealed tightly to its housing. This is what provides the seal between two foreign atmospheres at connection points.
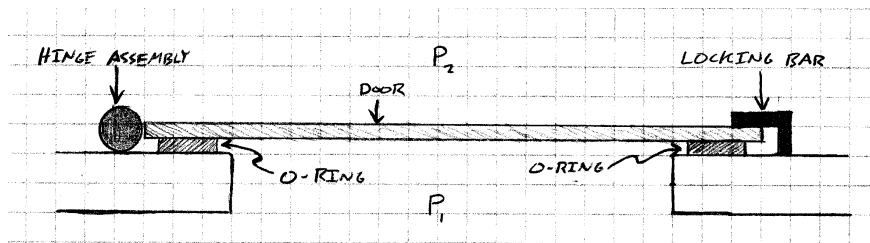
Figure 1.12: Hermetic Sealing Mechanism

Note that a mechanism may be necessary to hold the door shut, depending on which compartment depressurizes. This is accomplished with a set of titanium bolts that extend behind the closed door

and hold it shut. This design is only required on one side of the door because the other side is fastened securely by the door's titanium hinges.

The total mass of the door is 325 kg, of which 300 kg is titanium in the door and 25 kg is glass and nitrile rubber. The 25 kg of glass and nitrile rubber are used to provide a small porthole in the door, for viewing to determine the safety of opening the door, and for the O-ring style seal that keeps the door airtight.

While these doors are admittedly quite massive and therefore difficult to move, well-maintained hinges allow it them to be opened and closed by a single person. Note that the doors are positioned sideways in the "gravitational" field of Freyr to avoid dangerously uncontrolled forces when opening and closing the door; this helps make Freyr safer and easier to operate.

1.4.8 Medical Facilities

Freyr's medical facilities have several goals, outlined below.

1) Treat minor illnesses, abrasions, etc;
2) Perform most non-critical procedures with local personnel;
3) Provide Earth-Freyr interfaces for complicated procedures;
4) Research medical applications of space technology;
5) Develop treatments for diseases;
6) Provide a trauma management system; and
7) Provide treatments for all diseases to the maximum reasonable extent.

The first goal is accomplished easily with Band-Aid style adhesive bandages, antibiotic ointment, sterile bandages, local anesthetics, braces, and other standard first aid equipment. These are stored in several locations around Freyr and are reasonably accessible. Specifically, first aid locations are at eight points around each habitation decks, four points around the outdoor deck, and at twelve locations in the industrial torus and four locations in the storage torus. The widespread distribution of these facilities ensures that basic first aid supplies are never too far away, and signs are located at 20-meter intervals to indicate the direction to the nearest first aid storage location.

Hospital

Freyr's hospital is located on the lower habitation deck of the Life Support/Habitation torus; this location ensures proximity to the lower life support deck as well as the ability for isolation from the rest of the habitable areas of Freyr. It contains the facilities for all of Freyr's other medical goals.

One of the capabilities of the hospital is disease diagnosis. In addition to the n expertise of Freyr's doctors, this section of the hospital contains diagnostic machinery to perform many tests on Freyr's inhabitants, if necessary. These machines include an MRI (magnetic resonance imaging) machine, a CAT (computed axial tomography) scanner to take high-resolution images of bodily structures and/or sites of damage. The diagnostic ward can also communicate with doctors on Earth to obtain

a second opinion, and ultimately has the same capabilities as most any hospital diagnostic ward on Earth.

For time-critical patients, the hospital has an emergency room: this area of the hospital is used for stabilizing patients before they are discharged (for minor injuries) or moved to surgery or rehabilitation areas (for more serious wounds). The emergency room is available at all times and always has at least one doctor on staff. This doctor could also be filling out paperwork or doing other tasks while not tending to patients so as to increase the efficiency of the hospital system. The emergency room works on the principle of triage, like a field hospital, with the result that the most severe injuries are dealt with first and that doctors will not waste time trying to save anyone who cannot be saved. This is a harsh reality of life on a space-based settlement.

The hospital also contains more elaborate operating rooms for non-time-critical patients. These operating rooms are equipped with the same types of equipment that Earth-based operating rooms have, including general anesthetic, scalpels, clamps, and other surgical implements. These operating rooms also have the capability for robot-assisted surgery in difficult procedures, increasing survival rates, surgical effectiveness, and precision. Most surgeries performed on Freyr utilize minimal-scar techniques to reduce post-operation stresses and healing time, resulting in a shorter displacement from the workforce and decreasing the disruptive profile of surgical procedures in Freyr's society. For particularly delicate or difficult procedures, surgeons on Earth can be linked through the robotic surgical arm. Despite the time-lag of about three seconds for a round trip from the Earth to the Moon, these surgeons are able to operate the robotic arm to complete the surgery from Earth; the procedure will simply be slower.

In the case of a highly contagious and/or fatal disease, patients are kept in a negative-pressure section of the hospital. All entrance and egress points are hermetically sealed, and HEPA filters are used on all the effluent air from this isolation ward is filtered, sterilized, and then sent directly to the air processors. This helps to keep the disease isolated and prevents a particularly virulent disease from getting out of hand.

The hospital uses a water-cleaning system to complete the initial cleaning of implements that have been exposed to bio-hazardous materials, including wastes and any materials that may have been exposed to disease agents. Once this initial stage has been completed, the hospital uses a steam-sterilization system and a UV cycle in conjunction with high-intensity sonication to break apart organic materials and disrupt the structure of biological molecules. Implements to be used for surgery are then cleaned with a re-usable chlorinated solution. The solution is cleaned by high-gravity centrifugation and subjected to ultraviolet radiation after being used; its primary purpose is to disrupt viruses that may have survived the previous stages. After this cleaning cycle, implements are re-used and the solutions used to clean them are treated as bio-hazardous waste. All water used by the hospital is sent directly to an SCWO without checking for greywater status, as are most solid wastes and all organics. The SCWO then destroys the materials and results in clean water for re-use on Freyr.

The hospital is provided with a back-up power supply in the form of electrolyzed hydrogen and oxygen gases fed through a hydrogen fuel cell system. In an emergency, this system can provide minimal operational power (MOP) for the hospital for up to a week. An advantage of this power

system is that it also produces sterile, pure water for hospital use; on the other hand, the storage tanks for hydrogen and oxygen gases take up more space than other systems might.

While the hospital does provide some basic research facilities for determining new treatments and dealing with diseases, more support for this goal is provided by the biological research laboratory.

Biological Research Laboratory

This laboratory is located in the Industrial torus and is the site of Freyr's biological materials research. It contains the necessary tools and analysis equipment for identification of new diseases and for research of new cures for existing diseases.

Like the isolation ward of the hospital, this laboratory is under negative pressure to ensure that there is no release of bio-active substances. Additionally, its placement in the Industrial torus results in both lower gravity and an inert helium atmosphere, meaning that any accidental release of bio-active substances within the lab is automatically contained as they die in a helium atmosphere.

Inside the lab, safety protocols stipulate that all researchers wear a dedicated oxygen supply (as is the case for all workers in the Industrial torus) and that they always maintain a zero-contact strategy for handling materials. All dangerously active materials are handled in a glovebox with a disinfectant system in the vacuum chamber. The glovebox is under argon, available in trace amounts in the lunar regolith, so that leaks can be detected and fixed. Additionally, all researchers are required to wear eyeglasses, a hair net, a lab coat, gloves, long lab-grade pants, and disposable booties.

After Death

Once a resident of Freyr dies, the body must be dealt with[18]. In space, there are essentially three ways of dealing with a body: ejection, cremation, and solvation. Ejection reduces levels of rare (on the Moon, at least) minerals that are necessary for life on Freyr and litters in Freyr's orbit, making it not a viable option for long-term habitation, while cremation tends to produce toxic by-products. For these reasons, Freyr chooses to solvate the bodies of the dead.

This process is known as alkaline hydrolysis, and is uses a combination of chemicals, temperature, and pressure to dissolve organic materials and bodily tissues, resulting in complete breakdown of a human body in a few hours. The body is placed into a tank of either sodium hydroxide or potassium hydroxide solution and then subjected to pressures of about 60 psi (415 kPa) and temperatures of about 180 °C[77]. These conditions, after a few hours, result in a thick brown liquid and not much else. This liquid can then be sent to the SCWO system, which completes breakdown of the organic components and allows all of the elements to be recycled.

---

[18]This is pretty obvious.

Decon Procedures

Freyr's hospital system, and Freyr in general, uses a comprehensive decontamination protocol upon entry and exit of any sensitive area. These decon procedures are implemented at several locations to ensure minimal contamination and crossover between different environments. The ideal decon system is:

a) Effective (99% or greater)
b) Fast (ideally less than 30 seconds)
c) Non-invasive
d) Non-damaging
e) Zero-waste
f) Compact

These properties are taken into account when designing the decon system for each application. There are several types of decon procedures, which perform different functions depending on the needs of the portal being accessed. These include dust removal, biological sterilization, and gas purging. Each system is standardized to make the process of designing and installing a particular implementation simple and easy, reducing construction complexity and time while facilitating maintenance.

Dust Removal. Dust builds up on objects in the lunar environment and in some parts of the Industrial torus (most parts of this torus are generally dust-free, but a few, including the machining areas certain parts of the refining process, generate significant amounts of dust), and must be removed before those objects are chronically exposed to a human population. Small particles of dust must be removed because:

1) They can accelerate machinery decay due to abrasion,
2) They may produce faults in sensitive systems,
3) They may act as carcinogens, and
4) They may act as irritants or produce chronic disease in living things.

Clearly, dust buildup is a problem that must be addressed. Within the areas directly affected by a dusty environment, safety measures can be taken - vacuum suits on the Moon, for example, or respiratory masks in a dusty area of the Industrial torus. When it comes time to move between dusty areas and clean areas, however, this dust must be removed to avoid the problems mentioned above occurring on a large scale.

Dust removal is accomplished primarily through an electrostatic system, which causes the dust to be repelled from the object it is resting on or clinging to. This system consists of a conductive plate on which a charge can be placed; objects in contact with this plate also become charged, which results in the dust being repelled. At this point, a current of gas is fed through the decon chamber, carrying the dust with it and resulting in much reduced dust levels. The dusty gas is then fed through a multiple-layer thin-film ceramic filter to remove the dust; the filter is not only constructed of materials harvested from the Moon, but can also be cleaned simply by blowing gas backwards through it. The filter is expected to last through about 100,000 cycles due to effective

dust adsorption and the ease of cleaning; depending on traffic, this means that a filter could last for as long as ten years, although it is recommended that they are replaced after not longer than five years to ensure effective operation.

This system utilizes only electric charge and, very gradually, a ceramic filter; all other components of the system are not worn or can be reused immediately. In addition, the entire cycle is estimated to take about 20 seconds (the removal of dust is much faster than this, but 20 seconds allows for the removal of more dust and greater removal efficiency), which fits within the (admittedly arbitrary) guidelines set up for a good decon system. It can be implemented in a small volume and is eminently non-invasive and non-damaging. These reasons were why this method was chosen above methods such as direct mechanical air processes, brushes, and even high-frequency vibrations.

Dust removal is required upon entry to a lunar facility, after working in certain parts of the Industrial torus, and upon entry to Freyr for personnel arriving from the Moon. In the microgravity environment of the Spaceport, the procedure is marginally different; instead of standing on a plate, subjects grasp a conductive bar. Other than this difference, the procedure is the same and is actually easier due to the lack of acceleration, which makes dust particles behave a little more nicely.

Biological Sterilization.   At times, it is necessary to conduct a bio-sterilization of objects that have been in contact with disease agents or other harmful substances. Because of the nature of these threats, it is necessary that relatively extreme methods be employed to stop them from being conducted into non-sterile areas of Freyr. It is assumed that these biological materials will be encountered only on Freyr, and not on the surface of the Moon; if at some point a biological investigation laboratory is installed on the Moon, these sterilization procedures will need to be implemented there as well.

Biohazard materials are clearly dangerous. They can produce debilitating illnesses, result in the spread of long-term infections, or communicate non-fatal infections between multiple individuals. They are not good things to have around. Fortunately, they can be sterilized fairly easily and disposed of readily.

Most biohazards are in the form of a liquid or a liquid-bearing solid. This liquids and solids must be removed before a previously contaminated object may pass into an uncontrolled area. This sterilization is carried out in one of several fashions, depending on the object to be disinfected. Any metal instruments, as well as most plastic ones, are cleaned using a water rinse followed by a steam jet and dilute bleach rinse. This sequence first removes physical debris and liquids, then kills any remaining organisms on the object, then denatures remaining proteins to achieve complete sterilization. If necessary, sonication and UV radiation can also be applied to the object to ensure complete breakdown of organics.

Humans are required to wash their hands if they have been working at all with biological agents, and other precautions are taken for clothes worn inside the potentially contaminated area. All gloves are sent to the SCWO system for immediate recycling, lab coats and goggles are sterilized each day, and all external non-clothing items must be left outside the potentially contaminated area to avoid accidental contamination of an unknown object. If any biohazard is spilled on exposed flesh, the

affected individual is required to immediately report the problem and, as quickly as possible, wash the contaminated body part with water for fifteen minutes. Any open wounds must be covered by an additional layer of protective cloth (i.e. Band-Aid style bandages or equivalent), and any wound not treated in this manner will result in suspension from laboratory facilities for 30 days. These precautions ensure that while the typical decontamination procedure is not overly invasive for a researcher moving into an unsecured area, any breach of conduct or safety is dealt with in a comprehensive fashion.

Biological sterilization is available in all of Freyr's research areas, with a special focus on the biological science laboratories and the hospital. It is not required at most of these labs due to the nature of the materials being worked with, but it is available in case of emergency in all labs and can be used at a moment's notice. These research areas include any and all lunar research stations or other laboratory facilities, e.g. facilities on other planets or space stations.

Gas Purging.   A final type of decon procedure that Freyr carries out is gas purging. This consists of replacing one atmosphere with another, but because humans may have to be transported through such a barrier, it is necessary to perform the replacement without going to full vacuum - this procedure would result in damage, possibly permanent, and potential disablement for a long period of time. Instead, the procedure has to be completed at a fairly normal pressure, introducing some complications into the process.

In the strictest sense this is not a decon procedure because it does not involve the removal of any obtrusive substance except the atmosphere, but it is still a mechanism designed to ensure that two volumes do not mix, preventing an object that has been in one environment from transferring part of that environment to another section of Freyr.

Gas purging decon chambers operate on the mechanism of massive flow. The new atmosphere is fed into one side of the chamber while fans pull at the other side of the chamber, and the subject (or object) rotates to eliminate any residual pockets of gas that were protected from the flow. The pressure of the first atmosphere is maintained throughout this transition period to ensure full removal and comfort; over the next ten minutes, the pressure inside the chamber is gradually brought to the target pressure. Because oxygen masks are required in any low-pressure areas, acclimation is not a problem, but the physical effects of pressure must be gradually changed so as to avoid severe cases of nitrogen narcosis, burst eardrums, etc. Ten minutes is long enough for this adjustment period because the decrease or increase in pressure to which a subject will be subjected is not greater than 60 kPa (about 0.6 bar).

When the flow system is not in use, the chamber is sealed with isobutyl isoprene rubber seals to prevent gas leakage; because of the small pressure differentials involved, these seals do not need to be completely airtight or terribly strong.

Gas purging decon chambers are used when transitioning between the different tori of Freyr due to the different atmospheres in these tori. For example, the transition from the Life Support/Habitation torus to the Storage torus involves a pressure change, but also involves replacing a nitrogen-oxygen atmosphere with a helium-nitrogen atmosphere, which must be done to prevent contamination or accidental introduction of potentially harmful gases. This particular transition is

absolutely critical, because the boundary between the two tori must be secured to prevent potentially catastrophic gas leakage. Introduction of oxygen into the Storage or Industrial tori in large amounts could lead to rapid deterioration of components, explosions due to the volatility of oxygen, or other, more serious consequences. Because the diverse atmospheres in Freyr's different tori do not contact each other at any other points, the contact points of the tori are the only places where gas purging is necessary - all other inter-atmospheric portals lead into vacuum, meaning that an airlock is much more appropriate.

1.4.9   Emergency Procedures

In the event of an emergency on board Freyr, specific procedures are implemented to help ensure the safety of all inhabitants. These procedures are outlined below and highlights are collected into a table.

Fire: Because there are relatively few flammable materials on Freyr, fire is not a huge concern in the human habitation areas. In the industrial areas, however, fire is an incredibly important concern and is treated with substantial measures. If a fire breaks out, then once all humans have been reasonably evacuated from the area, the compartment is sealed off and dry, anoxic carbon dioxide is fed into the atmosphere. CO_2 starves the fire of its fuel and puts out the fire. The few exceptions to this response are fires against which carbon dioxide is ineffective, such as Class A or Class D fires. In the case of a Class A fire, argon is used to extinguish the fire through low-pressure total-immersion method; Class D fires are handled with Pyromet or a similar graphite-based extinguishing agent.

Pressure Breach: A loss of pressure on board Freyr must be immediately dealt with. Because of the thickness of the outer hull, it is extremely unlikely that anything but a large impactor could cause a hull breach, meaning that there is most likely extensive damage and a high rate of air loss near the breach. The sheer volume of Freyr, nevertheless, allows some time to respond to such a breach, and some steps can be taken. In the event of a relatively small hull breach (<1 cm), it is possible to stop the breach using automated vehicles on the exterior of Freyr, which can apply specialized hull sealing mechanisms to stop the leak. The smaller the breach, the more effective this method is. For larger breaches, it is necessary to abandon the compartment and allow the atmosphere to drain out, although some recovery may be possible by transferring atmosphere to neighboring compartments. In the event of total compartment loss due to such a breach, all humans inside the compartment evacuate to safe rooms to wait out the time until the compartment can be re-pressurized or until they are rescued by a salvage team.

Epidemic: Disease epidemics are treated on Freyr by sealing off the sick into designated compartments of Freyr and treating the disease within those compartments. A sealing mechanism much like an airlock is set up outside the compartment to allow treatment of the disease without releasing airborne pathogens, and patients are treated in an isolation setting to protect doctors and nurses.

Rioting: During a riot, compartments in Freyr are sealed off to prohibit access to sensitive and critical equipment. Police officers are not authorized to use physical weapons to control the crowd,

but rather are charged with ensuring that damage does not occur to public property and that there are no injuries or deaths. LRADs (Long-Range Acoustic Devices) are only used to deter access to life support, industrial areas, command and control, communications, and materials storage.

Solar Flare/CME Event: Depending on the amount of warning time and Freyr's orientation when the CME hits, inhabitants may be instructed to follow one of several plans. There is no direction from which Freyr is completely shielded, but in general it is possible for inhabitants to relocate to places that are less affected by solar flare and CME activity. These include the central core and areas directly around it, or areas of the disk that are to the rear of Freyr as viewed from the direction of radiation flux.

Life Support Malfunction: All affected life support units are immediately shut down, and Freyr's technicians make repair of these units their highest priority. While some or all life support units are offline, Freyr's inhabitants are required to subsist on reduced food or water intake, depending on which system was affected.

Table 1.13: Summary of Emergency Procedures

Emergency	Seriousness	Response
Fire	Low	Carbon dioxide suppression deployed.
Fire	High	Low-pressure argon suppression and/or Pyromet deployed
Pressure Breach	Low	External drones repair breach.
Pressure Breach	High	Compartment abandoned, emergency shelters used.
Epidemic	High	Quarantine conditions set up.
Rioting	Low	Surveillance, automated sensitive systems protection.
Rioting	High	Surveillance, police presence, automated sensitive systems protection.
Solar Flare/CME	Low	Radiation monitoring, inhabitants notified.
Solar Flare/CME	Medium	Radiation monitoring, inhabitants notified, young, elderly, and sick relocated.
Solar Flare/CME	High	Radiation monitoring, all inhabitants relocated.
Life Support Failure	High	Faulty units shut down and fixed as quickly as possible.

FOD

Foreign Object Damage is commonly considered to be a severe hazard to spacecraft, but this ignores the simple fact that space is really, really empty. It is estimated that a micrometeorite (10^{-6} meters in diameter) impacts the Earth approximately every 30 microseconds[78], but when this frequency is scaled to the area swept out by Freyr, it is found that the incidence of such a micrometeorite is only one per 4500 seconds (1.25 hours). Likewise, analysis of other size frequencies indicates that Freyr can expect a 1 millimeter diameter impact every 143 years, and a one meter diameter impact once every 147 million years. Clearly, impacts from foreign objects are not a problem for Freyr.

This is especially true because lunar space will remain uncluttered: Freyr takes care to maintain

its airspace as a clear area and does not introduce foreign objects into it. While LEO is home to many thousands of relatively large (>1 cm) objects that could cause severe damage to a spacecraft, lunar space is empty and remains so, helping Freyr prevent collisions with foreign objects.

Even if a large object were to impact Freyr at high velocity, the damage to the settlement's shell would likely not be critical. Objects as small as one millimeter in diameter can produce a clear hole through existing spacecraft, but these skins are far thinner than that of Freyr. Even the thin shell surrounding the Storage torus, the Spaceport, or the Core can absorb the impact of such an object easily, and the 23-cm shell of the Life Support/Habitation torus is expected to sustain an impact by a 1-cm object at 10 km/s without catastrophic failure.

If a large (>1 cm) object approaches Freyr at speed and the settlement cannot be removed from the danger zone, some preventative measures can be taken. For example, the tori can be evacuated to emergency shelters, measures can be taken to destroy or partially vaporize the incoming object, and spacecraft can be moved into its path in a last-ditch attempt to save the settlement. In the end, however, it must be accepted that a sufficiently energetic collision simply spells death for Freyr and, more than likely, most of its inhabitants.

Such a collision, however, is vastly unlikely - and another reassuring calculation is the choked-flow[19] mass transfer rate across a 1 millimeter-diameter hole is given by the equation

$$\dot{m} = A * v_s * \rho$$

In the above, A is the area of the opening, v_s is the speed of sound, and ρ is the density of the gas. Note that the speed of efflux is equal to the speed of sound because the flow is choked. Based on this formula, the mass transfer rate is equal to:

$$\dot{m} = \pi * 0.0005^2 * 340 * 1.048 = 2.774E - 4 \, \text{kg/s}$$

The transfer rate, on the order of 10E-4 kg/s, gives a response time of about 30 billion seconds (one thousand years) before the internal pressure becomes dangerously low (assumed to be at 0.9 times the initial pressure, or 81 kPa)[20]. Additionally, a 1 cm-diameter hole only increases the flow rate by a factor of 100, reducing the available response time to 300 million seconds (ten years). Finally, if a one meter in diameter hole were punched in the side of Freyr, increasing the flow rate by another factor of 10,000, the response time would still be 30,000 seconds, or almost nine hours. Clearly, even a very large impactor would not damage the settlement to the extent that a response is not achievable. In fact, to attain a response time (to 81 kPa) of under one hour, the hole would have to be nearly three meters in diameter, at which point the settlement has larger problems to worry about than leaking air.

---

[19]The mass flow is choked because the exterior pressure is 0.

[20]This assumes that the mass flow rate is constant. In reality, atmospheric density depends on pressure, and the speed of sound depends on density, so the actual time taken to reach these lower pressures is longer. A constant rate is assumed to provide a large error margin.

1.5 Community

1.5.1 Age Demographics

Freyr is, of course, a relatively isolated place. It is very difficult to travel to Freyr from the Earth's surface, and so Freyr's residents are, for the most part, on their own when it comes to population sustainability, community development, recreation, and other aspects of life. It is necessary to produce demographics on Freyr that reflect this isolation and allow its life to continue without a large degree of dependance on Earth.

A natural requirement of any self-sustaining population in an enclosed space is that the birth rate be equal to the death rate, at least to within a close margin from year to year. If this balance shifts, then either Freyr's population will decrease, on the whole, or it will increase beyond Freyr's capacity. Either of these eventualities would hold unfortunate consequences for Freyr.

Due to Freyr's small population size, it is optimal that every person on Freyr reproduce: the risk of birth defects or genetic diseases from inbreeding is reduced when there is a larger population of reproducing individuals. The natural average is two children per pair of adults, which results in a new generation the same size as the one before it. Actual population dynamics, however, indicate that the ideal for population size is not attainable: about 3.4% of American adults in 2013, for example, identified as something other than "straight,"[79] indicating that the actual reproducing population of Freyr is smaller than the population of adults of reproductive age.

Based on a life expectancy estimate of 75 years, which seems reasonable given both the hazards on Freyr and advances in medicine, it is clear that approximately 25% of Freyr's population is 18 or younger, making Freyr a little older, on average, than the population of Earth in 2014[80]. This leaves about 75% of the population as adults, and perhaps 55% as being of reproductive age.

Based on about a life expectancy of 75 years, Freyr's birthrate should be 267 new births per year[21], or 13.4 births per thousand people per year, which seems reasonable based on current world numbers, which range from below ten to over 30[81]. This number could be increased a little to account for some infant mortality. This birth rate seems likely to be achieved without intervention, so unless the population of Freyr is truly growing or falling uncontrollably, there is no effort made to interfere with the reproduction of its inhabitants.

Based on an equal birth rate and death rate, the population of Freyr should stabilize into a fairly uniform distribution of population size versus age. Depending on the precise distribution of age at time of death, the population could take one of several routes; a population plot based on an arbitrary model is given here. This model assumes that deaths only occur after age 18, then remain constant until age 55, at which point a variable function takes over and the death rate accelerates. This model is unquestionably inaccurate, but may be reasonable. Different statistics for male and female inhabitants are not given, although at the time of writing females tend to live longer than males. It is possible that this trend will continue, in which case the ratio of male to female inhabitants will gradually decrease as individuals age.

---

[21] $20000/75 = 266.666$
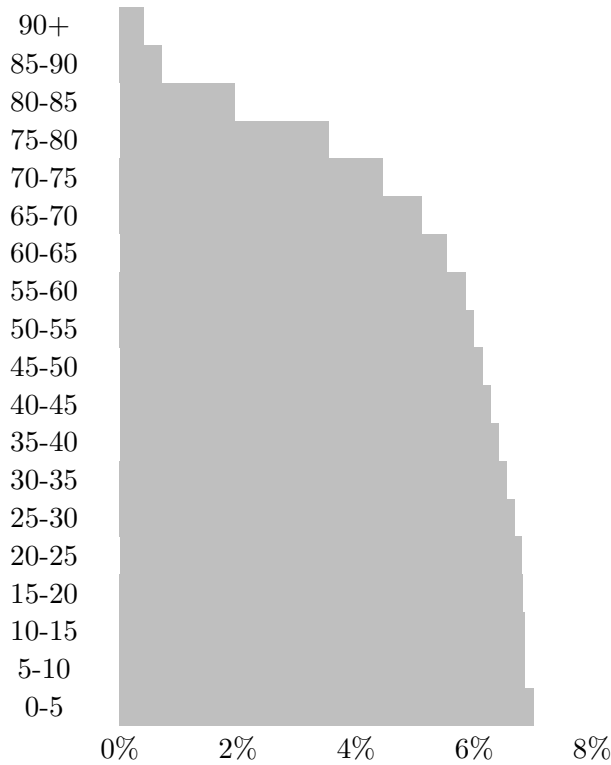
Figure 1.13: Population Graph for Freyr

This clearly shows a gradual decline in population from age 18 to age 55, followed by a fairly sharp drop-off around age 70. This drop-off corresponds to the gradual pressures of living in an orbital settlement catching up to Freyr's inhabitants; deaths could well be localized in this fashion. About 267 deaths per year are expected, or about two every three days.

Workforce

Defining Freyr's workforce as people over 18 and below 70, in years, it is discovered that the workforce comprises about 65% of the total population. Of the remainder, about 25% is composed of children under 18, and about 10% is composed of seniors over 70.

65% of Freyr's population corresponds to a workforce of 13,000. This is a large workforce, but not a huge one; clearly, every hand is needed to keep Freyr sound. Based on the rate at which equipment failure and maintenance occurs on the ISS, with a large proportion of the astronauts' time being spent on routine maintenance, Freyr's maintenance personnel comprise about 4000 persons, nearly a third of the workforce as a whole. This proportion is slightly smaller than the portion of time spent on maintenance on the ISS due to the increased robustness of Freyr's systems and economies of scale. In addition to these people, there are about 6000 persons dedicated to manufacturing and industrial pursuits. About 1000 to 2000 operate lunar facilities at any given time, bringing the total number of persons involved in industrial pursuits up to about 7500. Another 500 people perform other jobs, mainly relating to human aspects of Freyr. These include governmental jobs

(about 60), teaching positions (about 150), and research (about 250). These categories account for 12,000 of Freyr's workers; the remaining 1000 may be distributed where necessary. As of now, these divisions are arbitrary but seem reasonable; it may be that they have to be drastically adjusted once the needs of Freyr become truly apparent.

Relationships

This is a burning question for many. Based on the number of people within five years of age of someone between the ages of 22 and 37, there will be about 650 people of the opposite sex near the same age as a given individual in the prime dating pool. Expanding this pool to include people on the other habitation deck, which has an opposite day/night cycle but is otherwise pretty much the same, the number of date-able people for an individual in their 20s or 30s is well over 1000, and likely closer to 1400. This doesn't seem to be a problem.

Even within the high school, considering people aged 16 to 18, there are some 400 date-able people. When those between 18 and 22 are included in this number, it rises to nearly 1000.

The conclusion taken from these data is that there is no shortage of potential dates on Freyr, alleviating social pressure and helping to encourage healthy exploration of identity.

1.5.2 Population Cross-Section

The initial population of Freyr is controlled roughly for sex balancing, achieving a 50/50 balance of male and female. Beyond that, however, there are no criteria concerning who can and cannot live on Freyr other than capability. Freyr does not ask for race/ethnicity, income, or family history in the settlement application.

There are some qualifications that cause preference to be given. A family history of cancer, for example, could result in decreased preference for a particular applicant, and it is preferable to establish a relatively young workforce for the construction and initial habitation of Freyr. In general, however, the most important factor is an individual's skill set - for example, an experienced and accomplished welder would likely be preferred over a molecular biologist for the initial stages of construction when welding is a more valuable skill than biology.

With this in mind, it is expected that the population of Freyr will roughly resemble that of Earth in terms of composition.

Religion

Freyr has no official religion, but members of all religions are welcome. Freyr's government is non-denominational, as are all aspects of life on Freyr, but spaces are provided for private or small-group worship for those who wish to pursue it. These spaces include a non-denominational chapel that groups may sign up to use. It is expected that about 15-20% of Freyr's population will be unaffiliated with religion, and that the remaining 80-85% will practice some form of religion[82], but

the exact distribution is unknown and will not be known until Freyr is constructed. Note that these rough demographic statistics are based on current data and may not remain accurate.

A consequence of selecting Freyr's population by skill set instead of focusing on another trait is that no religion will have a majority on Freyr. While this may result in some fractionation of Freyr into different groups, it is unclear how that might work out, and it is just as clear that with such a small population, it is inevitable that religion will have to be unimportant in day-to-day interactions. It is hoped that with so many other concerns that must be addressed to keep Freyr sound and safe for its inhabitants, religious disputes will fade into the background and not impact the community on Freyr in any way.

The right of religious expression is also upheld on Freyr insofar as it does not infringe on another's right to religious expression. As such, the Muslim call to prayer may be played or sung at the appropriate times so long as it is not disruptively loud, and while religious believers can passively recruit new members by announcing meetings or worship services or by posting (limited) public announcements, religious door-to-door soliciting is discouraged and may be considered a crime if egregious or repeated.

Religious organizations on Freyr cannot distribute payment to individuals, and because all individuals on Freyr are required to hold a job valuable to the entire station, there are no individuals who are solely members of the clergy. This is not intended as restricting religion, but rather is meant to ensure that Freyr has the full capability to keep itself running.

Valuable Skill Sets

Freyr has a need for many different skill sets in its inhabitants: it is a community of only 20000 that must provide practically all services for itself. Due to this massive task, all residents of Freyr must have some specialization that it helpful to the settlement. These include:

- Plumbers
- Welders
- Machinery Operators
- EVA Specialists
- Surgeons
- Pilots
- Robotic Mechanisms Operators
- Life Support Technicians
- Research Biologists/Chemists/Physicists
- Lunar Mining Operators
- Spacecraft Specialists
- Flight Control Officers
- Reactor Specialists
- Communications Officers

And many others.

It is clear that many different tasks must be completed every day to keep Freyr flying and safe,

allowing most individuals to pursue their passions in a way that benefits Freyr. It is just as clear, however, that those residents who want to be artists or creative writers will be facing a bit of a problem; there are only so many applications for these skills on Freyr, and every hand is needed to keep the settlement profitable and running smoothly.

While this does place some limits on what Freyr's inhabitants can do with their lives, the restrictions *are placed by the fact they they are living in an orbital settlement, not by Freyr's management.* It is simply necessary that some luxuries be given up for life on such a settlement.

Socioeconomics

Freyr's socioeconomic background is very difficult to predict. While individuals from developed countries may be incidentally preferred due to skill sets and schooling developed, it is also true that many of the most capable workers live in developing countries. One hurdle to overcome is the individual contribution to the cost of launch to Freyr, although this is unimportant to Freyr's total cost and could be waived when necessary (see 3.2.1). It is therefore expected that Freyr's population will be drawn fairly evenly from different socioeconomic backgrounds, roughly corresponding to Earth demographics.

Ethnicity

Freyr, as mentioned above, does not discriminate based on ethnicity when bringing people to the settlement. This seems to indicate that its ethnic makeup will roughly resemble that of Earth.

Specific ethnicities are not, in general, enumerated here. It is expected that dozens or hundreds, but likely not thousands, of ethnic groups will be represented on board Freyr. As with religion, it is hoped that on Freyr, these groups can put aside any mutual antagonism for the greater good of the settlement; while, for example, Israelis and Palestinians regularly clash here on Earth, on Freyr there will be fewer tensions and everyone will be removed from their ancestral debates, leading to progress and possibly positively affecting the conditions on Earth's surface by helping to resolve conflicts.

The close quarters of Freyr, with all inhabitants living in the same relatively small volume, is also projected to alleviate tensions and encourage cooperation, furthering Freyr's goals and increasing efficiency as Freyr's different ethnic and historical groups are able to work better with each other.

1.5.3 School

School on Freyr is separated into three levels: primary, secondary, and post-secondary or trade school. Primary school encompasses children from age four to age eleven, and teaches one core curriculum of science, mathematics, English, social studies, and history, all at a basic level. Additional classes available are a foreign language elective, which may need to be taught by an outside expert, and art/PE. Secondary school is intended for children between twelve and 16 and offers increased

specialization, although core classes are still required. In secondary school, the curriculum becomes more rigorous and students are encouraged to follow their interests and find a field that they enjoy learning; throughout the course of secondary school, they become more specialized within this field. Finally, post-secondary or trade school is where students go to finish their education and become prepared for entry into their chosen field, and focuses on each student's interest rather than on a core curriculum.

Primary School

In primary school, teachers have several objectives. These include literacy, a firm grounding in logic, emotional development, and other basic skills. In the first two years, the focus is mainly on learning to read and write, as well as basic mathematics, social skills, and problem solving. Games are provided for students, and two full hours out of every day are set aside for play, especially with puzzles, logic games, memory quizzes, etc.

After the age of six, students are exposed to additional subjects: basic science, some social studies, and true logic. The next three years are used for the development of ideas learned in the first two years into fully-fledged and integrable objects, leading to logical use of mathematics, language, and problem solving. Art also has a place in these three years, and is given an hour a day for students to develop their creative abilities. Near the end of this period, students are introduced to writing with a purpose, and reading and writing assignments are given to give students valuable practice with their skills.

Once children are eight, their education is supplemented with some homework, but for the most part remains the same as it was for the past two years. At ten, students are introduced to more advanced science topics, including chemistry, physics, and biology, all at basic levels. Around this time, students choose an advanced topic to learn about, typically in math or one of the sciences, and they receive individual instruction in their chosen topic (again, still on a fairly basic level).

Secondary School

For the first two years of secondary school, a wide curriculum of science, math, english, foreign language, and history is taught. All students are required to take these five core classes - although there are different foreign language electives available and different students may be at different levels in the curriculum. In the second two years, by contrast, students are encouraged to select one particular topic and focus on it above the rest of their subjects. A broad range of courses are still required, but specialization begins to take hold during these years.

Also in the second two years of secondary school, students are given access to Freyr's digital library. This allows them to conduct research on their own, and since Freyr holds subscriptions to many major scientific journals, students finishing secondary school already have access to a large repository of advanced knowledge.

By the end of secondary school, students have found a field in which they feel comfortable and which they want to pursue.

Post-Secondary School

Many fields that are applicable to Freyr require nothing more than a secondary school education and an apprenticeship, but many others require further education. Students on Freyr can work with an advisor in their field who is present on Freyr to complete their education in these fields - for example, working in the hospital as an equipment sterilizer, then as a clerk, then as a physician's assistant, and finally earning a position as a doctor or, after more training, a surgeon. A student might also conduct research with an established chemist, biologist, physicist, etc. to gain experience before moving into one of those fields.

The alternative to an apprenticeship or additional job-specific training is to take classes from an Earth-based university. students enrolled in this sort of program take the classes in an on-line format, submitting homework and tests online as well as receiving lecture notes, videos, and lab instructions. After they complete their course of study, they are presented with a diploma from that college or university and move on to job experience.

Freyr also works with universities on Earth to establish cooperative programs. For example, a student on Freyr could conduct research, talk with a mentor on Earth, develop their methods and conclusions, and then earn a Ph.D. despite the fact that Freyr does not have an accredited institution on board.

1.5.4 Social Opportunities

With only 20000 people on Freyr, and really only 10000 in each of two groups that are awake at the same time, social interaction is a must. Social opportunities must come from within rather than without, and 20000 people thus have to form their own cohesive communities. Given Freyr's small size, community events occur more seldom than they might in a larger community, but each of them is more integral to the community itself.

Examples of events that might go on for entertainment are sports tournaments, an organized showing of a film, dances/parties, and community service. Other community gatherings or social events could mark an accomplishment of a particular citizen, a birth or death, or a major event within Freyr (think along the lines of an anniversary party). All of these activities are intended to be planned and organized by Freyr's inhabitants as they wish and as makes sense to them, so they are not detailed too much here.

With such a small community on Freyr, people will just know each other, and general sub-communities will tend to develop within the social framework as Freyr's inhabitants get to know each other in groups. This will help to foster close groups of people, but as opposed to larger communities where such groups become isolated, Freyr is too small for groups to become completely separate, and will instead become home to loosely joined groups of like-minded people. While this is perhaps not an ideal social situation, it is far better than an attempt to artificially plan Freyr's societal structure, and will result in a decent communal spirit with closely bound subgroups.

Among the 10000 people who are on each habitation deck, it is expected that several or many groups will develop. It is all but impossible to prevent the formation of cliques within a population

as large as this one, but it is hoped that given Freyr's isolated state, people will work with each other rather than against each other in all situations. Despite this hope, it is clear that the different innate divisions of the population of Freyr will result in potentially antagonistic social groups. These potential antagonistic tendencies are one reason for the existence of Freyr's police force.

1.5.5   Recreation

Recreation is a big part of life aboard Freyr. When Freyr's inhabitants are off work and not sleeping, they have many options to pass the time. These include 1g activity and sports, low-g sports, weight training and fitness activities, and nonphysical activities detailed under "Entertainment."

Recreation areas are placed under the jurisdiction of the legislature as detailed in 1.5.2. Specifically, the Community Subcouncil has authority over renovations to facilities, changes to infrastructure, and other aspects of community recreation areas as necessary and prudent.

Freyr's habitation setup allows for large open spaces in the center of the habitation areas, which can be used for outdoor sports (Ultimate Frisbee, Futbol/Soccer, and others) or for long-distance exercise (running, bicycling, roller-blading, and others). A path extends around the circumference of Freyr and is divided into two halves, walking and running; it proceeds only one way around Freyr, a three-mile loop, but it is possible to walk back off of the path rather than continue all the way around. Bicyclists use the "running" side of the path, and are required to announce their presence as they approach behind runners.

Freyr's population is free to use this greenbelt area as they wish: it is entirely possible that sport leagues will be created or that new sports will be invented on Freyr to satisfy the wishes of its inhabitants. This is absolutely to be expected, and the goal here is to provide open spaces that can be used to the greatest satisfaction of all Freyr's settlers.

Another option for colonists is low-gravity sports, which are available on Freyr's upper decks. The gravitational acceleration experienced by players is about 0.1g, allowing revolutionary sports to be invented and played. Closer to the center of Freyr, with lower effective gravity, it is possible to jump high enough that the Coriolis effect becomes noticeable, leading to interesting gameplay dynamics and techniques; for example, near the rotational axis a player moving up the wall at a reasonable speed would experience a greater Coriolis force than a centrifugal force, making gameplay possible on one of the walls of the room as well as on the floor. It is effectively impossible to predict what the sports that evolve on Freyr will be like, given these conditions, but one can imagine 0.1g tag in which players are able to leap four or five meters into the air, which would certainly be an interesting game. Another possibility is gymnastic training, where motion happens more slowly and trainees can become used to the motions before attempting them in a higher-gravity or 1g environment.

Just as with 1g recreation facilities, the inhabitants of Freyr have the final say over maintenance and control of the low-gravity recreational spaces. It is left to them to discover the most fun and best games for a low-gravity environment, and to use the spaces as they wish.

Weight training and fitness activities are two other forms of recreation on Freyr. Weight training

is available through two gym areas in the habitation levels, and consists mainly of bodyweight exercises and free weights due to the versatility and multiple-use potential of those forms of exercise equipment. These weights and equipment are made from lunar iron and aluminum, and include both free weights from one to forty one kilograms (2, 3, 5, 8, 11, 14, 17, 20, 23, 26, 29, 32, 35, 38, and 41) and bodyweight exercise equipment like padded benches, pull-up bars, a ballet bar, rings, and yoga mats. This equipment allows Freyr's inhabitants to maintain their fitness, especially if they spend a lot of time on the upper decks where gravity is lower, and they provide the versatility to perform most exercises with weights and the rest of them without; providing the equipment for specialized fitness is prohibitively complicated to manufacture (at first, anyway) and prohibitively heavy to lift from Earth: while Freyr's inhabitants can choose to provide specialized equipment in one or both gyms once Freyr has the manufacturing capacity to construct the equipment, this is their choice and the machines cannot be provided from the beginning.

The weight training gyms are located at the meeting point of the day/night cycle, which means that they can be used at any time of day and are never completely in the dark. They can sponsor fitness activities or classes to help promote the overall health of Freyr; such activities or classes can also be organized by individuals who are motivated to do so.

Zero-g recreation is not typically available on Freyr, but may be a possibility at certain times. This is because zero-gravity space is only available in the non-rotating section of the central core, which is constantly used for industrial work, docking and undocking procedures, training, or maintenance work. It is, of course, possible that zero-gravity recreation is allowed at certain times, but as a general rule it is not available.

1.5.6   Entertainment

Entertainment on Freyr is essentially nonphysical recreation. There are several avenues for entertainment on board Freyr, from watching archived film and TV show content, to reading a book, to socializing, to shopping with friends at the "mall."

Freyr's habitation is deliberately designed to encourage time outside the home, and the capacity for entertainment on Freyr reflects that philosophy. Most possibilities for entertainment, such as community activities, social gatherings, and public spaces, are exclusively outside the home, and because Freyr is enclosed, WiFi can be offered just as easily "outdoors" as indoors. Climate control for a comfortable temperature means that going outside is not inconvenient. With no reason not to go outside, then, Freyr's inhabitants are passively encouraged to find entertainment as part of a community, forming and supporting social bonds.

Digital

Digital entertainment on Freyr is archived in Freyr's databases and accessed via personal computers. These media include a wide selection of films, TV shows, and web pages that have been archived; they are static and non-interactive as a rule. TV shows are generally kept for a period of a month

or two after air, then deleted from Freyr's files, while films may be rotated in and out depending on interest or lack thereof in Freyr's populace.

Digital media on Freyr are all openly available to its inhabitants, and can thus be downloaded and stored freely. This includes all digital media in Freyr's library.

Digital media can be uploaded or downloaded by Freyr on request due to large bandwidth, but this service may take some time to find a sufficient break in communications use for complete download. Freyr is not cut off from Earth, then, but the time lag between Earth and Freyr, as well as limited bandwidth because of the difficulty of wireless communication over such vast distances, makes it difficult to maintain any kind of real-time uplink.

1.5.7 Computing

Computing on Freyr is managed through several methods. A computing core is located in the central core of Freyr, and eight substations are scattered through the habitation areas. These stations are networked and consist of powerful processors connected to reasonable memory banks with 15 monitors. The use of an actual substation monitor can and must be booked in advance due to limited physical capacity, but the direct access to the computer mainframe is so powerful that only some tasks truly require it. For everyday computing, Freyr's residents are provided with personal computers that they can use for entertainment, basic productivity, and other general computer tasks.

Keyboards on Freyr are not physical keyboards, but rather laser-projection keyboards[83], with a few exceptions. This is because laser projection keyboards can be changed between configurations instantly and without hassle, whereas a physical keyboard would have to be replaced. Additionally, laser projection keyboards are not physically massive and can be customized by each individual according to user preference for optimal typing. The exceptions to the standard of laser projection keyboards are some control workstations that require a more tactile interface: the one drawback of laser-projection keyboards is that they provide no tactile response to the user, which can lead to uncaught mistakes and is aesthetically unpleasing to some users. Control systems for Freyr must be handled accurately, which makes a physical keyboard desirable in a few cases.

The central stations of Freyr's computer mainframe all run the UNIX kernel, with computers that interface with residents of Freyr running Artemis, a Linux distribution optimized for networking across different parts of a network to increase workflow. Artemis is a lightweight distribution modeled after Arch Linux that is kept up to date by Freyr's inhabitants and interested programmers Earthside. It uses APMP, which stands for APMP Package Management Protocol, to work on a rolling update configuration where new packages are automatically installed each time the system is booted. Each individual has a username and password that unlock a portion of the drive, and another portion is shared between all users for broad network purposes; Artemis itself is also kept in this shared partition. Users can create folders that multiple users have viewing and editing rights to if they want to work on group projects, a feature that is also used to allow parents to view their children's accounts while their children are not yet adults. Artemis utilizes a command-line interface with some "desktop" widgets in place (clock, display of folder hierarchy currently

accessed, and currently running processes is the standard setup), but can support programs with a full-blown GUI. Typically, an Artemis program will have a basic and functional GUI without any bells or whistles, and files are accessed through the command line.

Primary Station

The primary station in Freyr's mainframe computer network is located in the Command and Control center, in the central core. Users on these consoles are signed in as both themselves and as root_PROXY and do not have access to user files unless those files have been linked to their personal account. As root_PROXY, users do not individually have sudo privileges, but three root_PROXY users can together authorize sudo commands, which are required to control Freyr's operations.

In order to sign on to the Primary Station, users must have root_PROXY in their account description, which can only be edited by root (the Secretary of Communications). This ensures that if a sudo command is used, it is authorized by three separate people who have all been granted access to the Primary Station by root and therefore know what they are doing.

The primary station has a one-way link with the substations: it can use them for its functions, but the substations cannot access the Primary Station's processors or memory.

Secondary Substations

The eight substations that are distributed throughout the habitation areas of Freyr are networked together to create a computer system capable of fast processing of large jobs. Each substation consists of ten processor clusters with four cores each and a total of 160 GB of local RAM; storage consists of several different types of file storage. Inhabitants of Freyr can purchase PCIe SSD jump drives that have up to 1 TB capacity and are Ultraport capable, with a data read/write rate of more than 10 GBps; these are used for ultrafast access to data and can be daisy-chained to allow a total of 5 TB in PCIe SSD memory. For jobs that allow for slower memory access, data is pulled directly from Freyr's storage archive for that individual, which takes longer but is capable of more volume transfer over time. Data can also be accessed from a personal computer via SSH if the computer is on, or a personal computer can be connected to the substation via an Ultraport-USB linking cable.

Substations are wired to each other through a LAN protocol over fiber optics; they use SSH to communicate securely and distribute processing jobs between the substations. Within a single substation, tasks are distributed via the Completely Fair Scheduler (CFS)[84], an O(1) algorithm for distributing processes within a single machine; between substations, Distributed resource Management (DRM) is used to assign tasks to individual substations according to current use. That is, a substation that has a lower workload than the others will be used to run parts of power-intensive tasks given to another substation, evening out the demand on the substations and dramatically increasing computational speed[85]. By evening out the load on the processing cores this way, the substations are able to complete tasks faster, use off-duty processors to speed up work, and keep the

system running smoothly at any time of day or night. Furthermore, because of Freyr's size of only a few kilometers, linking the substations into a network does not significantly increase processing time due to lag between processors, and the relatively small network size means that Freyr's DRM algorithms can be less computorially intensive, leading to further time savings.

Substations are mostly used for very CPU-intensive tasks that cannot be run in a timely fashion from a personal computer, such as many-particle physics simulations, computorial analysis, and real-time data processing. Often, these tasks take a long time to run even on the substation network, but the operator does not need to be present for all of the computational time. After the time required for initial set-up and beginning the program's run, operators can dedicate their console to the next user and thereby make the substations accessible to the greatest number of people possible.

Storage

Storage on Freyr is accomplished through several means. As mentioned above, inhabitants of Freyr have access to 1 TB PCIe SSD drives; additional data storage is located in the central core and in archive caches located with the processor substations. Some storage is also located on personal computers, but most is located in these central areas.

Each inhabitant of Freyr has a 500 GB allotment of hard drive space. Additional storage can be purchased in the form of PCIe SSDs, but 500 GB is the base allotment. Additionally, there are resources shared by the community that all inhabitants have access to, such as archived web pages.

Freyr's storage is used for several applications: personal file storage, system file backup, archive of web pages that may be particularly useful to residents, and storage of static materials (books, journals, films, artwork, etc.). Personal files and static materials are kept in distributed storage locations by the processor substations, while web page archives, backups of Freyr's critical files, and system programs are stored on drives in the central core to provide a centralized hub for both communications with the outside world and preservation of necessary file hierarchies.

Note that the values given here are preliminary and represent reasonable estimates for what Freyr's inhabitants will need. Based on today's technology, these are very reasonable estimates, but they may change in the future and therefore should not be taken as definite allotments.

Personal Computers

Residents of Freyr have their own personal computers for everyday use and are encouraged to use personal computers instead of the substations whenever possible. To facilitate use of personal computers, the systems are kept up to date with adequate processor power and drive storage, and software updates for Artemis Linux are designed to accommodate somewhat dated machines (as opposed to planning the obsolescence of technology as software develops). Personal computers can connect physically to Freyr's wired network, or they can connect wirelessly to Freyr's distributed 802.11 ac/n[86] WiFi network. Freyr's WiFi is set up in star-ring format, meaning that it depends on

a central network moderator (in the central core) to access materials located outside Freyr and in Freyr's wired system, but allows computers connected to it to communicate using a secure network protocol called SC-DTP (Secure Communications and Data Transfer Protocol) that is optimized for medium-size networks such as the one on Freyr.

Personal computers are encrypted by user choice and can be separated from Freyr's wireless or wired networks at any time, supporting user privacy but ensuring that any activity that requires the network keeps the computer connected.

Personal computers can be used with any OS, along with the proper drivers for SC-DTP. Standard options are Artemis, OSX, and Windows, although other operating systems are available from Earth. The default OS is Artemis, but this can be overwritten easily with another OS. One large advantage of Artemis over other OS setups, however, is its small disk size: Artemis only takes up 1 GB of disk space for a bare-bones install, and even with some productivity software Artemis is still very lightweight, while other operating systems take up several times as much disk space, leading to less space for files and slower performance due to bloatware.

Ultimately, personal computers on Freyr are intended for everyday use for tasks like communication with other inhabitants, text editing/programming, video streaming, and basic productivity. They can comfortably run most programs, but for heavy-duty computing the substation network should be used to reduce processor time. Note that, even in this case, programs to be run on the substation network should still be written on a personal computer to minimize use of console hours at the substations.

To facilitate this everyday use, personal computers are modeled after the concept of a 2-in-1 computer, which features a slim keyboard that can be detached from the main body of the computer to effectively produce a tablet with a separate keyboard. Screens have a semi-matte finish to discourage glare but satisfy users who dislike fully matte screens; this configuration makes reading easier, as on an e-book reader, while still allowing a high degree of functionality in the computer itself. Personal computers are also the medium typically used to view streamed video content, with the exception of community events and presentations.

Apart from these personal computers, Freyr's inhabitants do not typically have networked devices (smartphones and the like). Many do have watches that are capable of communication, but in a community as small as Freyr's there is simply no need for such devices. Removing them from the population allows better interpersonal communication without terribly affecting the ability of residents to communicate at all. It's not such a long walk from any part of Freyr to another; the longest possible distance is only about one mile.

Encryption

Communications within Freyr can be easily encrypted using a built-in Artemis protocol. When a user account is created, Artemis assigns it a large pair of prime numbers, or keys - one public, one private. It then stores the public key in the community repository and seals the private key into a section of its memory that is not opened to the network under any circumstances. By publicizing

every person's public key, Artemis ensures a flawless proof-of-identity protocol using public key authentication.

In a public key scheme, each person has two keys that are used to encrypt and decrypt their communications. Each key precisely undoes the other, so that a message encrypted with the public key can only be decrypted with the private key[87]. This allows messages to be authenticated and signed: when sending a message, the sender encrypts it both with the recipient's public key and with their own private key. When the message is received, it requires both the recipient's private key and the sender's public key to decrypt the message, absolutely authenticating the message as having not been tampered with and having been sent by who it says it was sent by. This standard of cryptography is secure because of the public key, so Artemis broadcasting the public key over the central database is incredibly important for the scheme to work.

Individuals are encouraged to keep their own set of public keys on their personal computers to avoid any alterations to the central database from altering their perception of who sent them a message, making the system more secure.

1.6 Administration

To maintain independence from any one country or group of countries on Earth, Freyr is its own independent nation. It is not a part of any nation, nor a territory of Earth, but its own country. This does, of course, have several implications.

1. Freyr is not funded by any government, but instead paid for its products and services.

2. Freyr's operations are all internally controlled.

3. Freyr is not subject to the political whims of any nation on Earth.

Of course, there are complications involved with Freyr being an independent country. Not the least of these is that, as a settlement in space, it is possible that Freyr will become irreparably damaged and that its residents will have to be evacuated to Earth. Without a nationality (especially once people begin to be born on Freyr), where do they go? This question and others are important, and have to be answered.

In effect, Freyr is a corporation that interacts with but exists separately from any Earth-bound country. It does have its own governmental system, and is its own nation, but Freyr's income is not due to taxes on individuals, corporations, imports, or exports; instead, Freyr itself produces goods and provides services in exchange for the money it needs to remain afloat. In this fashion, it acts almost like a communist country, with a few key distinctions. First, individuals have the right to start their own businesses within Freyr, setting up a secondary capitalist market system. Second, Freyr's inhabitants are treated as shareholders in a company might be; while production by Freyr does not come directly back to any individual, Freyr's inhabitants are paid in a system much like stock options, meaning that when Freyr is successful, its inhabitants reap the rewards.

Freyr provides several services to its residents, such as police, fire, and ambulance service, that are governmental obligations and are therefore funded by the government, while other non-essential services are provided by private industry on board Freyr. Necessarily, certain laws must be very different on Freyr than they are on Earth, and it is very difficult to anticipate what these differences may have to be beyond the most rudimentary distinctions.

1.6.1 Divisions of Government

The government on Freyr is divided into two portions: a civilian government that deals with the societal structure, broad-view policies, and residential life of Freyr, and a station-oriented government that deals with Freyr's day-to-day operations. This division is only official, however, as the station-oriented government is subject to the decisions that the civilian government makes. It can be thought of as a branch of the civilian government, focused not on the life of the station but on keeping it alive.

Freyr does have a police force, but it has no army due to there not being a need. The police force is composed of fifteen officers, one per every 650 or so residents. This is made possible by Freyr's unique situation: criminals cannot flee to another inhabited area, and because Freyr is constructed as an in-orbit settlement, central files include the fingerprints and iris-scans of all residents.

Clearly, on Freyr more than on Earth surveillance is a large concern. Freyr is in a much more fragile position than any Earth nation in that a single person with bad intentions could wreak massive destruction on the station, so some surveillance is absolutely necessary. The problem is that with too much surveillance, which would be all to easy to install while Freyr is being built, there is no privacy anywhere on the station. Freyr's answer to this conundrum is that surveillance is provided for, but only in critical communal spaces (the police station, brig, governmental offices, etc.) and not inside private homes. Because the influx and efflux of materials from Freyr is monitored and accounted for (as it must be, on a space settlement), there need not be provisions for surveillance inside private homes. Additionally, email and electronic communications are not read or opened, and residents are provided with all reasonable privacy in their day-to-day lives.

1.6.2 Civilian Government

Freyr's civilian government fulfills all the functions of government that we are used to on Earth. It makes laws, defines ordinances, regulates business, and has ultimate authority on Freyr over long-term decisions. It is composed of three branches, much like the United States' government: the executive, legislative, and judicial branches, each of which has a different role to play in Freyr's governance.

Executive

The executive branch carries out the laws made by the legislative branch, maintains relations with Earth and other space settlements, oversees the station-oriented government, and has the authority to make emergency decisions of an effective period of less than 30 days.

These powers allow the executive branch to maintain authority over the settlement while providing an interface with the exterior world. There are five positions in the executive branch, some of which are elected and some appointed.

The President is elected by the general public, and once in office has the power to appoint a Secretary of Communication and a Secretary of Operations - though, often, the best people to fill these positions will already be in office and no changes will have to be made. A Secretary of Finance and a Secretary of Education are both elected in the same cycle.

The office of the President comes with a two-term limit. That is, any one individual can only be elected to the presidency twice. Elections are held once every five years so that any year divisible by five is an election year, making the Presidency an office that cannot be held for more than 15 years - if the president dies while in office, the Secretary of Operations takes his/her place and may thus spend up to five years in office without being elected.

Likewise, the other offices in the executive branch have a four-term limit, so that no one may hold the office for more than 25 years. These offices, while not as powerful as that of the presidency, still risk ossification in a population as small as Freyr's and so have term limits.

Table 1.14: Executive Branch Offices

Office	Appoint/Elect	Description
President	Elected	Overall Management of the settlement. Approves Laws. Acts as the public face of Freyr.
Secretary of Communication	Appointed	Manages communication with Earth. Oversees intrastation communication network. Coordinates trade meetings, conference calls, and other communication with markets.
Secretary of Operations	Appointed	Interfaces with station operations management. Provides information about station operations to the public. Files records of station activity.
Secretary of Finance	Elected	Keeps track of Freyr's finances. Cross-checks records from government, operations management, and industry. Provides quarterly report on station finances.
Secretary of Education	Elected	Presides over Freyr's school. Helps to set school curriculum. Provides education resources to residents.

Legislative

Freyr's legislative branch deals with making laws, providing a long-term vision for the settlement, and working with the residents of Freyr to adapt to changing conditions and sentiments. Given the isolated and relatively restrictive nature of life on Freyr, it is of the utmost importance that government respond to the will of the people, which is the function that the legislative branch serves. To help the legislative branch best fulfill their obligations, it is by far the largest branch of government and is composed of 25 members, drawn from districts within Freyr.

These 25 members form a body known as the Parliament, and make decisions based on the mandate from their constituents. Because of the small size of Freyr (one Parliament member represents just 400 citizens), members of Parliament are able to meet with their constituents and actually determine what they have to say, creating trust in Parliament and letting individual citizens know that their representative is looking out expressly for their opinions.

The duties of Parliament are as follows:

1. To provide a legal structure for society within the settlement;

2. To regulate commerce and banking within the settlement;

3. To ensure the public safety.

Taxes. Due to the structure of Freyr as a government/industrial complex, there is no need for either taxes on internal transfers or on imports or exports. Note that Freyr is not under a communist system; communism works only so far as all involved are willing to give their work to the government in exchange for a sum of money determined by their needs, and quickly degenerates into a chaotic state. Instead, Freyr acts like a corporation in that all residents receive a "paycheck" in credits that can be converted into Earth currency and invested on Earth or used for any desired non-essential purchases on Freyr.

Judicial

The judicial branch deals with the enforcement of the law and with the treatment of criminals. It has direct authority over the police force, can declare laws and executive actions void with a unanimous consensus, and can conduct trials and hearings on any matter Freyr is involved in. The judicial branch has final authority over the legality of Freyr's actions and internal regulation.

The core of the judicial system is a group of three judges who preside over trials, hold hearings, and hold the legislature and executive accountable. They are elected for twenty-year terms and cannot be re-elected, and they must hold a part-time job in addition to their judicial duties. These restrictions ensure that the judges will be unbiased without thought of re-election and that they stay in touch with the experience of every citizen of Freyr by continuing to work.

The judicial branch is given control of the police force for multiple reasons, but the most important is this: by being associated with the judicial system, the police are bound even more closely to uphold the law and are made directly answerable to the judges who decide matters of law. Additionally, binding the police to the judicial department ensures that they will cooperate with any investigation and that police records are immediately available to the judicial process.

Minor Infractions. In the case of minor law violations, a hearing is held and presided over by one of the judges. Theses hearings are limited to four hours and are to be used for:

1. Traffic violations (pedestrian/bicycle).

2. Petty theft.

3. Building code violations.

4. Minor property damage.

And other non-serious legal matters. At these hearings, evidence is presented and a decision is reached by the judge; penalties decided upon can include a fine of up to the equivalent of $100 and community service but cannot include a mark on the permanent record or permanent restrictions on activities.

Criminal Trials. In the event of a criminal trial, the first step is a jury trial: five jurors[22] are selected from Freyr's population and a trial is conducted with a judge presiding and a jury hearing evidence. The trial is limited to one day to avoid disruption to work on Freyr, and may be conducted between 0800 and 2000 hours. This is intended to keep the trials concise and is sufficient to deal with the vast majority of cases.

Criminal trials are used for all infractions more serious than a hearing can deal with, e.g. breaking and entering, premeditated violence, etc. Penalties decided upon may include a fine of any amount, community service, a mark and note in the permanent record, temporary or permanent probation, demotion, and expulsion from Freyr.

Appeal. The verdict of a criminal trial may be appealed in one of two ways. The verdict can be appealed, or the law itself can be appealed.

In the first case, the trial goes to a panel composed of the three judges, who hear arguments again and reach a decision that can either uphold the earlier decision or modify it, as they determine is lawful. In the second case, the judicial panel of Parliament is convened to discuss the law and evidence is presented to them arguing for and against the law's existence. This panel can choose to uphold the law or to overturn it, in which case Parliament as a whole may choose to replace the law with a new version that it sees fit to enact.

The decision reached by either appeal process is final, but both appeal processes can be engaged for the same case and either of them may overturn the conviction.

1.6.3 Station Operations

Mostly separate from the civilian government is the structure of the Station Operations hierarchy. This is less of a governmental structure and more of a military-style administrative structure, with a clearly defined chain of command.

Station Operations has authority over the day-to-day workings of Freyr: dockings, undockings, life support, structural maintenance, and the other essential functions of the settlement. In these capacities, it is supreme and cannot be challenged; outside of them, it must bend to the will of the people and of the civilian government. That is to say, Station Operations is absolutely in charge of keeping Freyr intact, and the civilian government is absolutely in charge of steering its political and societal course.

At the top of the hierarchy is the Station Manager. His/her job is to maintain knowledge of the maintenance, docking and undocking, life support status, reactor state, and all the other processes going on to keep Freyr on point. The Station Manager is ultimately responsible for the upkeep of Freyr, and reports to the Secretary of Operations.

Below the Station Manager are five Subteam Administrators: Reactor, Berthing, Life Support, Structural A, and Structural B. Each subteam has a particular area of responsibility and expertise,

---

[22]Five is few enough to avoid complications due to the small population size, and is an odd number to ensure a decision.
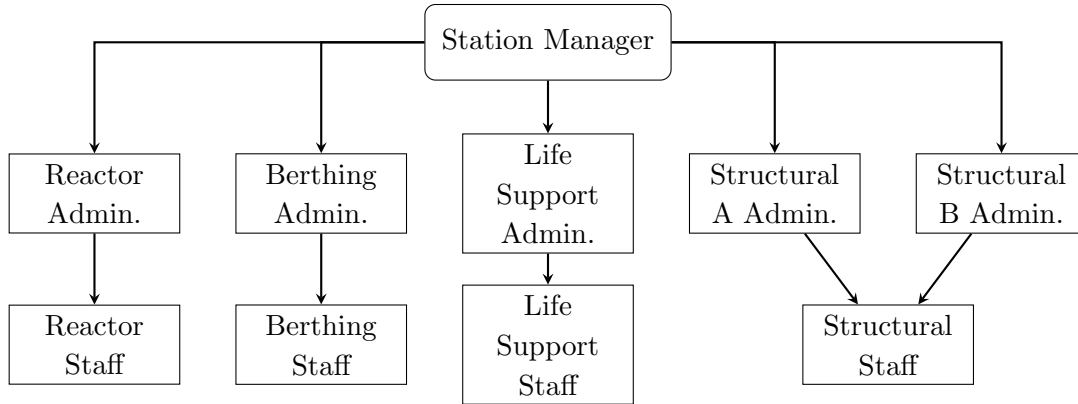
Figure 1.14: Station Operations Hierarchy

and does its part to keep Freyr running. The responsibilities involved in various parts of mainte-nance are distributed between these five subteams to ensure professional work and a high level of expertise in every repair. Specific duties are detailed below.

Below each subteam administrator in the hierarchy is a team of dedicated staff. These teams are specialized to the subteam they work on so that each subteam administrator only has to interface with the Station Manager and their own subteam, providing more thorough modular support and allowing a high level of expertise in every job by enhancing specialization and independence. Despite the separate nature of each subteam's staff, the different subteams work with each other very frequently; the reason for their specialization is that specialized teams generate true experts.

1.6.4   Money

The key problem with money on board Freyr is that the society is just too small for it to be useful. In a group of only 20,000 individuals, the economy is not large or diverse enough for money to be a large concern, especially because Freyr itself provides many basic services such as food, water, and electricity. Nevertheless, a moneyless society is a fantasy with more than a couple of dozen inhabitants, meaning that some form of currency must be used on Freyr.

The currency decided upon for wages is a system, similar to stock options, called credits. Credits are given out for work on a part of Freyr (not all jobs are paid equally, for some are inherently more useful than others) and act as a share of Freyr's profit. These credits can be redeemed in one of two ways: they can be used as cash, at an appropriate exchange rate given Freyr's total profit and the number of credits in circulation, or they can be traded back to Freyr in exchange for goods or services on board the settlement (for example, buying cargo space on a craft going to LEO so that a businessman can transfer goods to Earth for sale). Internally, there are no initial restrictions placed on any informal monetary or bartering system that residents may set up; while restrictions on these systems may be placed as Freyr develops if necessary, it is anticipated that a completely internal system of barter or monetary exchange will be stable on the settlement.

Table 1.15: Subteam Responsibilities

Subteam	Responsibility
Reactor	General Thorium Reactor Operations
	Thorium Reactor Maintenance
	Power Distribution
	Electricity Management
Berthing	Docking Craft
	Undocking Craft
	Docked Craft Maintenance
	Fueling
	Docking Port Maintenance
	μg Maintenance
Life Support	Maintenance of Algae Tanks
	Cleaning of Components
	Maintenance of Pump Equipment
	CO_2 Scrubber Upkeep
	Water Quality Monitoring
	Atmospheric Monitoring
Structural A	Interior Structure Repair
	Interior Mechanical Maintenance
	Pressure Containment
	Interior Facilities Upkeep
Structural B	Exterior Structure Repair
	New Construction Work
	Pressure Containment
	Exterior Structures Maintenance

The Credit System

Freyr's credits are set up as an electronic currency. Banking files are kept in triplicate hard-networked computer databases to ensure that there is no fraud; the computers are kept in separate locations to preclude damage or point alteration, and any transfer is kept local until the other computers receive authentication from both parties. Keeping the currency digital has some drawbacks in terms of security, but it is no less secure than physical money (which can be stolen) and carries the benefit of not requiring the printing of any money and reducing the burden of keeping track of and carrying around physical money. It is anticipated that credits will be accessed either via an RFID chip (or credit card) or by submitting a signed digital receipt for each transaction.

This credit system relies on a couple of mechanisms that regulate the currency and maintain its value. For example, as credits are handed out, the total number of credits in circulation increases. To fix this problem, Freyr's administration periodically multiplies all credit values in accounts by a constant, which reduces the number of credits in circulation while not disadvantaging anyone by

ensuring that all accounts are affected equally. Note that this is not strictly necessary, but that it keeps the number of credits in circulation nearly constant. This step could be done away with if Freyr's administration and population decided it was no longer necessary.

The main advantage of the credit system is that credits are dynamically controlled from inside Freyr and correspond directly to Freyr's value as an institution, meaning that the credit depends only on the stability of the world economy to keep itself stable. To ensure this stability, Freyr keeps its profits in a variety of places, including the Swiss franc, the U.S. dollar, gold, and other relatively stable commodities.

Each credit is defined as having a certain value according to:

$$\text{value}_{\text{credit}} = \frac{\text{profit}}{\text{number of credits}}$$

This relationship ensures that each credit is "worth" some amount of profit that Freyr has accumulated, proportional to the number of credits in circulation. Thus reducing the number of credits in circulation by multiplying each account my some constant does not change the amount of profit represented by each account, and spending credits on items from Earth decreases Freyr's profit by a corresponding amount, keeping the amount represented by each credit stable and again keeping the amount of profit represented by each account constant. The two things that potentially change the amount of profit represented are the transfer of credits from an individual to Freyr or another individual and the distribution of credits in exchange for work.

In the first case, transfer of credits between accounts, the only two accounts affected are the two involved; the total number of credits remains constant. In the second case, distributing credit in exchange for work, problems begin to arise: adding more credits to the system dilutes the credits already in circulation, reducing the amount of profit represented by any individual credit. The solution, of course, is that work typically results in more profit, which in turn increases the value of each credit. One unfortunate effect of this system is that the retired and elderly may face a gradually decreasing store of funds as younger workers inundate the market with more credits; however, as long as Freyr's profits and the credits given out for the work that generated those profits stay in a fairly constant ratio, there should not in theory be any depreciation of the credit as currency.

Credits can be exchanged in one of two ways, as mentioned above. One of these ways is in the purchase of goods from Earth to be shipped to Freyr. In this case, the credit is removed from the individual's account and used by Freyr to buy the item on Earth and pay for its shipment on board the next cargo rocket. The other way, typically more useful to someone on board Freyr, is exchange for services or products on board the settlement. That is, an individual with enough credit can buy items or services from Freyr in exchange for their credit. An example of this would be a group of people deciding to acquire a spaceship for their use. With enough credit, they could buy that ship from Freyr itself and use it for their business (or conceivably for enjoyment). Note that credit transferred back to Freyr is no longer in circulation, but that this does not affect the value of remaining credits because Freyr loses value equal to that credit in the transaction.

It is possible that credits could become the preferred currency within Freyr as well as a convenient

method of storing money earned with an internal system. This seems more likely to come about if Freyr decides that it is not necessary to reduce the number of credits in circulation periodically.

1.7   Industry

A major reason for Freyr's existence is the presence of industrial operations on board and on the lunar surface. Without industry, Freyr would be essentially a glorified ISS, orbiting the Moon and doing science but relying on the Earth for funding, supplies, and a reason to be. That is unacceptable: changing economic or political conditions on Earth cannot be enough to stall mankind's exploration into space. Therefore, industry has a place on Freyr and on the Moon.

Much of Freyr's industry is based on lunar materials - that is, processes on Freyr depend on the use of lunar materials. Typically, processing occurs on Freyr, while extraction and purification processes take place at ISRU facilities or specialized bases on the lunar surface. While some processing does occur on the lunar surface, such high-quality minerals can be obtained on the Moon that only minimal separation and processing is required before materials are shipped to Freyr to be refined or made into finished products.

In order to be maximally efficient with lunar materials, Freyr is equipped for several different kinds of material processing. The central core and surrounding levels of Freyr contain equipment that can be used for organics synthesis, fuel manufacture, isotope separation, metal refining and casting, ceramic production and firing, molten salt electrolysis, and other processes vital to the ability to process different kinds of minerals. Because Freyr is such a small community, all of these processes cannot be maintained simultaneously for lack of experienced manpower, but Freyr's small size also means that batches of materials do not need to be constantly produced, but can rather be produced on an as-needed basis.

Industrial processes on Freyr make use of waste heat from the LFTR's Brayton cycle wherever possible to increase efficiency and reduce waste through the reactor's operation, with electrical elements serving as a backup and as the means for final heating to operating temperature. A preheating technique is used in all industrial processes, which involves the hot product being passed around the cool reactants to increase energy retention within the process and reduce heating requirements. In the case of a reaction that must take place at cold temperatures, the same process cools the inflowing material and helps to warm up the reaction's products, again helping with system energy retention.

Freyr's capacity for industrial processes and the vast range of processes that can be carried out on board, combined with Freyr's unique position near the edge of the Earth-Moon system, mean that it is very economical for prospectors in the asteroid belt to send raw materials back to Freyr for processing, paying a fee in the process, instead of setting up their own large and expensive processing operations. Until it is economically possible for firms working on asteroid mining to contract for their own station, Freyr is the most logical point for materials processing and enrichment.

The industrial processes used on Freyr are intended to provide useful materials for Freyr, its lunar facilities, and other spaceborne objects. It is understood that very few items are worth transporting back to Earth for use, with some exceptions for special cases.

1.7.1   Variable Gravity

An advantage of locating industrial resources on Freyr is that due to the nature of rotational gravity, materials that are processed near the center of rotation have a much smaller weight for the same mass, making it easy to move large volumes of material easily. At the edge of the central core, for example, materials only weigh 5% of what they would on Earth, and when lifted off the floor their weight decreases further until, at the center of the central core, they weigh nothing and can be moved exceedingly easily.

For example, materials can be unloaded into the non-rotating section of Freyr through an airlock and then passed through the ferrofluid-moderated joint between the rotating and non-rotating sections. At this point, they can be released; they are still free-floating and are not yet rotating with Freyr. A crane counter-rotating with respect to Freyr can then grab the material and slowly rejoin the rotating section, gradually providing an angular acceleration to the materials and allowing them to be handled close to Freyr's center of rotation while being controlled and locked to the rotation of Freyr.

While having low gravity close to the center of Freyr is a nice aspect of rotational gravity, keep in mind that lowering anything down even one deck will cause its weight to increase. Thus, to maximize the benefit of lower gravity and avoid the penalty of hauling finished materials up along Freyr's rotational axis, it is necessary to set aside a good deal of space near the center of Freyr. This causes unfortunate complications with regard to the optimal placing of Command & Control equipment, communications equipment, and many of Freyr's vital functions, but it is a compromise that is worth making given the vast advantages of low-gravity industry.

Note that industrial processes are better off in a low-gravity environment than they are in a microgravity environment due to the ease of processing conferred by having a definite directional acceleration; microgravity processes tend to be messier and require more maintenance. Low gravity (like the 5% at the outer edge of the central core) provides the weight reduction benefits of a low-gravity environment while avoiding the complications of having no predominant acceleration.

1.7.2   Safety

Of course, industrial safety must be taken very seriously on Freyr. On Earth, a factory can be evacuated, but on Freyr there is nowhere to go and the accident can only be waited out or directly combated. This necessitates strict regulations on industrial processes and means that processes must be thoroughly tested before they are allowed to operate on Freyr.

To help ensure the safety of Freyr from any potential industrial accidents, precautions are taken in the vicinity of industrial equipment or processes. All high- or low- temperature processes must be contained by an insulating barrier with a specific thermal conductivity of less than 300 watts. This means that the thermally insulating layer must be thicker for high-temperature applications and must cover the entire exterior of the process. In addition, most industrial processes, including those that involve molten materials or pressures in excess of 15 atmospheres, are contained behind a containment wall of 0.25 cm titanium or aluminum to help contain the spread of a molten material

spill or to help absorb the energy of a shock wave. This measure will not solve the problem of, say, a molten salt spill or a pressure vessel failure, but it will reduce the damage caused by such an event and provide a layer of protection for humans on board Freyr.

The most useful safety measures used on Freyr are none of the above, but rather routine inspection. High-wear components are inspected once every 40 days, and others are inspected every 160 days. The inspection schedule is kept computerized and notifications are automatically sent to inspection personnel to ensure timely inspections of the required components. If, during an inspection, any component is found that has a possibility of failure within the next two inspection cycles, the system is temporarily shut down to allow for replacement of that component at the earliest convenience, and the worn component is recycled in the very industrial system it once was a part of. This system of inspections is the most effective tool at Freyr's disposal for preventing industrial accidents.

In addition to mechanical dangers, there are occupational hazards associated with working for extended periods of time in a low- or micro-gravity environment. Studies of astronauts on the International Space Station have shown that extended microgravity exposure can, according to the National Space Biomedical Research Institute, result in[88]:

1) Bone decalcification, which can be accelerated by radiation exposure and weakens bones drastically;

2) Muscle atrophy, which can occur at the rate of multiple percent a week and causes a large decrease in strength, especially in the cardiovascular system;

3) Congestion, due to fluid movement in the absence of gravity;

4) Back pain, due to spinal lengthening in microgravity; and

5) Balance problems due to inner ear fluids shifting without gravitational "anchoring."

Clearly, it is inadvisable to have workers who are monitoring the processing of thousand-degree molten metal be unsteady on their feet due to balance problems. While all of these symptoms have been reversible after extended periods of time back in normal gravity, it is still unknown how long-term or chronic exposure to low- or micro-gravity conditions will affect permanent characteristics. It is also almost entirely unknown how the human body reacts to conditions of low gravity, because the only time when humans were in a gravitational field between 1g and 0g was when the Apollo missions landed on the Moon, and the short time frame of those missions (less than 3 days on the lunar surface[89]) did not provide enough data to characterize human reactions to intermediate gravity conditions.

To err on the side of caution and preserve the safety of all it inhabitants, Freyr's goal is to minimize the effects of low- and micro-gravity environments. This is done by mandating a maximum of eight hours per day at gravities less than 0.5g, and a minimum of eight hours per day at normal gravity (1g), which is designed to help reduce the effects of a microgravity environment by limiting daily exposure. In addition to these exposure limits, 10 minutes of physical exercise are required per every hour spent below 0.5g, and five minutes for every hour spent between 0.5g and 1g.

Children are not allowed in areas with gravity lower than 0.5g for extended periods of time, and must be accompanied by a parent or guardian, or an adult explicitly authorized by a parent or

guardian, to visit these areas. They are also limited to three hours a day between 0.5g and 1g. These limits are intended to avoid growth and development problems, and their conservative limits on low-g exposure for children reflect the current lack of knowledge about the effects of low-gravity environment on physiology and development.

Once more is known about the effects of reduced gravity on human physiology, these standards may be relaxed or tightened as appropriate; initially, they are set as they are to promote the health of Freyr's inhabitants in every way possible and ensure that there is no inadvertent damage to individuals due to inadequate standards that resulted from a lack of knowledge about the effects of low gravity environments.

The one exception to the eight hours a day rule is the spacecraft construction industry detailed in 1.6.8. Workers in this industry must spend large amounts of time on extravehicular activities on a daily basis, and effective EVA operation is obstructed by the necessity of spending 67% of their time at 1g, far from the spacecraft construction facilities. As a result, workers in the spacecraft construction facilities spend weeks at a time in a microgravity environment in the non-rotating section of Freyr, both to allow them to acclimate to a microgravity environment and to ensure that they can be maximally productive while on duty. This configuration allows for extravehicular activities of up to ten or twelve hours a day. This limit is imposed by the spacesuits themselves, in fact, and workers on duty in the microgravity environment of Freyr's non-rotating section can spend even more time each day working to complete interior construction of probes or spacecraft components if that turns out to be the best solution.

1.7.3   Types of Industry

Freyr has several types of industry, partitioned into three broad categories:

1) Lunar surface industry;

2) Gravitational Freyr industry;

3) Non-gravitational Freyr industry.

Lunar surface industries include the extraction and purification of metal ores and oxides, the extraction of helium-3 and other volatiles from lunar regolith, processing of the lunar ice caps into water, and other industrial processes that are - sure enough - based on the lunar surface.

Gravitational Freyr industries are industrial processes that take place on Freyr in the presence of a centripetal acceleration. For example, molten oxide synthesis is conducted in this environment to allow easier containment of molten components, and the LFTR is located here so that passive draining can occur in the event of a system failure.

Non-gravitational Freyr industry is located in the Spaceport. This category includes crystal synthesis, spacecraft construction, repair preparation, and other tasks that are better suited to a microgravity environment. If an industrial task works better without a gravitational influence, it is in this category.

1.7.4   Helium-3 Production

Helium-3 is one of Freyr's principal exports due to its scarcity on Earth and its promise as an effective nuclear fuel. ^{3}He undergoes aneutronic fusion with ^{2}H, deuterium, resulting in the release of huge amounts of energy:

$$^2\text{H} + {}^3\text{He} \rightarrow \text{p} + {}^4\text{He} + 18.35\,\text{MeV}$$
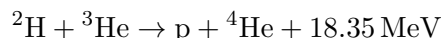
This reaction is favorable for fusion for several reasons: the energy output is high, the Lawson criterion is low, and deuterium is readily available in small concentrations in seawater[90]. Additional benefits include the lack of harmful radiation produced by this process: unlike nuclear fission, fusion does not result in radioactive waste, and this particular reaction does not release neutrons but rather protons and α particles, which are more easily contained because of their charges. While self-sustaining fusion has not yet been attained using deuterium fuel, ^{2}H-^{3}He fuel fuses more readily and is far easier to maintain. By providing a supply of ^{3}He obtained from lunar regolith, Freyr makes it economically possible to use large-scale nuclear fusion as a terrestrial power source, and because of the scarcity of helium-3 on Earth, Freyr may retain a strong proportion of ^{3}He for sale, allowing better profit while also increasing economic opportunities and profitability on Earth.

Based on the current price of oil, one metric ton of ^{3}He is worth over \$5,700,000,000[91]. On Earth, only about 500 kg will be available on a reasonable time scale; 1.1 million tons of ^{3}He are bound in lunar regolith. With extractor equipment, Freyr removes this ^{3}He and exports it to Earth, providing a source of clean energy that results neither in greenhouse gas emissions nor radioactive waste and receiving payment to the tune of \$200 billion per year, which corresponds to approximately 35 tons of helium-3 delivered to Earth.

Helium-3 industry on Freyr consists of several stages: extraction from the lunar regolith, transport to Freyr, isotope separation, and then transport to LEO for transfer to commercial vehicles for descent through the atmosphere.

Extraction

Helium is deposited on the Moon by the solar wind and then binds to titanium dioxide in lunar regolith. It is primarily found in the mare regolith of the Moon, where it makes up as much as 50 ppm by weight of the regolith.

Because of its relatively low concentration in lunar regolith, the extraction of any large amount of helium requires that 20000 kg of lunar regolith be harvested for every 1 kg of helium recovered. This effort is partially compensated, however, by the extraction of large amounts of other volatiles: 0.12 kg of nitrogen gas, 0.55 kg of carbon dioxide, 0.52 kg of methane, 1.06 kg of water, some ammonia, and 1.97 kg of hydrogen[92]. In addition, the processed regolith can be transported back to the nearest ISRU for further processing and the production of metals, ceramics, and composite materials on Freyr.

The actual extraction of helium from lunar regolith is accomplished by heating the regolith to drive out and evolve volatile gases. It was found[92] that heating the regolith to 700 °C, or 973 K, is sufficient to evolve all the adsorbed volatiles, including helium-3, from the lunar regolith. While this is impractical to do by most means, and heating twenty tons of lunar regolith for an end result of 0.323 grams of helium-3 by chemical or artificial means is absolutely impractical, a simple solution exists in concentrated solar power.

When the extractor's location on the Moon is illuminated by the Sun, mirrors such as those used in solar concentration power plants[93] to concentrate solar radiation into a high-intensity beam that heats a vacuum chamber containing regolith. Off-gassing from the regolith is then collected in the chamber, removed by vacuum pump, and then stored in tanks until the lunar night.

The advantages of using mirrors to bake out the helium are many: mirrors on the Moon's surface do not degrade because of the vacuum environment, sunlight provides a constant (for about two weeks) source of power for the system, no fuel is required to heat the regolith, and temperatures can easily reach above 973 K.

After the extractor's storage tanks have been filled, processing ceases until the lunar night (unless, of course, replacement tanks can be procured and installed). During the lunar night, which lasts two weeks and can plunge as low as 100 K (-173 °C)[94], leading to the liquefaction or deposition of ammonia (-35 °C), methane (-161 °C), carbon dioxide (-78.5 °C), water (100 °C), and, with a little extra refrigeration, nitrogen (-196 °C)[95]. These liquids and solids enter a second holding tank through a one-way drain in the bottom of the storage tank. Helium remains in a gaseous form and is kept in the storage tank. With its primary storage tank now empty except for helium, which ends up concentrating in the tank as more and more cycles pass, during the lunar day the extractor again begins to process lunar regolith and collect the gases.

Once the collection tank is full of helium, it is detached from the extractor and carried back to the ISRU by a mover unit.

A version of this process is described in U.S. Patent Application 09/861,085[96], but the view presented here is different from that stated version in that this implementation utilizes a fleet of small harvesters that deliver their products to a central storage and transport station, while the stated implementation utilizes a central processing and storage facility.

Extractor The helium-3 extractor vehicle consists of a tracked frame with a grinding/collecting arm that chews the regolith and deposits it on a conveyor to the body of the machine. From there, a series of containers and processes result in the processing of the regolith and extraction of volatiles.

Once the regolith has been ground, it is moved to the solar heating chamber, which is located above the main body of the vehicle and just above the parabolic solar collector. This solar collector is secured at both ends but can rotate to follow the Sun for optimum solar energy capture and regolith heating. The conveyor feeds into this chamber for a time, until the bottom of the chamber is covered with a layer of regolith, and then ceases; while this batch is being processed, the grinding arm is inactive.

The heating chamber is made of fused quartz, which is transparent to allow the passage of light, can be manufactured entirely from native lunar materials, and easily resists the high temperatures induced by the high-intensity incident sunlight (quartz softens at more than 1800 K[97]). This chamber is airtight and holds the regolith and any evolved gases.

Once the evolution of gases is complete (ca. 15 Earth minutes, although this may vary with regolith composition and degree of gas adsorption), the evolved gases are pumped into the holding tank and the processed regolith is removed from the heating chamber and either left behind or transported back to the ISRU. The process is repeated, with more regolith deposited into the heating chamber and another four hours of processing.

The extractor's parabolic mirrors are coated with aluminum and robotically polished to achieve a high and uniform degree of reflection[98]. Aluminum is readily available in the lunar regolith, and although it has a relatively high thermal coefficient of expansion, a mirror optimized for operation during the lunar day can deform temporarily at night when it is not needed.

The pump used to transfer gases from the heating chamber to the storage tank is an oil diffusion pump coupled to a turbomolecular pump. The oil diffusion pump can achieve vacuum as high as 10^{-12} torr, which is $1.3*10^{-15}$ atm, lower than the average "atmospheric" pressure on the Moon[94], while the turbomolecular pump maintains a low outlet pressure, required for the diffusion pump to work properly[99]. These pumps are located inside the body of the extractor, and therefore a seal is required to keep the gases from escaping upon removal of the storage tank; this seal is provided by a positive-pressure double hatch system that seals off both sides of the connection to ensure minimal gas loss to the lunar environment.

The extractor itself and its equipment are solar powered, using photovoltaic cells to provide usable power for the extractor's operations. During the lunar day, excess power is put towards the electrolysis of water in fuel cells, which then provide power during the lunar night to help with liquefaction of nitrogen gas in the storage tank and to run the extractor's diagnostics and critical systems. While PV does not provide an astronomical amount of power, it is much more effective on the Moon than on Earth due to higher irradiance and during times of low power use, power can be stored as hydrogen and oxygen gases for use during times of peak load. This added capacity helps to move the extractor along its tracks and provides the requisite power for operating the grinding arm.

Each extractor is projected to have a mass of about 70 tons, of which about 10 tons must be manufactured on and lifted from Earth in the early stages of Freyr. The rest of the mass can be constructed from native lunar materials and thus is processed by ISRUs and constructed into machinery. The cost of the 10 tons is about $2 million for the parts themselves and $62 million for lifting them into orbit.

Transportation   The storage tanks are transported back to the nearest ISRU by small vehicles called movers. These vehicles are essentially just a drivetrain, an operation cabin with minimal life support, and a frame for the storage tank. They are powered by lithium-ion batteries and are fitted with zero-puncture wheels to help ensure reliable operation. No processing is conducted on

these vehicles, which can be recharged at either end of their journey. The range of a fully loaded mover is not greater than 50 km; with no tank, they can travel more than 200 km.

ISRU Activity

In the ISRUs, further processing takes place. The liquefied and/or solidified components are separated using a fractional distillation process, in which the temperature is gradually raised and components boil off in the opposite order of their condensation. This allows the capture of different gases in their own containers, which in turn allows them to be useful. The separated gases are then re-liquefied by exposure to the lunar night and are shipped to Freyr for use there if they are not needed on board the ISRU.

More importantly, the helium that remains in the storage tank is liquefied and placed into pressurized Dewar containers that are further insulated by liquid nitrogen to keep the helium liquid and therefore reasonable for transport. These dewars are then stored in a special area of the ISRU, insulated by MPET insulation, until they are transported to Freyr on an LTV for isotope separation.

Isotope Separation

When helium is extracted from the lunar regolith, it is assumed to consist of 0.0323% ^{3}He and 99.9677% ^{4}He, the atmospheric proportion of helium-3 to helium-4[100]. While both helium-3 and helium-4 are useful, only helium-3 has a commercial purpose, and so the isotopes must be separated on board Freyr and the helium-3 purified for shipment back to Earth. Helium-4 is kept on Freyr for use in medical diagnosis, reactor coolant, leak detection[101], and other uses.

It is very difficult to separate the isotopes of an element due to the fact that they behave chemically identically and are very similar in most respects. Isotope separation is, in fact, the most complicated part of the entire helium-3 harvesting process, which is why it is carried out on Freyr.

Isotope separation is accomplished by the combination of a cryogenic filtration and distillation process[102]. First the mixture of helium-3 and helium-4 is cooled in cryogenic piping outside Freyr's hull, which allows heat to radiate out into space and pre-cools the helium to near its boiling point. Then the helium mixture is liquefied by adiabatic expansion cooling, and the resulting mixture of liquid helium-3 and helium-4 is filtered thermally. This results in a moderately enriched helium-3 and helium-4 mixture, which is then subjected to cryogenic distillation: helium-3 has a boiling point of 3.2 K, one degree K lower than that of helium-4[103]. This difference in boiling points means that it the helium mixture is held at just above the boiling point of helium-3, the helium-4 will boil off faster and helium-3 will be enriched in the liquid left behind. This process is repeated until the desired purity of helium-3 is attained.

Of course, this entire process is extremely cryogenic, dealing as it does with liquid helium, and so it is conducted primarily in the environment of space, in a region of Freyr's exterior shaded from sunlight so that the helium is not heated by solar radiation and the process requires minimal external cooling. It is more convenient, however, to locate the temperature-controlled distillation

process inside Freyr so that the temperature can be precisely maintained at the requisite point. The facilities for helium isotope separation inside Freyr are insulated from the rest of Freyr's interior by five layers of MPET insulation (Appendix C) and are also kept separate by a 1.5 mm sheet of titanium metal to help ensure isolation. Incoming helium is fed past purified helium-4 in a countercurrent fashion to further pre-cool the helium and reduce the amount of cooling required for the process.

Once the helium-3 has been separated from the helium-4, it is bottled into Dewars of 100 L capacity for transport to the Spaceport, where it is placed into cryogenically insulated storage tanks for transport on an ETV to LEO.

Delivery

Freyr does not deliver helium-3 to the surface of the Earth, as a default. Instead, in a process that is the converse of materials delivery to Freyr, helium-3 is shipped from Freyr to LEO using an ETV and then picked up by a private firm or a space agency that transports it to Earth's surface after passage through the atmosphere.

In some cases, Freyr may provide heat-shielded containers for the helium-3 to pass through the atmosphere safely without the use of a contractor, but it still collects payment for the helium-3 while the helium is in orbit and takes no responsibility for the delivery of the helium-3 to the surface of the Earth or to the end users.

Note that to deliver one ton of helium-3 to Earth, it is necessary to process 62 million tons of regolith, about the volume of St. Petersburg's New Mariinsky Theatre[104], which is clearly a large but not entirely unreasonable amount. Because each extractor can process 80 cubic meters per load, and 96 loads per Earth day for 14 days, repeated 13 times during the year, an extractor can process 1,400,000 cubic meters per year, or 4.2 million tons per year. To extract one ton of helium-3 per year, it is necessary to have 15 extractors working full-time. At initial capacity, then, Freyr is provided with ten extractors to save on operational and transport costs, and more are built as demand for helium-3 and Freyr's resources increase, with possible upgrades to processing capacity and processing time (due to increased temperature capability, larger mirrors, etc.).

Based on the cost estimate for an extractor delivered to the lunar surface, the initial cost for constructing extractors on the Moon is about $700 million, plus at least two years. Once the extractors are up and running, however, this deficit can be made up in less than three months even as the extractors produce what will become Freyr's atmosphere and the basis of its life support system. Within a year of extractor operation, Freyr will have turned a $3 billion dollar profit, enough to outfit the operation with new extractors and pay for further development.

1.7.5   Volatiles Production

A by-product of helium-3 extraction from lunar regolith is the production of large amounts of volatiles also adsorbed in the regolith. The most common of these are hydrogen, water, carbon dioxide, methane, nitrogen, and helium-4, all of which have uses on Freyr.

Once these gases have been extracted from the regolith during the baking process, they are liquefied during the lunar night, transported to an ISRU, separated, re-liquefied, and then transported to Freyr.

Hydrogen is used as fuel for ETV and LTV use, to be heated in the core of the NTR engines. The lighter the fuel, the greater the specific impulse of these engines is (See 2.2.1 and 2.2.2), so hydrogen is the best possible fuel to use. About 6000 tons of hydrogen is produced for every one ton of helium-3.

Carbon dioxide and methane are used to replenish life support on Freyr and as sources of carbon for organics and plastics manufacture. Because the Moon is carbon-poor, these resources will be invaluable to having a supply of plastics on Freyr. About 1700 tons of carbon dioxide and 1600 tons of methane are produced for every one ton of helium-3.

Nitrogen and water are also used for life support replenishment, and may also be used as the base ingredients for fertilizer when nitrogen is reacted with hydrogen to form ammonia. About 3300 tons of water and 400 tons of nitrogen are produced per ton of helium-3.

Helium-4 has many uses on Freyr: for use in VASIMR engines to maintain Freyr's rotation, as coolant for the LFTR, and if necessary as an atmospheric additive. Helium can also be used to check for leaks and perform many other tasks on Freyr. About 3100 tons of helium-4 are produced per one ton of helium-3.

These volatiles, supposedly a by-product of helium-3 production, are actually incredibly valuable to Freyr. If these were not produced, Freyr would have to expend an additional $80 billion to lift equivalent materials from Earth to LEO, not counting the expense of transporting them to the Moon on an ETV or of purchasing the materials. These savings are realized along with helium-3 production, driving up the return on investment for lunar helium extraction.

1.7.6   Metal Processing

ISRU units process lunar regolith to extract the materials needed for Freyr's construction, maintenance, and exports. Lunar regolith consists of a variety of materials, all rich in materials necessary for the sustainability of Freyr: titanium, iron, aluminum, calcium, magnesium, and other metals are among its chief constituents. These materials are all mixed together in the regolith, often combined with silicon dioxide in covalent crystal structures, making it reasonable for a single large ISRU to extract and process many elements and materials for use on Freyr.

Metal processing is started in ISRU units on the lunar surface, but is finished on board Freyr. This saves the initial cost of transporting refining and purification equipment to the lunar surface and allows for a single central facility for typically high-temperature purification and refining processes, vastly simplifying the process of ISRU operation. Because the materials transported to Freyr include both what goes into the final product and a large amount of oxygen and other elements bound in crystalline forms, there is not an extra transportation cost associated with transport of separated raw materials rather than finished products, which again allows for better efficiency and lower cost for metal processing.

Once metals have been processed on board Freyr, they are either used for construction jobs on Freyr, put towards the construction of spacecraft for exploration or colonization missions, shipped back down for maintenance and upgrades to lunar facilities, or transported to Earth. Because Earth has its own minerals, the last option is almost never used and refined metals are almost always kept on board Freyr or put towards lunar facilities.

Titanium

Titanium is found primarily in the form of titanium dioxide, TiO_2, which is often termed titania. Titanium dioxide is the primary source of titanium here on Earth as well as on the Moon, but conventional refining techniques have trouble separating the titanium from the oxygen it is bound to.

TiO_2 is found mainly in the lunar maria: specifically, in a mineral called ilmenite, which is composed of 53% TiO_2, 44% FeO, 2% MgO, and 1% other compounds by mass[105]. This mineral makes up about 20% of the Apollo samples from lunar maria, indicating that it is widespread and available at and near the surface - both attractive properties for a fledgeling mining operation.

Ilmenite, due to its iron content, can be separated from lunar minerals like SiO_2 by magnetic means, which provide a cheap and practicable way to obtain nearly pure (>98%) ilmenite from a sample of lunar regolith[106] This ilmenite is then further processed within the ISRU facility as it goes through a 950 °C oven in a process called roasting, which facilitates the magnetic separation of its components[107]; the ilmenite is then separated by magnet and the different components are stored for transportation to Freyr by LTV.

Once the TiO_2 extracted from ilmenite arrives on board Freyr, it is taken to the central core, where metal refining occurs close to the LFTR to take advantage of high-grade waste heat and to provide a centralized area for high-heat metal processing. To extract Ti from the TiO_2, the titanium dioxide is passed into a molten oxide electrolysis cell, which heats the TiO_2 to its melting point of 1843 °C and uses an electric current to drive a reduction-oxidation reaction that produces oxygen gas and titanium metal[108]. The titanium is deposited on the collection cathode, while oxygen gas collects as bubbles at the anode. This process avoids the use of chlorine and other elements that are toxic and very rare on the Moon and ensures that the only products of the reaction are titanium metal and oxygen, both of which are useful to Freyr and can easily be used on board.

$$TiO_2 + 4e^- \rightarrow Ti + O_2 + 4e^-$$
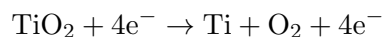
Titanium that has been extracted from TiO_2 using molten oxide electrolysis can then be cast into bars, shaped into structural plates, or otherwise worked to be useful in the various applications Freyr has for titanium.

Iron and Steel

Iron, like titanium, is extracted from ilmenite. While free iron does exist on the Moon[109], it is rare, and a far better source of iron is ilmenite ore.

The ilmenite ore is obtained identically to that used for titanium processing, but the mechanism for extracting iron from FeO is somewhat different. A slightly endothermic reaction between FeO and H_2 proceeds as follows in the presence of heat:

$$FeO + H_2 \rightarrow Fe + H_2O$$
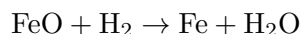
This reaction becomes exergonic at all values of K according to the estimation $\Delta G = \Delta H - T\Delta S$:

$$\Delta G = (0 - 285.83 - [0 - 271.9]) - T\frac{188.83 + 27.15 - [130.58 + 60.75]}{1000}$$

$$0 > -13.93 - 0.02465\,T \implies T > 0\,K$$

Standard thermodynamic values are provided below[110].

Table 1.16: FeO + H_2 Redox Enthalpies and Entropies

	Std. Enthalpy (kJ/mol)	Std. Entropy (J/mol-K)
FeO	-271.9	60.75
H_2	0	130.58
Fe	0	27.15
H_2O	-285.83	188.83

This reduction by hydrogen method is impractical for titanium processing due to the highly positive ΔG of the corresponding reaction of hydrogen with titanium dioxide; standard thermodynamic values are provided below for comparison.

Table 1.17: TiO_2 + H_2 Redox Enthalpies and Entropies

	Std. Enthalpy (kJ/mol)	Std. Entropy (J/mol-K)
TiO_2	-944.7	50.29
H_2	0	130.58
Ti	0	30.76
H_2O	-285.83	188.83

It is clear from this table that the reaction will be unfavorable because ΔH_{rxn} is so positive. Calculations show that this reaction becomes exergonic at $\Delta G = \Delta H - T\Delta S$:

$$\Delta G = (-285.83 + 0 - [-944.7 + 0]) - T\frac{(188.83 + 30.76 - [130.58 + 50.29])}{1000}$$

$$0 > 658.87 - 0.03872\,T \implies T > 17016\,K$$

Because this reaction would have to occur at 17000 K to be favorable, it is safe to say that it is not a practical way to separate titanium and that molten oxide electrolysis is a much better more practicable method.

Once iron has been separated from oxygen via hydrogen reduction, it may be smelted into the required shapes or exported as raw iron. Iron may also be alloyed with carbon in Freyr's single-batch blast furnace to produce medium-carbon steel, but because it is currently unknown whether large amounts of carbon exist on the Moon, steel production is not anticipated to be a large component of Freyr's economy[111]. Low-carbon steel, on the other hand, may be possible given that small amounts of carbon dioxide or monoxide may be released during ^{3}He processing because they are bound in the same rocks as the helium.

Aluminum

Aluminum will be valuable to Freyr due to its light weight, high strength, and good conductivity[112]. Aluminum can also be worked easily, making it desirable for milling-intensive operations on Freyr.

Aluminum is readily available in the lunar regolith as anorthite, which has the chemical formula $CaAl_2Si_2O_8$ and is therefore approximately 19% Al by mass[113]. Apollo 16, which landed in a highlands area of the Moon, observed anorthite concentrations typically between 75% and 80% but varying up to 98% pure anorthite, a clear indication of anorthite's abundance on the Moon and especially in the lunar highlands.

Unfortunately, anorthite is more difficult to process into aluminum than bauxite, the most common source of aluminum on Earth. Bauxite can be refined into aluminum through a combination of the Bayer process, which produces alumina (Al_2O_3), and the Hall-Heroult process, which reduces alumina into aluminum metal and oxygen gas[114]. Because anorthite contains more metals that just aluminum and because of the difference in how the two minerals bind with silica in regolith, anorthite must be processed a different way.

Anorthite can be processed into oxygen gas and aluminum, calcium, and silicon by means of the FCC Cambridge Process, which electrolyzes anorthite in a bath of molten calcium chloride. This process is similar to the molten oxide electrolysis process for titanium extraction, but reduces all the oxidized elements in anorthite, resulting in a mixture of aluminum, calcium, and silicon. These elements are easily separated once they have been precipitated out at the cathode by means of fusion separation (selective melting)[115]. The total process operates at 550 to 850 °C and is more energy-efficient than existing processes in terms of energy expended per kilogram of aluminum produced.

This process is carried out in proximity to electrolytic titanium extraction so that heat can be exchanged between the two processes to reduce incident power load to run the processes. Consolidating the molten salt electrolysis in one place also helps to contain the high-temperature conditions required and makes it possible to power both reactions with waste heat from the LFTR, further increasing efficiency and reducing the electrical load on Freyr.

Once anorthite has been separated and aluminum has been produced from the metal precipitate, the aluminum is used for fixtures of construction on board Freyr, is shipped down to the Moon for construction there, or is used for spacecraft construction. Unlike titanium, there is no economic reason to export aluminum to Earth due to the ease of aluminum extraction on Earth and its low cost.

Aluminum may be less suitable for exterior applications, whether on Freyr, on the Moon, or on a spacecraft, because of its high coefficient of linear expansion, which places extra stress on components and makes aluminum less desirable for wide-temperature-range applications. As an interior structural member, however, aluminum is incredibly useful due to its light weight, high strength, corrosion resistance, and a host of other processes. It is particularly suitable for interior detailing, fixtures, and appliances.

Thorium

Thorium is one of the most desired metals on the Moon. It is mainly present on the near side of the Moon, with the exception of the Compton-Belkivich thorium anomaly[116], and is present at about 13 ppm over a large area of the near side of the Moon. This is the same area where iron and titanium are concentrated[117], meaning that thorium extraction is relatively economical through processing of soil to extract iron, titanium, aluminum, and other metals. Due to its relative scarcity, however, thorium is not mined independently, but rather extracted as a by-product of other extraction processes. This allows the processing of a large amount of lunar soil for extraction of thorium without incurring the expense and difficulty of processing vast quantities of lunar regolith simply for their thorium content.

On Earth, thorium extraction is relatively difficult because thorium combines easily with other elements, meaning that it takes a good deal of work to separate out thorium[118]. On the Moon, however, thorium is mostly found in close proximity to KREEP (potassium, rare-earth elements, and phosphorus)[119], and due to the underoxidation of the Moon's surface[120], thorium is found less tightly bound to other minerals, simplifying the separation process.

An additional advantage of lunar thorium over earthbound thorium is that on Freyr, the equipment is already set up for molten salt electrolysis, which is indiscriminate in what it metals it reduces. This process works for thorium just as easily as any other metal, and produces metallic thorium in addition to aluminum, titanium, or any other metal it is used with. Specifically, anorthite tends to contain small amounts of thorium in addition to aluminum, calcium, and silicon, and so is a slow but steady source of thorium for Freyr.

The main drawback to thorium is that because it is so rare, it cannot be produced in the same massive quantities as aluminum, titanium, iron, or other metals. Freyr does not, however, use thorium in massive quantities, so this is not a huge problem and does not pose an obstacle to Freyr's development. It does place limits on the construction of new nuclear reactors, but new reactors are not required commonly and can be assembled using the uranium produced from thorium that has been gathered from lunar regolith over a long period of time.

Rare Earths

Rare-Earth elements, often found in conjunction with thorium, are also to be found on the Moon. Studies suggest that the Moon contains large amounts of tantalum, europium, and other rare earth metals[121], which would be produced along with thorium at the end of the refining process of aluminum, titanium, and other lunar metals.

Europium, tantalum, niobium, and other rare earth metals may be very rare across the Moon's entire surface, but asteroid impacts have greatly disrupted the Moon's magma processes in the past, says Leonard David[122], and these disruptions have almost certainly caused rare earth metals to become very enriched on the local level in some places. Specifically, the Western part of the Moon's far side seems to be rich in rare earths.

Because rare earth metals are often found near or directly with thorium deposits, it is very reasonable to expect that thorium processing operations will also turn up rare earth elements, which can then be purified, separated, and used in Freyr's operations.

Additional testing and survey work is required before it is clear what exactly the Moon holds in terms of rare earth metals, and how feasible it will be to extract them[123]. This exploration will require at least some feet on the ground for drilling cores, but NASA expects that they will find highly concentrated rare earth metals in and around impact craters, especially on the far side of the Moon.

Rare earth metals are very valuable for Freyr because of their unique properties. Tantalum, for instance, makes an excellent first layer in a "Graded-Z" style radiation shield, used on Freyr and on manufactured spacecraft to deflect radiation[124], while neodymium is used in powerful magnets and lanthanum is used in hydrogen storage systems[125]. The wide range of uses for these rare earth elements and the relative ease with which they are produced by Freyr's mining operations leads to rare earths being a powerful force in Freyr's economy.

1.7.7   Ceramics

While metals are very useful on Freyr and do provide solutions for many material requirements, there are jobs that metals cannot perform, especially high-temperature functions and insulation. Ceramics, especially "advanced ceramics" composed of pure carbides, nitrides, oxides, and others, are very hard, have low thermal conductivity, are resistant to corrosion, and are relatively lightweight[126], making them very useful for many jobs on board Freyr.

Additionally, ceramics are made from plentiful raw materials and are not only harder but also stiffer than steel and other metals and alloys. One particular class of advanced ceramics, called Sialons or O-Sialons, has outstanding thermal properties and can be shock-heated and cooled for many cycles with very little thermal damage or structural decay. This makes them particularly useful for smelting operations and for channeling molten metals[127].

SiO$_2$

SiO$_2$, silicon dioxide or silica, is present in great amounts in the lunar regolith. The average concentration in lunar soil is about 45 wt. %[128], and silica can be easily extracted as a by-product of titanium, aluminum, iron, and other lunar metals. This makes it not only easy to extract but also easy to find in the lunar regolith.

Silicon dioxide can be used in many applications, including turbine blades with complex cooling channels, structural components of spacecraft and stations, high-temperature containers for plasma or nuclear fuel, and high-strength glass[129]. Many components on Freyr are composed of SiO$_2$ or ceramics containing SiO$_2$, lending a variety of advantages to the station.

Silicon dioxide can be extracted from anorthite by reacting silicon produced in the FCC Cambridge process with oxygen gas that is evolved during electrolysis. This technique, however, results in a large amount of energy usage for the same amount of SiO$_2$ produced and is thus less favorable than simply using slightly purified anorthite itself.

Anorthite can be gathered from the lunar surface using a magnet, and then FeO and other oxide contaminants can be extracted using chemical methods. The resulting substance can be directly fused into a form of aluminosilicate glass lacking a few of the trace constituents. This aluminosilicate glass has a density of 2.46 g/cm^3, a Young's modulus of 72.05 GPa, a high shear modulus and bulk modulus, and an ultimate yield strength comparable to pure quartz[130], providing excellent properties for vacuum windows and high-performance glassware. Because this substance can be easily and cheaply made from abundant lunar regolith, it is an extremely attractive material for Freyr's use and is used in many applications on board. It is, for example, used for the viewing ports in pressure doors and for windows that look out onto vacuum; these are especially important for viewing docking operations, observing external repairs, and keeping track of external activities.

SiO$_2$ is fused into quartz crystals for use in nuclear thermal rocket engines, high-temperature fittings for nuclear reactors, low-cost crystal abrasives, and extremely hard cutting edges, for example.

CaO

Calcium oxide can also be refined from anorthite, and when applied as part of a glaze of flux it imparts extra strength and a matte finish. It can be used to protect a glaze or finish against corrosion due to its good corrosion resistance[131]. Calcium oxide is also used in the production of durable ceramics, but is not itself useful in this capacity because it tends to react with atmospheric carbon dioxide until it forms calcium carbonate, CaCO$_3$[132].

Calcium oxide can also be used as a component of Portland cement, which is essentially composed of silica, alumina, and calcium oxide[133]. While this is useful for lunar uses, it is not economically or physically useful to transport cement to Freyr.

Anorthite

Anorthite ceramics can be fired from pure anorthite powder, resulting in a strong substance that does not absorb water and is fairly lightweight. Kobayashi and Kato (2013) found that firing at 1000 °C resulted in a material 94% as dense as water but with nearly zero water uptake[134], which could be very useful for structural and functional purposes on board Freyr. Anorthite ceramics can also be used as components of silicate ceramics, ceramic fibers, and other applications.

Ceramic Uses

In addition to the uses mentioned above for ceramics produced from lunar minerals, Freyr has several other uses for advanced ceramics.

Ceramics are used for laser manufacturing, dynamic RAM chips, piezoelectric crystals[135], chemically-resistant nozzles[136] for use with corrosive, high-temperature, or abrasive fluids, crucibles, bearings, rotors for spiral pumps[137], dental work, and a vast variety of other applications[138], all of which Freyr will almost certainly have a need for.

Ceramics could be used in the nozzles of rocket engines, as insulating material to prevent heat loss from high-temperature systems, to produce knives that hold an edge for longer and are harder than steel or other alloys, and for extremely hard cutting edges. While it is unknown what uses Freyr and its inhabitants may find for ceramic components, Freyr's ceramic manufacturing capability ensures that they will have the capacity to produce the ceramic required.

1.7.8 Perfect Crystals

Perfect crystals are called perfect because they contain no defects, in this case due to the absence of gravitational stresses on the forming crystal. This means that they exhibit many properties not typically observed in crystals, or enhanced qualities that are also present in flawed crystals.

Note that when talking about defects and flaws in this case, the intended meaning is nano-scale flaws that may be invisible to the eye or microscope.

Perfect crystals grown in the Spaceport can be mass-produced fairly easily and then exported to Earth, used for research on board Freyr, or put into service on Freyr. The large range of applications for perfect crystals means that Freyr's capacity to produce them will be in high demand.

Production

The production of perfect crystals varies, but many techniques utilize melts that are then slowly allowed to crystallize. Other methods could include gradual deposition (electroplating or precipitation; electroplating will work better).

These processes will work with many crystals, including semiconductors, metals, oxides, carbides, nitrides, and other materials. While they can be carried out in macro-gravity environments, higher

quality crystals are obtained by microgravity manufacturing and much less infrastructure is required.

Perfect crystals are produced in the Spaceport.

X-Ray Diffraction

Perfect crystals are very useful for X-Ray Diffraction analysis because their consistent planes and crystal structures generate highly precise XRD images. Additionally, perfect crystals of complex molecules can be used to determine those molecules' shapes more easily and to characterize samples effectively.

X-Ray Diffraction works on the principle that certain angles reflect well off of crystal planes (basically), so it's not difficult to see why perfect crystals are preferred: all the planes line up.

Structural

Perfect crystals often have desirable properties that can be marred by impurities in the crystal, such as a high bulk modulus, good resistance to shear forces, and many other useful properties. Components made from perfect crystals could be used in small-scale load-bearing applications, especially in scientific equipment that requires a highly predictable background signature.

1.7.9   Spacecraft Fabrication

A major sector of Freyr's economy depends on being the primary departure site for space exploration. Freyr has the capability to manufacture spacecraft and probes for launch to Earth orbit , other planets, Sun observation, or beyond the outer planets. These missions may be manned or unmanned depending on the requirements; Freyr has the capability for either.

To facilitate spacecraft construction, Freyr has isolation capabilities at the end of the central core opposite the thorium reactor. Spacecraft components are assembled inside the core cylinder, then moved to the central axis and released into space through an airlock. Construction of larger spacecraft is carried out outside Freyr, while small spacecraft may be released from the airlock in one piece.

Probes

Freyr is an ideal place from which to launch probes for multiple reasons. First, its location outside Earth's atmosphere means that no expensive booster stage is required; probes can be constructed and launched directly with very efficient electric engines. Additionally, Freyr's location in space makes isolation and sterilization much easier than it is on Earth, and Freyr's orbit means that significantly less ΔV is required than a launch from Earth's surface would require. Launching from

Freyr, moreover, allows probes to be built in the optimal spaceflight configuration, rather than being constrained by the necessity to fit inside a certain fairing.

Probes manufactured on Freyr are powered by either solar panels or RTGs, depending on their destination (probes to Jupiter and beyond are typically powered by RTGs due to low solar flux) and are propelled by Hall effect thrusters with a specific impulse of 5000 seconds that utilize xenon fuel. Xenon is available in lunar regolith and is cheap enough to be economical for space probes. The high specific impulse of these thrusters ensures maximal ΔV on missions, but the trade-off is in lower thrust; this compromise can be avoided by means of a boost from a manned mission utilizing an NTR engine for greater acceleration early in the probe's trip.

Launching probes from Freyr carries another benefit as well: with no chemical stage, and no volatile fuel or major moving parts, launch incidents and probe damage are all but unheard of. This increases the probe success rate. Ultraclean conditions on Freyr are maintained by the vacuum of space and by special isolation chambers, avoiding contamination of the probe's instruments by foreign particles or other materials.

Manned Missions

Manned missions launched from Freyr carry many of the same benefits as probe launches, with some additional benefits. Launch from Freyr, once again, reduces required ΔV by a huge margin, and returning used spacecraft to Freyr for refurbishment is much easier than repair in LEO and preserves the expensive spacecraft for future missions. Furthermore, due to the large mass and physical size of manned missions to other planets, assembly in orbit is required; no foreseeable launch system is capable of lifting hundreds of tons of material into orbit. Construction just outside Freyr, where structural components are available for support and control, is much easier than standalone construction in LEO; moreover, the controllable environment just outside Freyr allows better reinforcement of spacecraft.

Manned spacecraft consist of several sections: mission-specific components, lifeboat capsule, passenger/crew quarters, and a service section including life support, power, and propulsion. The mission specific components and lifeboat have their own secondary power supplies. Depending on the specific mission, different components for each section are used from a stock selection to reduce cost. All components use a standard connection and docking system to ensure compatibility and reduce mission cost by allowing production of standard components.

The human habitable modules must, of course, provide a breathable atmosphere, food and water, and radiation protection for their occupants. Due to the shorter timeframes and smaller scales of these missions, no attempt is made to provide a social structure other than a military-style hierarchy and there is no possibility of providing artificial gravity for the spacecraft's crew. These exceptions to rules that Freyr must follow simplify the design of manned spacecraft for exploration missions, but the remaining considerations nevertheless provide a great level of technical complexity.

Lifeboat. The manned spacecraft all include one or more lifeboat capsule(s) that are capable of sustaining the astronauts for a limited period of time should something go wrong with the craft as

a whole. Lifeboats are also used as permanent bedding areas for the crew, eliminating the need for extra sleeping areas and simplifying design. An additional benefit of sleeping in lifeboat capsules is that the lifeboat can be sealed at night, providing greater security against a depressurization of the primary spacecraft.
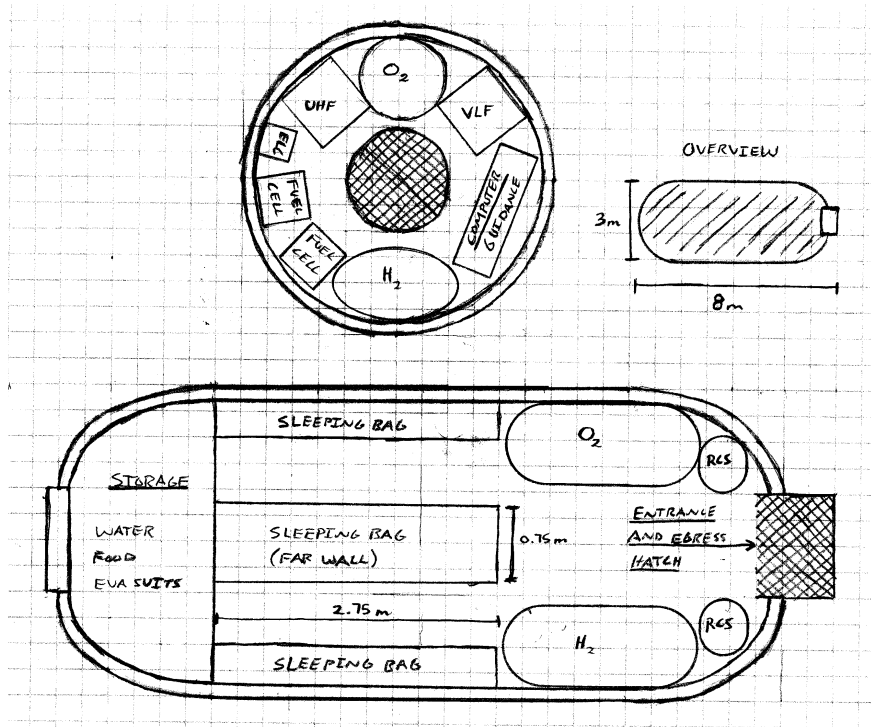
Figure 1.15: Lifeboat Design

Each lifeboat has dimensions of 8 meters length by 3 meters diameter, providing cramped but livable conditions for four humans. It contains a 50 liter tank of LOX and a 100 liter tank of LH_2 to be used in a fuel cell electrical system or, in extreme emergencies, used as propellant by passage through an expansion manifold, and LiOH canisters for CO_2 management. It is equipped with both a VLF antenna for communications with Freyr and a UHF system for communication with other lifeboats or local spacecraft. The lifeboat does not have an airlock, but instead must be depressurized for each EVA and then re-inflated with oxygen from its stores.

In an emergency, lifeboat modules are intended to be temporary reprieves from a difficult situation. They do not have enough oxygen, electrical capability, or propulsion to return to Freyr or Earth; instead, they let crew members plan and carry out the repair of the primary vessel. If the primary vessel has been compromised beyond hope of repair, it is understood that the lifeboats will not save the crew.

Depending on crew size, multiple lifeboats may be attached to the spacecraft so that every crew member has a spot in a lifeboat. That is, two would be used for a crew of six, five for a crew of seventeen, and etc.

123

Mission Specific. "Mission specific" components may range from a lander to the initial components for a permanent base, or may simply be probes that can be deployed precisely on a planet/moon or in orbit. While these probes could potentially be launched directly from Freyr, carrying them on a manned spacecraft allows precise control over eventual placement and helps to place them into optimal locations for data collection and site evaluation while allowing human evaluation of the system and its characteristics.

It is expected that most manned missions will include a lander or outpost, as these are the only activities that truly cannot be completed robotically. Some objects, however, may be deemed interesting enough for specialized human exploration or rover/lander-assisted human exploration.

Life Support. Life support on manned spacecraft is mainly provided by the service module, although some life support functions are contained in the crew habitation areas. Life support includes food, water, radiation protection, breathable atmosphere, heat, and cleanliness.

Food is provided for the crew by one of two methods. For small missions, food for the trip is stocked in nonperishable supplies, while for larger missions aeroponic facilities are used to supply food. Additional food can be provided by the Spirulina algae used for atmospheric maintenance. Food is stored and produced inside the crew habitation module(s).

Water is stored inside the crew module(s). A tank made of aluminum contains 155,000 liters of water and a hollow area, providing 113 cubic meters of space with great protection from radiation. Water is recycled from urine and greywater through a reverse osmosis process in the service module, and the filtrate is used to provide growth nutrients for the algae or are stored in a separate tank inside the service module.

Radiation shielding is provided by several systems throughout the spacecraft. The habitation module(s) and lifeboats have an outer skin of graded-Z shielding[139], which is much more effective than a single, thicker layer of material at preventing radiation passage due to the successive Compton scattering of radiation off of successive layers of the shield with lower Z-values (Z is the atomic number of the material). This shielding is 12.5 cm thick on both the lifeboats and the habitation module(s). Additional shielding, for extreme cases such as solar flares and CMEs, is provided by the water storage tank, which puts an additional meter of water in between the crew and the exterior radiation. Because water is high in hydrogen, it is quite effective at shielding against ionizing radiation, and one meter of water reduces incident radiation by 47 times, allowing through only 2.1% of incident radiation. This provides greater protection for the crew during days-long CME events that would otherwise impart unacceptable levels of radiation.

An atmosphere that the crew can survive in is maintained in manned spacecraft the same way it is maintained on Freyr: with Spirulina algae that photosynthesize carbon dioxide and water into glucose and oxygen. For very short-term missions, this process may not be necessary, but all missions outside of the Earth-Moon system make use of such a system because of its time-cumulative benefits over an LiOH system or comparable chemical system. However, in the absence of gravity special methods are required to ensure CO_2 saturation in the algae tanks. In a gravitational or pseudo-gravitational field, carbon dioxide can be simply bubbled through the algae tanks, but in μg bubbles do not propagate, but rather hang in solution. To solve this problem, CO_2 is dissolved

in the water to create a saturated solution of carbon dioxide. The increased levels of dissolved carbon dioxide in this system are required to achieve comparable metabolic production but cause problems because of the following reaction:

$$CO_2 + H_2O \longleftrightarrow H_2CO_3$$
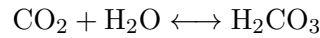
This substance, carbonic acid, lowers the pH of the solution, which can kill algae and poison the life support system; to counteract this problem, a small amount of sodium bicarbonate, $NaHCO_3$, is introduced into the solution. Sodium bicarbonate acts as a buffer and further reduces carbon dioxide conversion into carbonic acid via the common-ion effect. Additionally, the algae tanks must be essentially flushed of air to ensure good circulation and to prevent pump degradation.

Heat for the crew is provided by waste heat extracted from the S-CO_2 used in the reactor's Brayton cycle between the expansion turbine and compressor. This heat is low-grade (<100 °C), meaning that it can be used to heat the crew areas or for tasks such as heating water for bathing but is unsuitable for use in chemical reactions, cannot be efficiently dissipated in radiators, and cannot be used to boil or sterilize water. Electricity can be used for these purposes, or waste heat can be channeled from another, hotter part of the S-CO_2 cycle.

Cleanliness is an absolutely critical requirement for manned space missions. Fragments of food, droplets of liquid, or general debris can easily clog vital equipment, and properly dealing with human waste avoids sanitation hazards. One of the most critical functions, apart from constraints to keep debris from flying about, is water purification. Without water purification, urine and other wastes cannot be recycled, requiring thousands of kilograms of water to be brought for even relatively short missions. To avoid this and help produce a closed-loop life support system, manned missions make use of SCWO technology coupled with a reverse-osmosis system to purify water, followed by UV sterilization. Reverse osmosis, or R/O, uses mechanical pressure to force water against an osmotic gradient and through a semipermeable membrane, concentrating impurities on one side of the membrane and allowing pure water to pass through to the other side. 6 kWh of energy is required to desalinate 1000 L of seawater[140], so our system does not require a noticeable portion of the spacecraft's electricity. Note that while the SCWO system is useful for highly particulated water, an R/O system provides a backup and may be more energy efficient during periods of low waste throughput.

Power. Manned spacecraft, in contrast to probes, cannot be put into standby mode; they must continuously provide life support for the crew. This life support requires much more power than running a computer, as humans have a much tighter condition tolerance than machines. It is plain to see that RTGs are not a logical choice for manned spacecraft: their design is not easily scalable, and linking together numerous smaller units is impractical. Solar panels are a practicable alternative, but only for inner Solar System missions (e.g. missions to Venus or Mars) due to radiative flux requirements. Thus, when considering manned missions to the outer Solar System, Freyr has developed a power source that is at once consistent, power dense, and light enough to be practical for interplanetary travel. The solution is a water-cooled liquid uranium reactor coupled to two gas-core nuclear thermal reactor (NTR) engines with an I_{sp} of 1500 seconds. Uranium is available from lunar mining and as a product of Freyr's breeder reactor, at an enriched enough

level to give excellent reactor performance. Manned spacecraft, in fact, utilize a scaled-down version of Freyr's closed Brayton cycle generation system, using an S-CO$_2$ turbine-compressor system to generate electricity.

The size of the power generation system on board a manned spacecraft varies depending on the spacecraft in question, but the service module is built to accept two 28-cm turbine-compressor units, used independently but providing redundancy in the power supply. Each turbine[141] is capable of producing 10 MWe when operating at a pressure ratio of 3.3. The smaller turbine size reduces efficiency, but 40% is still attainable with an S-CO$_2$ system of this size, requiring the rejection of some 25 MW from the spacecraft. One benefit of a smaller turbine, however, is the increased feasibility of energy recuperation by transferring energy from the pre-compressed stream of S-CO$_2$ to the stream after compression, increasing compressor efficiency. This step can increase efficiency to 50%, reducing the power rejection requirement of the spacecraft to only 20 MW.

The use of a liquid thorium reactor leads to several benefits, including the ability to redistribute the nuclear fuel to optimize for electricity production or propulsion. This eliminates the need for fully separate propulsion and power units, leading to lower vehicle mass and increased mass efficiency.

Satellites

There are many advantages to launching satellites from Freyr. Not only do rockets not have to be launched out of the costly near-Earth gravity well, the ΔV from Freyr to GSO or a 12-hour orbit is lower than the ΔV from LEO to those orbits, making in-space maneuvering easier and less costly. Additionally, satellites can be constructed without hinges that weaken the structure, which would be necessary for the satellite to fit inside the fairing of an Earth-launched rocket. A final benefit of satellite launch from Freyr is that multiple missions can be combined into one larger payload due to the ease of launching larger payload from Freyr (satellites are typically limited in scale by the to-orbit mass capability of the launching rocket).

Resupply/Cargo

Once outposts or permanent stations are established on other planets or in their orbits, Freyr will provide resupply and cargo services. These services are provided through vehicles similar to those used for manned missions, but incorporate a robotic control system rather than a human crew. For cargo missions, the service module's life support capability is removed and replaced with a combination of some storage space and a robotic control system for the spacecraft. All components are kept modular; only the interior of the service module is affected.

Configuration Similarly to the manned spacecraft, cargo and resupply craft consist of an aft service module that provides propulsion and power connected to several separate modules. Instead of being configured for human habitation, these modules are configured to allow maximum cargo

space, increasing efficiency. No lifeboat modules are attached to the modules as a standard, but the modules are configurable for lifeboat attachment.

Construction Personnel

For obvious reasons, much of the construction of Freyr's spacecraft must be completed outside the settlement, in the vacuum of space. This allows the use of a smaller and easier-to-maintain airlock, as components can be constructed in vacuum and made into a sturdy structure there. Additionally, it is convenient to assemble modular components into complete vessels outside Freyr because, once launched, the components never have to be brought back through the airlock.

Not all construction can be carried out by drones due to the increased dexterity and decision-making capability of a human on the site. While drones may be constructed that can be operated in complete virtual reality remotely, human operators on EVA will not be made obsolete, especially when it comes to troubleshooting and mobility.

To facilitate spacecraft construction, then, human operators must be able to go on EVA on a regular basis with little preparation. Despite advantages in spacesuits due to switching to an MCP design, some prebreathe time is still required before EVA. To eliminate this requirement, construction workers on an active spacecraft construction job live in a low-pressure pure oxygen environment while on duty, eliminating time-costly prebreathe requirements.
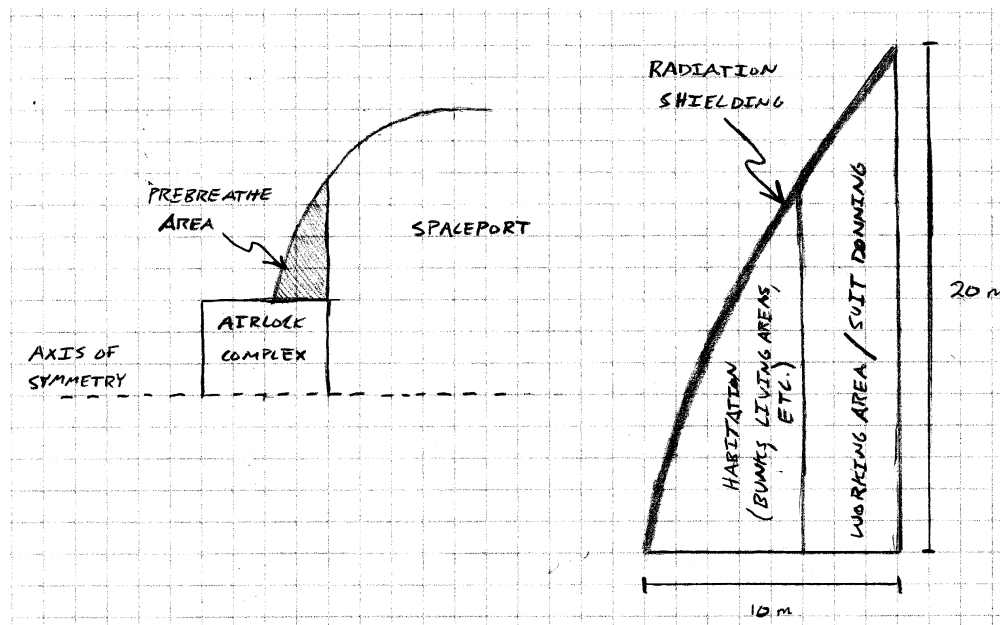
Figure 1.16: Diagram of Prebreathe Environment

There are definite safety hazards associated with life in a pure oxygen environment. Fire and explosion hazards are extremely high, transition back into a nitrogen-oxygen atmosphere can be strenuous, and carbon dioxide concentration is a much greater hazard due to low total pressure. These hazards, however, are manageable with an experienced crew and do not present an insur-

mountable obstacle to short-term life in a pure oxygen atmosphere. The benefits of breathing pure oxygen while on duty for spacecraft construction work far outweigh the risks and drawbacks.

1.8   Communications

For Freyr to be effective economically and to maintain critical contact with spacecraft, lunar stations, and Earth-based facilities, Freyr must have substantial communication systems. To be truly connected, Freyr must be capable of maintaining contact with all of these systems at once, and due to its polar orbit around the Moon, Freyr cannot do this on its own. The solution utilized by Freyr is a network of geocentric and heliocentric communication satellites that collectively maintain lines of sight to the requisite communication targets.

These satellites are relatively small, and are built to service a fairly small communications network. That is, they are not on the same scale as many geostationary communication satellites that are built to provide service for millions of people, but are rather meant to maintain a dozen or two links. These satellites are known as Comsats, and orbit in several locations to ensure complete connectivity.

A typical geostationary telecommunications satellite, SkyTerra-1, has a mass of 5400 kg. It uses a radio reflector dish to provide communications service for millions of cell phone customers[142]. Due to the large size of the necessary radio antenna for interplanetary communications, even without interference from the Earth's atmosphere, the actual receiving antenna cannot be much reduced in size, but with the reduced bandwidth requirements allow the use of antennae manufactured in orbit without the use of a parabolic dish; instead, a grid of high-gain linear antennae may be used to cut down on mass without decreasing communications ability. These satellites can be much less massive and costly than traditional communication satellites, and are much easier to manufacture in orbit.

1.8.1   Comsat Network

Comsats are placed in several orbits to ensure communications with any necessary target. The first to be deployed are placed at the EML1 through EML5 points, with the exception of EML3. The four remaining points have several advantages: stationkeeping is simplified at all of them, but especially at EML4 and EML5, satellites at EML1 and EML2 provide coverage for the entire lunar surface (which can be supported by satellites at EML4 and EML5), the combination of four fixed-position satellites ensures that Freyr and all lunar stations are always in sight of at least on satellite without having to account for the individual orbits of the satellites, and satellites at EML4 and EML5 can provide communications with spacecraft on the far side of the Earth. While EML3 would provide some additional coverage of spacecraft and facilities on the far side of the Earth (one side is the "far side" at any given time), the coverage already provided by the geostationary communications network and satellites at EML4 and EML5 can cover these targets, especially because Freyr can purchase time on existing communication networks.

Subsequent satellites must provide service to settlements, spacecraft, and probes beyond the Earth-Moon system. The primary issue is the problem of solar conjunction between Earth and the target; during a period of conjunction, communications are obstructed by solar interference and, of course, the physical presence of the Sun between the Earth and the communications target. Despite the

relatively rare occurrence of conjunction between any two given bodies, it is necessary to provide communications to a manned settlement or expedition. Obviously, time-lag is still an issue, but that is simply a delay in communications instead of a days-long or weeks-long communications loss. To ensure that conjunction is not a problem for Freyr and its missions, a relay satellite is placed at the SEL5 point, 60 degrees ahead of Earth in its orbit. This ensures that the Sun does not obstruct communications between Earth and any other body by maintaining at least one of the two relay options (Earth and SEL5) in view of the target at all times (the 60-degree phase shift guarantees this).

There are two types of Comsats: laser-based Comsats and radio-based Comsats. Infrared laser-based Comsats have a much greater bandwidth than radio communications (622 Mbps for a single link on LADEE[143] and 6 Tbps on proposed MEO communication networks[144]) and exhibit lower power consumption than radio signals, but are not appropriate for long-distance communication and are thus only used for high-traffic pathways inside the Earth-Moon system. These Comsats are located at the EML1, EML4, and EML5 points.

Radio-based Comsats, unlike laser-based Comsats, bust be registered for a wavelength in the radio spectrum and are capable of long-distance transmissions, albeit at lower data transfer rates. These Comsats are used for communications outside the Earth-Moon system; they are located at the EML2 and SEL5 points. While the lack of a laser-based Comsat at EML2 does limit the bandwidth available to installations on the dark side of the Moon, the relatively low amounts of useful minerals present there means that there will be no need for large bandwidth to be available.

1.8.2   With Earth

Communications with Earth are provided through several means. When Freyr is in sight of the Earth, it is possible for communications to be broadcast directly from Freyr to visible Earth stations, but this is not done for several reasons. This would require Freyr to have quite powerful antennae for broadcast and reception through Earth's atmosphere, and once direct communications were no longer possible, transmissions would be temporarily interrupted as Freyr's communications were shuttled through one of the relay satellites.

Instead, Freyr's communications are always directed through a relay satellite. This means that Freyr does not have to broadcast and receive through Earth's thick atmosphere, while the relay satellites are expressly designed for communication through atmosphere, near planets, and in all manner of conditions. Additionally, the constant use of relay satellites allows for seamless handshake handoffs of communications as one satellite hands communications to another, transitions which are managed by a computer-controlled system.

Communications with Earth are handled by laser-based Comsats.

1.8.3   With Lunar Facilities

Various mining, processing, refining, and production facilities are located on the Moon's surface. These have individual tasks that they must be optimized for, leading to a distribution of facilities

across the face of the moon, with different facilities being located where they are best able to carry out their intended industrial process.

These facilities communicate with the laser-based Comsats at EML1, EML4, and EML5. When Freyr is within sight of the facility, the two may exchange information directly due to the smaller and more interruptible data traffic between lunar facilities and Freyr.

Some lunar facilities may be located on the dark side of the Moon, out of sight of the laser-based Comsats. These facilities communicate through the radio-based Comsat at EML2, which provides somewhat decreased data transmission speed but nonetheless keeps the facility in contact with Freyr and, if necessary, with Earth.

1.8.4   With Vehicles

Communications with vehicles to and from Freyr are accomplished both with Comsats and with communication arrays on Freyr and the vehicles themselves. Freyr does not maintain contact with all vehicles at all times, but it does make contact with vehicles at prescribed points along their trajectory.

Freyr has a scheduled check-in with each vehicle, manned or unmanned, every 48 hours. This is simply routine communications upkeep, and communications can also be established in case on an emergency at other times. Additionally, all of Freyr's vehicles notify the settlement when they are about to make a burn and again when the burn is complete. These are not conversations between the vehicle and Freyr, but instead are targeted packages of data containing telemetry and vehicle statistics.

Freyr maintains several flight zones. Spacecraft within 50 km of Freyr must remain on the official Freyr flight control channel of 101.7 MHz FM for any necessary updates and send telemetry data to Freyr every five minutes; spacecraft within 500 km must file a flight plan with Freyr flight control, and spacecraft passing within 5000 km of Freyr must alert Freyr authorities to their presence. If spacecraft are operating more than 5000 km away from Freyr, no communication is required, but Freyr maintains a communications channel for communications with these spacecraft.

If a vehicle is coming in for docking, it is first handled by the central Freyr flight control, then handed off to docking officers at the particular docking port once it is within two hundred meters of the target. Docking officers then guide the vehicle into its final course adjustments and inform the pilot about the proper course to take for a successful docking. Below is a transcript from a typical approach, featuring an ETV that breaches the 50 km barrier.

[ETV CLOSES TO WITHIN 50 KM OF FREYR]
ETV Commander: Freyr control, echo tango victor zero three requesting guidance interface, over
Freyr: echo zero three, go ahead, over
ETV: range is five zero clicks, bearing eight five decimal seven by zero two decimal one, closing velocity plus two five decimal seven, over
Freyr: roger that, we have you on instruments, continue on present course and maintain radio

presence, over

[GAP IN COMMUNICATIONS]

ETV: Freyr control, echo zero three, range one zero clicks, requesting final approach and docking procedure, over

Freyr: roger, echo zero three, decrease closing velocity to one zero decimal zero and await further instruction, over

ETV: roger, decreasing closing velocity to one zero decimal zero, over

[GAP IN COMMUNICATIONS]

Freyr: echo zero three, proceed to airlock four at plus two four zero, decrease closing velocity to zero three decimal zero, over

ETV: roger that, setting course for airlock four at plus two four zero and decreasing closing velocity to zero three decimal zero, over

[GAP IN COMMUNICATIONS]

Freyr: echo zero three, transferring you to foxtrot romeo alpha four control, over

ETV: foxtrot romeo alpha four, echo tango victor zero three, request docking instructions, over

Airlock 4: echo zero three, reduce closing velocity to zero on my mark, three, two, one, mark, over

ETV: closing velocity is zero, over

Airlock 4: roll to zero three zero, over

ETV: rolling to zero three zero, over

Airlock 4: translate at zero nine zero to zero zero decimal one, over

ETV: translating to zero nine zero, zero zero decimal one, over

Airlock 4: expect contact in four six two, over

ETV: roger that, four six two, over

Airlock 4: range is two five decimal zero, we are go for docking, over

Airlock 4: range is one zero decimal zero, we are go for docking, over

Airlock 4: range is zero five decimal zero, final decision is go for docking, over

Airlock 4: echo zero three, you are docked and secured, hard seal, over

[END COMMUNICATIONS WITH DOCKING CONTROL]

Note that after initial contact is made, "echo tango victor" is shortened to merely "echo"; Freyr's airspace is not busy enough to have more than one craft with a designation that could reasonably be shortened to "echo zero three."

Communications with unmanned spacecraft are not so two-sided, and consist of data and commands in compressed binary format rather than voice or even video communication to save bandwidth and for ease of signal processing by the spacecraft.

1.8.5 With Other Planets and Stations

Freyr maintains communications with other planetary bases, orbital research stations, and settlements as well. These communications are, by necessity, somewhat different that communications with facilities close to Freyr or with Freyr's vehicles. Instead of having any hope of keeping up a con-

versation, messages are cached on board Freyr and in the computers of the corresponding station, settlement, or base, and then sent in a single coherent packet to maximize network efficiency.

Freyr communicates with these stations through the relay satellites at SEL_4 and SEL_5, which are already equipped with long-range transmit/receive antennae. Packets are sent via a directional antenna aimed by a computer that optimizes the transmission for the direction of the target facility.

Each of these larger units is given its own unique two-letter callsign. Two letters is convenient for relatively fast and easy transmission and speech, while the combination of two letters allows for 676 unique settlements, stations, or bases before the naming convention has to be revised - and allowing numbers into the convention would raise this number to 1296 while hardly changing the system. For example, Freyr is "FR," while the ISS might be "IS" and Skylab could have been "SL" or "SK" depending on which name was available and what the inhabitants preferred to set as their callsign. While it is, admittedly, hard to come up with a name that can be addressed as "XQ," the Zebulon Pike Research Station would have the callsign "ZP," certainly a strange one, and the different iterations of Mir could have been called, for example, "M1", "M2", etc.

Messages are prefaced with this callsign, both to route the message and to ensure that the recipient knows who the message was for. Within this message protocol, individual messages can be bundled into a large packet without losing their own coherence, allowing discrete chunks of the overall message to be private (and potentially encrypted) communication.

1.8.6   Bandwidth

Communications on Freyr must have large bandwidth to supply 20000 people with information and to communicate with numerous other facilities. Because Freyr is intended as a permanent method of settling space, it is worthwhile to link Freyr to the Internet on Earth (or at least part of it).

This requires a large amount of bandwidth - not a problem on Earth because of the high data transfer rate of fiber optic cables (2.5 GBps in a single cable strand[145]), but it's not possible to connect to Freyr with fiber optics.

Instead, Freyr uses optical data transmission with lasers, mentioned above in 1.8.1. This system, as implemented on NASA's LADEE spacecraft in 2014, demonstrated downlink speeds of up to 622 Mbps and uplink speeds of up to 20 Mbps; another spacecraft, LCRD, is projected to have uplink and downlink capabilities in excess of 1.2 Gbps from LEO[146].

Considering that perhaps 10% of Freyr's population could reasonably be simultaneously using the uplink/downlink system on board, Freyr must have the capability to support some 2000 connections. Not all of those connections will be constantly active, however, and there could be a maximum of approximately 400 requests per second. Based on current trends, it is likely that a website will be about 3000 KB by the time this network is operational, and could be larger. Freyr therefore should have the networking capability for an uplink of at least 15 GBps, although downlink will not be such a large concern.

These transfer speeds will be attainable with advances in technology and with several transmissions arrayed in parallel. To ensure connectivity, transmission stations are located on the top and bottom of Freyr, allowing both for easy maintenance due to low "gravity" and for connectivity no matter Freyr's orientation. Because the transmission is done with light instead of radio signals, it cannot penetrate Freyr itself; there must be a line of sight between the transmitter and the receiver.

Clearly, connection will be faster when Freyr is on the near side of the Moon and slower when it is on the far side.

The 15 GBps channels for civilian communication are augmented by dual official communication channels, each with a capability of 2.5 Gbps. These are arranged in an N+1 configuration to ensure that communications are not lost, and are separated from each other by distance to keep any single event from destroying both channels. These channels are used to relay diagnostics, spacecraft communications, and other information between Freyr, Earth, and other space-based facilities, and are by default encrypted using 4096-bit RSA (varying levels of encryption are also available for civilian use).

Freyr's communications with spacecraft at close range are accomplished using radio signals because the only necessary signals are some telemetry data and voice (video is possible but poor-quality). The lower bandwidth of these radio signals is acceptable because of the much reduced volume of traffic on the channel. Freyr uses one 500 MHz channel for general flight control, with individual docking ports having their own VHF frequencies between 40 and 41 MHz. The bandwidth of these channels is, again, much lower, but the information to be transferred is also much smaller.

1.9 Maintenance

Freyr's maintenance is an extremely important part of its operation. Various systems must be constantly maintained to avoid failure, which would be catastrophic for Freyr and its inhabitants.

Maintenance on Freyr can be generally classified as either interior or exterior. Almost all of the interior maintenance is carried out by humans, with some assistance from automated systems. This prevents the need for an overly complicated robotic system that would just fail anyway.

The Structural A subteam is responsible for interior repairs, although Structural B members may be recruited for large projects.

Much of the exterior maintenance on Freyr is carried out robotically, with camera-equipped drone spacecraft that can be controlled remotely. For more information on these, please see 2.2.3. Of course, there is some maintenance that drones cannot perform, or that humans are simply better at. For example, any project that involves detailed construction is done by humans on EVA, and any major repairs are also done by humans. In short, drones are used for inspections and to perform basic repairs so that no humans have to venture outside Freyr.

The Structural B subteam is responsible for these EVA missions, although Structural A members are also trained for EVA and may be recruited for large projects.

1.9.1 Personnel

The Structural A subteam is divided into squads that each have their own smaller set of responsibilities. This helps to ensure a high level of performance on each repair, because the person who is performing the repair is able to focus on that specific process. These are the Pressure Squad, the Mechanical Squad, and the Structures Squad.

The Pressure Squad is responsible for keeping the pressure in each torus at the required level. It also monitors for leaks using automated sonic equipment and fixes what it can from the inside. it also monitors atmospheric composition and cooperates with the Life Support subteam to ensure that all habitation systems are functioning properly.

The Mechanical Squad is responsible for general interior machinery. The cable elevators, wireless and wired networks, most piping and shafts, and other mechanical services are all their responsibility. This squad is the nuts and bolts of keeping Freyr's interior from falling apart internally and is the largest squad in Structural A.

The Structures Squad is responsible for maintaining the integrity of structures inside Freyr's hull. For example, it ensures that each of the decks of the Life Support/Habitation torus is properly braced and supported, and inspects the Industrial torus to make sure that machinery is safely stabilized.

Likewise, the Structural B subteam is composed of several units: the Drone Squad, the Flight Ops Squad, the Repairs Squad, the Construction Squad, and the Sensors Squad. Each of these

has a different responsibility when it comes to making sure Freyr stays flying and structurally sound.

The Drone Squad operates inspection drones and keeps tabs on any potential problem sites on the exterior of the hull. Its primary job is to discover potential problems before they happen so that the Repairs Squad can fix them. This is one of the smallest squads due to the fact that the drones are doing most of the work.

The Flight Ops Squad carries out maintenance, repairs, and updates to the sections of the Spaceport involved in docking and undocking as well as any spaceships that are currently docked to Freyr. This includes refueling, checking connections and struts, maintaining airlock functionality, and managing umbilicals to spacecraft.

The Repairs Squad fixes any problems with the structure of the outside of Freyr. Micrometeoroid impacts are not expected to be a problem, but general wear and tear or equipment failure (e.g. broken attachment rod) would be the responsibility of this squad. This is one of the few groups on Freyr explicitly authorized to go on EVA, along with most of the rest of Structural B.

The Construction Squad carries out new construction on Freyr and on ships help externally. For example, it utilizes the parts for spacecraft passed through the airlock and assembles them into a finished spacecraft. This team is originally very large due to the huge amount of construction work involved in actually building Freyr, but then becomes smaller when Freyr's primary structure is complete and only sporadic construction projects are required.

The Sensors Squad maintains and replaces communications equipment, sensors, cameras, and other specialized equipment on the exterior of Freyr. This includes the external lights. This squad is kept small due to the small volume of repairs required.

1.9.2   EVA Suits

The EVA suit design on Freyr is significantly different from existing space suit designs. While current designs utilize an inflated "bubble" of air around the astronaut and exert ambient air pressure on them, Freyr's EVA suits use a mechanical counterpressure (MCP) design in which the suit presses directly against the spacewalker to provide pressure. The helmet is still filled with gas, and a hermetic seal attaches the helmet to the suit.

This design provides several advantages over traditional space suit designs. They are lighter, more maneuverable, have lower gas leak rates, have fewer seals and joints, and are more resistant to abuse. For example, if a traditional gas-inflated suit happened to scrape against a sharp protrusion on Freyr or a rock on the lunar surface, it could develop a leak that would depressurize the entire suit, leading to death for the occupant. An MCP suit, by comparison, would only be scratched; the skintight fabric would be supported by the astronaut's skin and would not tear. Even if an MCP suit did develop a puncture, it would not affect the suit's performance enough to result in death, and the hole could easily be patched with some vacuum-curing glue and a bit of reinforced fabric.

Figure 1.17: MCP Bio-Suit Concept (Dava Newman)

MCP suits are currently in development, so it is reasonable to assume that they will be ready for deployment by the time Freyr need them. In particular, the Bio-Suit, which is being developed by MIT researchers, is a promising line of investigation. It uses memory-alloy coils to allow the suit to be put on easily and then tightened in a shrink wrap-style package[147]. This has the advantage that the spacesuit is easier to put on while still providing the same level of protection from vacuum.

MCP suits are also advantageous in that they allow easier movement. While gas-inflated suits are bulky and resist movement due to their inflated joints, and MCP suit fits like a second skin, allowing movement much like a wetsuit. Tests have found that MCP suits only increase task time by 65% over a bare human hand, while a gas-inflated suit may increase task time by up to 500%. Thus MCP suits allow for faster movements and operations, increasing the capacity for an astronaut out on EVA to do work, fix parts, and reduce the amount of extravehicular time. This time savings could then be applied to completing more jobs within the original timeframe or getting more work done inside Freyr; on Freyr, a little extra time for maintenance can make a huge difference.

A final benefit that MCP suits provide is zero prebreathe time. In theory, MCP suits can be donned and tightened with the helmet pressurized to a comfortable pressure and without the need to breathe pure oxygen for a time and purge dissolved nitrogen gas. The danger of gas-inflated

suits, of course, is that they must contain relatively little pressure to maintain low mass, and reducing atmospheric pressure without time for decompression can result in a condition known as "the bends," which involved bubbles of gas evolving in the bloodstream as the solubility falls with decreasing pressure. This is of particular concern for SCUBA divers, but in this case the bends would be absolutely debilitating if not life-threatening. By exerting near-atmospheric pressure on the body and containing a high-pressure area in the suit's helmet, MCP suits can almost completely avoid decompression sickness. Note that despite the lack of necessary prebreathe time for donning MCP suits, Freyr is designed with a prebreathe area for workers who routinely go on EVA to ensure that long-term health problems do not arise. As more research is done on the capabilities of MCP suits, this prebreathe area may be scratched from Freyr's plans.

Furthermore, by reducing the number of joints in the suit to just one or two, MCP designs reduce air loss rates and help ensure that suits are not clogged or locked up by dust, e.g. dust on the surface of the Moon, which Apollo astronauts said wore out their suits quickly.

It is estimated that a single MCP suit will cost about \$100,000 and mass about 15 kg, meaning that the total cost of one MCP suit manufactured on Earth and delivered to Freyr could be as much as \$200,000. To outfit Freyr with enough suits for sufficient external repairs and construction (about 50 suits is the estimated requirement), the cost will be \$10 million. Adding in suits for a couple hundred lunar colonists and construction workers, the cost of acquiring and transporting a sufficient number of MCPs could be as high as \$100 million. This assumes that the suits are already developed and that plans are available or that suits can be bought COTS. The latter scenario could drive prices up by up to 30-40%.

1.9.3   External Maintenance Logistics

External maintenance of Freyr is a complicated procedure. In an attempt to simplify the process, sensors and other delicate components are primarily constrained to the Spaceport and the core, which allows relatively simple replacement because the effective gravity in those places is not greater than 0.54 meters per second squared. For these repairs, relatively simple apparatus is required, in the form of adjustable slacklines and handles for movement (titanium is paramagnetic, so directly attaching magnetically to the hull is not practical).

At times, however, it may be necessary to conduct repairs to the shell of one of the tori or to sensor/communications systems on these surfaces. These repairs are significantly more complex due to the centrifugal acceleration experienced, which can reach up to 11.4 meters per second squared on the outside edge of the Life Support/Habitation torus. The situation is exceptionally dangerous because gravity always points away from the center of Freyr, and the Coriolis force means that a fall of just a few meters results in translational movement at dangerous speeds.

To conduct these repairs, astronauts use a system much like rappelling: a harness is already built into the MCP suit, and ropes of 5/16" Amsteel Dyneema fibers are used to secure the harness to Freyr. These ropes are flexible and light, with 50 meters of rope massing just over 2 kg, but are also very strong; 5/16" (8 mm) rope can hold 13700 lbf (61000 N)[148]. Each of the ropes used on Freyr is not shorter than 300 meters, and some are significantly longer.

Astronauts on EVA who must venture to these areas of Freyr attach a rope to their harness while on an exterior platform. The ropes are permanently connected to eyebolts by locked-off bowlines. Then the astronaut begins to descend along the shell, clipping their rope to periodic carabiners spaced at 5 meter intervals. This keeps the rope hugging the shell and continuously provides immediate safety for the astronaut. When the shell starts to curve back under, producing a past-vertical surface, the astronaut is held to the hull by adhesive patches modeled on gecko footpads. These patches are self-cleaning and can support the astronaut's full weight as well as a few tools. By stepping along the hull in this way, astronauts are able to carry out repairs on any part of Freyr. Note, additionally, that astronauts can climb sideways, perpendicular to the centripetal acceleration, because they are supported equally by the carabiners. While on the outside of Freyr in this way, astronauts utilize a locking rappel mechanism that requires only one hand to operate if necessary, and the gecko adhesive pads are placed on the astronaut's boots, knees, and forearms so that at least one hand can be free. The rappel device is set up so that on all but the very underside of Freyr, both hands can be free while the rappelling rope and the astronaut's boots and knees support them. Once the astronaut reaches their destination, they can stand upside down on the hull due to the gecko adhesive on their boots and work upside down if necessary, although for some jobs it may be easier to clip into a nearby carabiner and hang from the rope to complete the job.

Figure 1.18: Locking Rappel Device

To minimize the hassle of making these repairs, each torus has four airlocks arranged near the "top" of the torus. These allow maintenance work on each torus without having to transfer between tori and reduce the necessary supplies of rope. On the industrial and life support/habitation tori, an additional four airlocks are located at the midsection of the torus to allow access to the bottom half of the torus. This further helps to make sure that overly long ropes are not required on Freyr.

To supply each torus with eight 300 meter ropes, Freyr will have to expend $36,600 for the rope itself and an additional $1.9 million to bring them to Freyr from Earth. In exchange for the safety of crew members on EVA fixing the shells of Freyr's tori, this is a very worthwhile investment and is a fraction of the cost of most systems that would achieve the same result.

Chapter 2

Support Systems

Freyr cannot survive and thrive on its own without facilities and structures in place outside itself. These include lunar facilities, transport vehicles, and Earth-launched supplies. Without these additional systems, Freyr could not operate fully, so they are included here to encourage a thorough view of space settlement operations.

Freyr's support systems provide several services to the settlement. While it is preferable to have a centralized manufacturing and sophisticated processing location, having distributed extraction centers is a more efficient method of providing the raw materials to Freyr. Support systems on the Moon can do this; by acting as distributed mining operations for Freyr, they increase the efficiency of Freyr's operations and make it possible for Freyr to focus exclusively on processing while providing a steady stream of raw materials.

2.1 Lunar Structures

Various lunar structures form a part of Freyr's operational group. These include water processing units, small metal refineries, and ^{3}He extraction facilities. These facilities provide support for Freyr's activities and grant access to materials suitable for space travel that do not need to be lifted through Earth's gravity well, being already in orbit around the Earth on the surface of the Moon.

Lunar structures are constructed mainly of fused regolith, which is heated with concentrated solar energy until it melts and produces a basalt-like substance through liquid-phase sintering[149]. First, lunar regolith is compacted and shaped roughly into the final desired shape; then solar concentrators are used to focus sunlight onto specific portions of the structure, melting the regolith and producing a glassy substance that is airtight due to the joining of adjacent particles during sintering and can be fused directly into the desired shape. The resulting substance has good strength characteristics and has the advantage of being entirely produced from lunar materials, with no import from Earth.

The importance of the use of this liquid-phase sintering cannot be overstated. It allows the easy construction of airtight lunar structures from native materials, vastly reducing the cost of setting up lunar operations. Additionally, because the sintering process can be carried out much like 3-D printing, laying down layer after layer and gradually building up a structure, it is possible to construct any shape required without the necessity of planning ahead every part. While sintering in this fashion can take a significant amount of time, it is still far more convenient than having to process and import materials to be assembled on-site. Additionally, fused lunar regolith provides a high-strength structure that can contain an atmosphere, protect from what micrometeoroid impacts it experiences, and support internal structures bolted to it.

Inside the sintered structure, a layer of MPET (Appendix C) provides thermal insulation, while lunar regolith and water provide radiation shielding in addition to the effect of the sintered regolith. An airlock is placed within one wall before it is sintered and formed into the final material, and during the sintering process becomes bonded to the wall itself, making a seamless connection and an airtight seal.
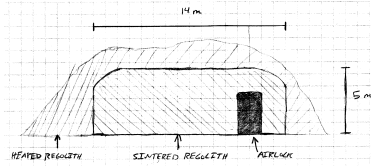
Figure 2.1: Typical Lunar Habitation Structure

Depending on their application, sintered lunar structures may be partially buried, embedded in a depression dug into the lunar surface, bare of other adornment and protection, or even completely covered with lunar regolith.

Because of the Moon's lack of an atmosphere, lunar structures do not serve as protection against atmospheric hazards or impacts, but rather solely to contain an atmosphere and provide some structure. They can, therefore, be made into whatever shape is most convenient, and do not have to reflect typical Earthbound construction constraints.

While the primary structural components of lunar structures are formed from lunar regolith, some components are constructed from processed lunar materials and a select few, such as computers, are manufactured on Earth and then shipped to Freyr and, from there, to the lunar surface. These materials include an airlock for entrance and egress, metal for interior fixtures, machinery and components, and the life support system.

2.1.1   ISRU Units

ISRU (In Situ Resource Utilization) units are essentially small refineries that are placed on the lunar surface to process native materials. These refineries are base stations on the Moon and act as such, being capable of supporting a permanent population and providing pressurized areas for the workers. Despite this, ISRU units are often left unmanned during periods of routine operation.

An ISRU unit consists of a structure formed of sintered lunar regolith containing the facilities necessary for habitation and any machinery that cannot be exposed to vacuum; an airlock allows both the entrance and egress of crew members and the import and export of materials for these machines. Outside the lunar regolith structure, the rest of the processing equipment for the ISRU's operations is set up. Control systems are passed through the sintered wall of the lunar structure to allow easy control of routine systems without the use of EVA equipment, and no extra protection is given to outside equipment. A dedicated launch and landing pad made of sintered lunar regolith is near the ISRU to facilitate landing and takeoff operations for LTVs that carry finished products to Freyr and act as personnel shuttles. This pad has width 20 meters and length 40 meters; it is composed of 5 cm of sintered regolith. This provides adequate support for an LTV while maintaining a relatively small structural capacity load on the ISRU, which makes it much more feasible to continue LTV operations between ISRUs and Freyr. Between the landing/launch pad and the ISRU is a wall (2m high by 7cm thick at the bottom and 3cm thick at the top) that prevents rocket wash from excessively impacting the ISRU.

Power supplies for ISRU units vary depending on the particular the facility processes. Some ISRU

units process large quantities of iron, aluminum, or titanium and therefore require a nuclear power supply, while others pressurize helium for isotope separation on Freyr and can be powered by solar panels with a fuel cell backup. Both types are detailed here.

The nuclear power source used for large ISRU units is based on a Russian UNITHERM concept reactor[150]. This power source provides 5 MWe through a self-contained coolant loop and turbine, albeit at lower efficiency than a larger reactor, and has an operational mass (without shielding) of 100 tons, meaning that it can be lowered to the lunar surface by a single LTV. The reactor is fueled by U-233 produced in Freyr's breeder reactor and only needs to be replenished once every 25-30 years with annual maintenance, leading to low-maintenance and low-cost operation. Shielding on the Moon is provided by distance and native regolith, and of course the habitat has its own radiation shielding in the form of lunar regolith placed on top of the sintered structure and water storage between the living areas and the roof.

ISRUs that use a solar power source utilize thin-film solar panels to reduce weight and setup difficulty. While these panels are somewhat less efficient (14%[151] as opposed to 18% or 19%[152]), they will improve in efficiency over the coming decades before lunar deployment and their lower mass and easier deployment means that they are advantageous for ISRU use. An ISRU that uses solar power utilizes 900 square meters of thin film solar panels for a total power output of 147 kW at a mass of 720 kg. This power is sufficient to run the station's diagnostics, pressurize helium for transport to Freyr, and provide power to the fuel cells that augment the solar panels and are used when the ISRU faces away from the sun for two weeks at a time.

The backup fuel cells have a mass of 40 kg[153] and are distributed in multiple sites around the habitat to ensure that the ISRU will have power for its critical systems even if one or more of the fuel cells goes offline or has a catastrophic failure. The collection of fuel cells is rated at 6 kW with 40% conversion efficiency, meaning that 15 kW of power must be dedicated to fuel cell electrolysis when the solar panels are active. 6 kW of power is more than sufficient to run the ISRU diagnostics and critical computer systems, and human habitation is possible but uncomfortable for short periods of time (weeks, not months). Production of 6 kW requires the consumption of 4.2 $\frac{l*atm}{min}$ of hydrogen gas and 2.1 $\frac{l*atm}{min}$ of oxygen gas, produced by electrolysis of water; this means that to last three weeks (150% of total runtime), the ISRU must have stores of 127000 liter-atmospheres of hydrogen and 63500 liter-atmospheres of oxygen, provided by 500- and 250-liter tanks, respectively, pressurized to 250 atmospheres.

2.1.2 Water Processing

A water processing ISRU is located in the far North or South of the Moon, where large deposits of water are hidden under a relatively thin layer of regolith. Their primary purpose is to extract water for use on Freyr from these ice deposits, though if more water is not currently needed on Freyr their production can be scaled back or electrolyzed into hydrogen and oxygen gases. It is estimated that the North Pole of the Moon alone contains 600 million tons of water ice[154], so these facilities will not run out of water to harvest.

These ISRUs are powered by a U-233 fission reactor running a 10 MWe S-CO_2 cycle. This turbine

can be throttled up or down depending on expected load, and the 12+ MWt from the reactor that would otherwise be waster is also used. The reactor is shielded passively with a layer of lunar regolith on the side facing the ISRU; on the sides facing away from the ISRU, no shielding is used. These ISRU units are powered with a nuclear reactor because many of the deposits of water ice on the lunar surface are located in permanently shadowed craters where solar panels could not power a facility[155]

Using the 10 MWe and 12 MWt produced by the nuclear reactor, a water processing ISRU carries out several processes. First, it utilizes grinding machines to break up the ice-containing regolith, which breaks it down into pieces from which the water can be extracted. Then, in a temperature-controlled chamber that uses some ambient lunar sunlight during the daytime and electric heating elements at night, it evaporates the water by raising the chamber's temperature to just over 100 degrees Celsius. This temperature is sufficiently low to ensure minimal off-gassing of other materials adsorbed into the lunar regolith, which could cause contamination problems with the water extracted.

Once the water has been extracted, it is passed through a cooling loop and re-condensed into liquid water. At this point, several options remain for the water. If additional rocket fuel (hydrogen gas) or breathable oxygen is required, the water is electrolyzed to produce those two gases, which are then stored; otherwise, the water is kept in the ISRU until it can be shipped to Freyr or another destination on an LTV.

The ISRU has a storage capacity of 500 tons of water in the form of a below-ground pool walled with sintered lunar regolith. Based on a water production rate of 0.3 tph, corresponding to processing about 1 tph of lunar regolith, a water processing ISRU can build up 100 tons of water reserves in just two weeks, the time it takes the Moon to complete half an orbit around the Earth. This corresponds to an LTV trip every three weeks, or two every six weeks, to take the water and move it to Freyr. Relatively few of these ISRUs are required at any given time, but because the deposits of highly enriched ice are not very large, ISRUs may have to be constructed at quite a rate, perhaps one every year or two. When an existing ISRU completes extraction of its local deposit, the essential equipment (including the nuclear reactor) is removed, the last of the water is shipped out, and the structure is abandoned while a replacement is built at another deposit of ice.

2.1.3 Metal Refining

Metal refining ISRUs are typically located in the Oceanus Procellarum region of the near side of the Moon. This location holds the highest concentrations of most metals (with the exception of aluminum, which is more commonly found in the lunar highlands). Particularly, titanium, iron, and thorium are most common in this area, especially around the Copernicus crater. Lunar regolith is mined around the ISRU, then brought back to the ISRU for processing and shipment to Freyr.

Full-scale metal refining ISRUs are powered by a 15 MWe S-CO_2 Brayton cycle from a 33 MWt reactor. Other than the difference in power (and therefore size), this power supply is identical to that used for a water processing ISRU.

Using this power, the ISRU grinds up lunar regolith and transports it back to the ISRU proper.

The vehicles used for this are initially powered by Li-ion batteries, though they may be retrofitted with hydrogen fuel cells as appropriate when improved systems become available and/or their Li-ion batteries lose charge. These vehicles require about half as much charging time as operating time[156] (based on small improvements over today's charge-discharge cycle and in line with increased battery capacity), meaning that on a fully operational schedule, the extraction machines can run for up to twelve hours a day (allowing six hours a day for unloading, maintenance, extra charge time as the battery degrades, etc).

Once the extracted regolith has been transported to the ISRU, it is separated into its composite oxides via selective reduction. This results in several different oxides, such as CaO, TiO_2, FeO, Fe_2O_3, Al_2O_3, and others, which can be easily separated using magnetic or chemical means. The resulting oxides and other compounds are stored in different areas of the ISRU to avoid cross-contamination; when workers enter the areas where the materials are stored, they are required to have (at minimum) a dust mask to avoid inhalation of large amounts of potentially very damaging dust. The materials are transported via a conveyor system to minimize human operation requirements, which helps keep humans in the ISRU safe.

The different materials are then packaged in different cargo sections of an LTV, again using a conveyor system to load them into the LTV's cargo tanks. Care is taken to load the tanks in a symmetric pattern so that the LTV is stable; this may result in not all of the processed material being transferred on any given LTV.

2.1.4 Helium-3 Extraction

Helium extraction ISRU operations require much less power than the other operations. These ISRUs are not stationary, but are in fact the mobile helium processing platforms themselves. To compensate for the lack of a landing/launch pad when out on the lunar surface, these ISRUs move to an open area on which an LTV can land - or clear such an area, if none are nearby - and wait there for the LTV. They drive up to the LTV after it has arrived and pump their cargo of volatiles into the LTV's tanks. Again, the tanks are loaded symmetrically, but this process is much easier when dealing with these ISRUs because the non-helium volatiles are not separated by the ISRU itself, simplifying the balancing process by reducing the number of components that must be balanced.

For more information on helium-3 extraction and processing, please see 1.7.4.

2.2 Additional Vessels

Several capabilities are required of Freyr that it cannot perform on its own. While these activities are still space-based and do not include intra-atmosphere travel, Freyr has to have support vehicles that can perform certain tasks for it.

For example, Freyr cannot descend to a planetary or lunar surface for any reason whatsoever; it has no way to land, and would be stranded if anything at all survived the impact. Instead, Freyr must make use of specialized, smaller vehicles to make these trips for it. and conduct its business in LEO and on the lunar surface. Three vehicles are detailed here: the Earth Transfer Vehicle, the Lunar Transfer Vehicle, and the Repair Drone. These are the only vessels used for Freyr's business, which encourages interchangeability and lowers cost due to modular components and mass production of particular spacecraft. Additionally, the use of only a few spacecraft standardizes Freyr's usage of vehicles by providing a standard for vehicle construction.

All spacecraft used by Freyr for its operations are given a callsign of the format FR-***-##. The FR is for Freyr and allows the later development of this naming convention to other settlements or for nations and corporations on Earth to allow communication between their crafts and Freyr. The next component of the callsign is three letters designating the vehicle type, and the final component is the vehicle's specific serial number, which identifies the exact vehicle in question. An example of this naming system would be the fourth Orion capsule registered with the United States, which would be given the callsign US-ORI-04 (United States, Orion, #4, pronounced "uniform sierra oscar romeo india zero four").

2.2.1 ETVs

ETVs, or Earth Transfer Vehicles, are used to move materials between Freyr and Earth. They remain in space and do not descend into Earth's atmosphere, allowing a more efficient design for space travel. These vessels act as shuttles for resupply materials, imports and exports, and residents as needed. They can also serve as lifeboats in the event of a critical system failure on Freyr.

Propulsion

ETVs are powered by gas-core nuclear thermal reactor (NTR) engines. Each of these provides 409 kN of thrust at a specific impulse of 1500 seconds[157]. Because the ΔV to Freyr is 4.1 km/s from LEO, the Tsiolkovsky rocket equation informs us that:

$$\Delta V = v_e \ln \left(\frac{m_0}{m_1} \right) = I_{sp} * g_0 \ln \frac{m_0}{m_1}$$

$$4100 = 1500 * 9.81 \ln \frac{m_0}{m_1}$$

$$\frac{m_0}{m_1} = e^{4100/14715} = 1.3213$$

The mass fraction of propellant is therefore equal to $\frac{0.3213}{1.3213} = 24.3\%$. This is feasible with current technology as long as some effort is put towards developing these NTR engines. As is clear from the calculations, NTR engines provide an effective bridge for the gap between high-thrust, low-efficiency chemical rockets and low-thrust, high-efficiency electric engines. While the combination of moderate thrust and high specific impulse does indicate that the engine's power is about 3 GW, existing literature on previously constructed reactors[158] indicates that these reactors can attain a power density of more than 10 MW per cubic foot, meaning that a 3 GW power source might take up 8.5 cubic meters, certainly attainable and not obscene in terms of scale. In fact, much of the engine's mass is accounted for by shielding that protects the rest of the spacecraft as well as any place it happens to land at from being irradiated.
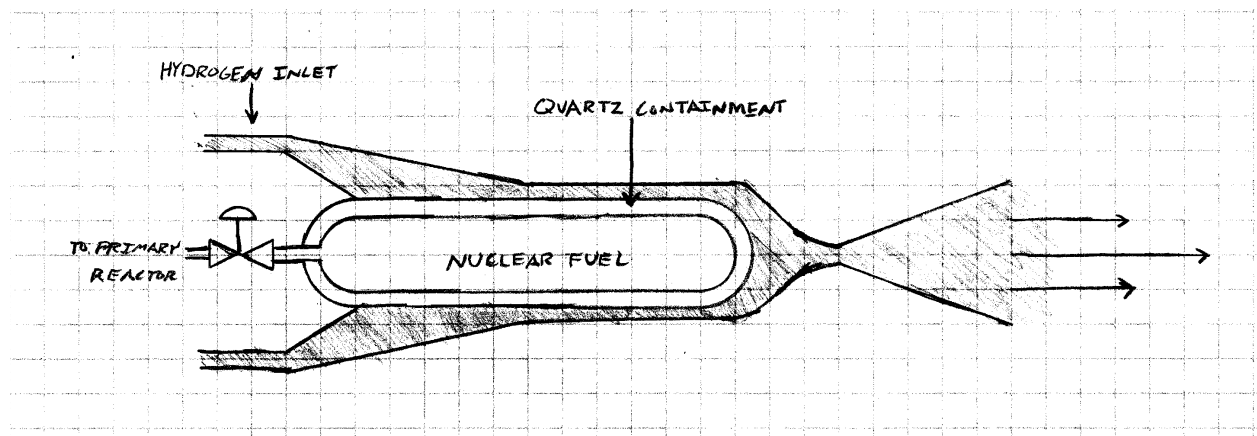
Figure 2.2: Basic Diagram of NTR Mechanics

While electric engines would be more efficient at transporting cargo to Freyr, there is a significant problem with the use of electric engines: the low thrust means that their acceleration is very low, which results in a large amount of time spent in the van Allen belts around Earth. These belts of ionizing radiation are held in place by Earth's magnetic field and represent a great danger to humans or vulnerable electronics passing through them due to the high radiation levels. The belts necessitate the use of higher-acceleration craft to avoid the debilitating and potentially deadly effects of prolonged exposure to high levels of radiation.

ETVs make use of two NTR engines for two main reasons: two engines will provide higher thrust and thus a faster transit time and lower radiation dose, and multiple engines provide a redundancy of propulsion in case of mechanical breakdown.

ETVs make expeditions on a round-trip cycle from Freyr to LEO and back. This means that they carry fuel for the journey down into Earth's gravity well and fuel for the journey back out of it, increasing the initial propellant mass fraction when the ETV leaves Freyr but eliminating the need for expensive fueling operations in LEO and reducing the cost of each mission. The total propellant mass fraction required for a round trip is equal to:

$$8200 = 1500 * 9.81 \ln \frac{m_0}{m_1}$$

$$\frac{m_0}{m_1} = e^{8100/14715} = 1.7459$$

The propellant mass fraction is 42.7%. That is, to be on the safe side, 45% of the inbound mass must be propellant, leaving 55% for the structural components and inbound cargo. Of course, the ETV travels on a Hohmann transfer orbit when transitioning between LEO and Freyr. This orbit leads to a transit time of 5 days (see Appendix B).

ETVs are also equipped with an RCS unit to aid in fine maneuvering and docking with Freyr. This RCS utilizes a monopropellant, hydrazine (N_2H_4), and can produce a total of 27.5 m/s ΔV by utilizing all of its 1000 kg of fuel. While this is not a large amount of ΔV, consider that this system is only used for turns (which can be very slow) and final approach on docking: not much ΔV is required of the system.

Structure

Simple reasoning shows that the more massive the ETV, the more cost-effective this is: the structural and engine mass becomes a smaller proportion of the total mass, allowing for more efficient cargo and materials transfer. The structure, however, cannot be constructed to an arbitrary size because of structural limitations and practicality for transfer to Freyr. The dry mass, including the NTR engines, fuel tank, and structural mass, is 90 tons, with additional mass resulting from habitable volumes and cargo space. The ETV consists of two NTR engines, a strut system, and life support mechanisms; fuel tanks form a part of the design but are relatively low mass and include optional fuel tanks that can be detached depending on need. The other components of the ETV - crew areas (see Appendix C) and cargo storage - can be added and removed in a modular manner, resulting in increased versatility and efficiency.
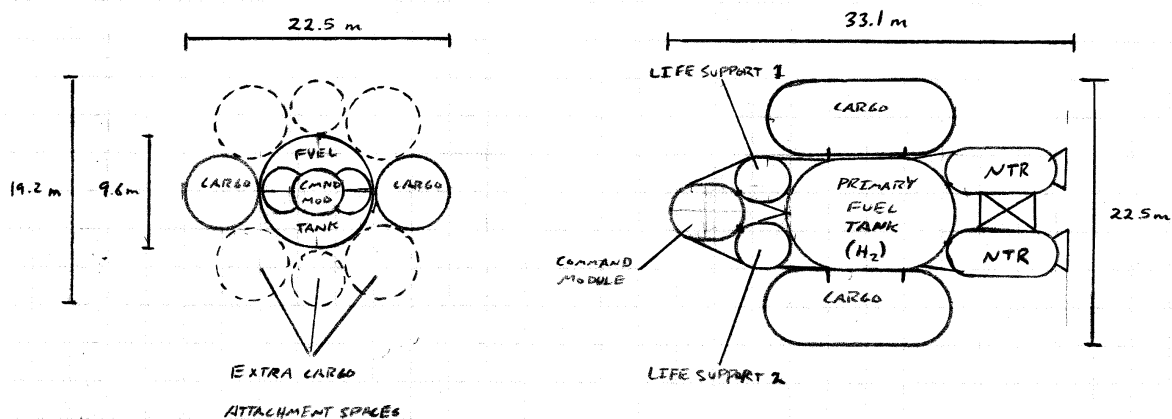
Figure 2.3: ETV Structure

When loaded with cargo or passenger areas to a total dry mass of 385 tons, as could be the case when delivering a cargo of ^{3}He or other products to Earth, the ETV has a fully fueled mass of 700 tons, or 700,000 kg. This means that the NTR engines can effect a linear acceleration of:

$$2 * 409000\,N \ = \ 700000\,kg \ * a$$

$$a = 1.17\,m/s^2$$

1.1 meters per second squared, sufficient to induce significant forces on passengers and cargo within the craft. Since the total ΔV one way is 4.1 km/s, this acceleration is provided for a total of:

$$\frac{4100}{1.17} = 3494\,s$$

3494 seconds, or just under an hour, is a small fraction of the total transit time ($\sim$431,260 seconds). Thus the balance of the transit time will be spent in μg and there is no reason to arrange the ETV for comfort during accelerating flight.

Flight Path

ETVs take a path similar to that used by the Apollo missions: a Hohmann transfer orbit between LEO and lunar insertion, with a TLI/TEI burn going each way. While a bi-elliptic transfer would be more efficient[159], a Hohmann transfer is a more direct route and in the case of an Earth-Moon transfer the savings is very slight.

To complete a Hohmann transfer, the spacecraft makes two burns: one at low Earth periapsis (making maximum use of the Oberth effect), to raise the apoapsis to lunar orbit, and one at apoapsis to circularize the higher orbit. Gravity-assisted capture around the Moon is typically impossible due to Freyr's polar orbit, and when returning to Earth aerobraking is not an option due to the relatively fragile structure of ETVs, which were constructed explicitly for spaceflight and were never intended to pass through an atmosphere. Likewise, lithobraking is not a desired outcome.

The total ΔV required for a Hohmann transfer is given by the equation

$$\Delta V = \sqrt{\frac{MG}{r_1}} \left(\sqrt{\frac{2r_2}{r_1 + r_2}} - 1 \right) + \sqrt{\frac{MG}{r_2}} \left(1 - \sqrt{\frac{2r_1}{r_1 + r_2}} \right)$$

This accounts for the ΔV requirement for each burn[160] (See Appendix B). In the case of the LEO-Lunar orbit transfer, the ΔV equation evaluates to:

$$\Delta V = 3108.2\,m/s \ + 829.7\,m/s \ = 3937.9\,m/s$$

This was expanded to 4.1 km/s to allow for a small margin of error in orbital maneuvering and to account for the slightly higher ΔV caused by non-instantaneous impulses. The Hohmann transfer orbit is half of an ellipse with semi-major axis $\frac{r_1+r_2}{2}$, meaning that the time required for the transfer is given by:

$$\Gamma = \pi\sqrt{\frac{(r_1+r_2)^3}{8MG}}$$

See Appendix B for the derivation. For the Earth-Moon transfer, this evaluates to:

$$\Gamma = \pi * 137274 = 431260\,\text{seconds}$$

This comes out to a total of 4.99 days, which again due to non-instantaneous impulse is extended to five days. While more direct routes are possible, and the transit can be made in shorter time windows, the Hohmann is much more efficient than these other options and adds only a little extra time.

To minimize the travel hassle between the Earth and the Moon, ETVs travel between near-polar orbits over the two bodies. This makes it slightly harder to launch materials into LEO to rendezvous with an ETV, but overall reduces the difficulty of getting materials to Freyr. An inclination change of 86 degrees over the Moon, for example, requires a delta-V of 2336 meters per second, increasing the trip delta-V by a factor of over 1.5. A plane-change maneuver in orbit over the Earth is even more costly.

The ETV's orbit over Earth is inclined somewhat less than 86 degrees: this lower inclination will account for lunar orbital velocity when the ETV reaches Freyr's location and allow it to enter Freyr's orbit without accounting for lunar orbital velocity. This makes the mission profile easier to execute.

An ETV trajectory (shown below) begins with a trans-lunar injection, or TLI, burn. This raises the ETV's apoapsis to roughly the altitude of the Moon's orbit and occurs at a particular point on the near-polar orbit over Earth. As the ETV moves out towards the Moon, it loses energy and therefore speed.
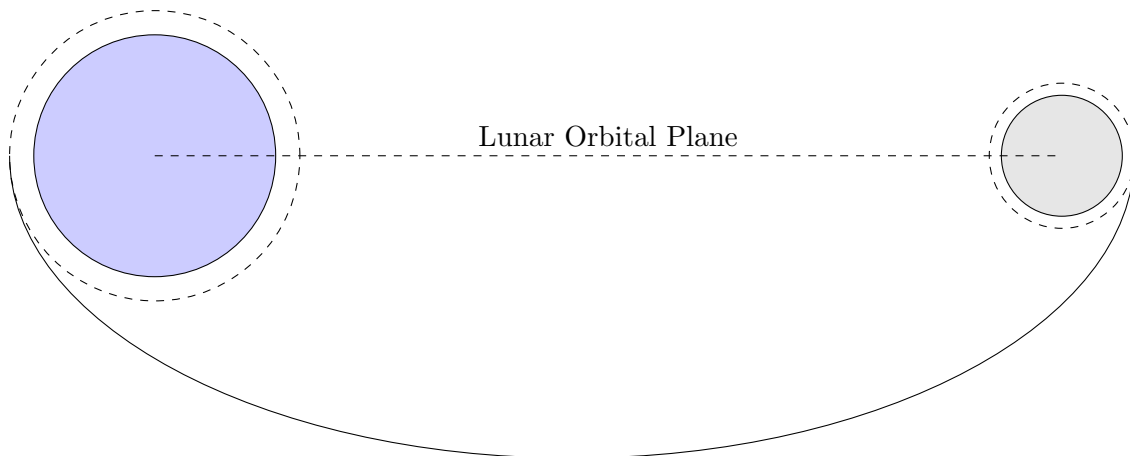
Figure 2.4: ETV Transfer Orbit

At a point about 85% of the way between the Earth and the Moon, co-altitudinal with EML1, the ETV begins to be pulled towards the Moon more strongly than it is pulled towards Earth. At this point, the ETV begins to accelerate towards the Moon. The velocity differential produced by TLI now corresponds to lunar orbital velocity, matching the ETV to Freyr's 86-degree inclination. A lunar orbit insertion (LOI) burn is then made as the ETV swings around the Moon, reducing its orbital velocity to close to that of Freyr.

To allow easier launch windows, the LOI burn is calculated on a case-by-case basis to make the ETV's orbit either slightly shorter than Freyr's or slightly longer. This allows Freyr to slowly catch up to the ETV, or vice versa, allowing launch windows to be optimized for efficiency of the TLI burn and optimal alignment between the Earth and the Moon.

ETV Specifications

Table 2.1: ETV Specifications

Structural Mass	90000 kg
Recommended Cargo Mass	295000 kg
Recommended Wet Mass	700000 kg
Engine Mass	64000 kg
Total Thrust	818000 N
Acceleration Empty	9.1 m/s^2
Acceleration Fully Fueled	1.1 m/s^2
ΔV With Cargo	8.920 km/s
ΔV With Fuel as Cargo	30.184 km/s
Crew Size	3
Crew Cabin Volume	205.1 m^3 / 7240 ft^3
Length	33.1 m
Width	22.5 m
Height	9.6 m
Std. Cargo Volume	4600 m^3
Potential Cargo Volume	>16000 m^3

Note that the ETV's height may be up to 19.2 m depending on the cargo configuration.

Fleet Size and Crew

Freyr maintains a fleet of four ETVs, designated FR-ETV-1 through FR-ETV-4. Additional ETVs may be constructed as situations demand, and Freyr may build ETVs on request for other entities. These developments would lead to ETVs with other unique callsigns.

Freyr's four ETVs serve its purposes fairly easily. Because the volume of material shipped between Freyr and LEO is expected to be relatively small, in the range of several hundreds of kilos per day,

it is not necessary to have a large fleet of ETVs that are each capable of transporting 295 tons of cargo each way. The vessels would simply never be used enough to justify their upkeep. At the same time, it is infeasible to operate on only one or two ETVs due to the possibility of equipment malfunction or the necessity of staying in LEO for long period of time while cargo is delivered. Because of the necessary compromise between a few spacecraft being more economical for Freyr and a larger number of spacecraft being more reliable and useful, the compromise chosen was four because ETVs not in use for Earth-Freyr transfer can be used for applications around Freyr as well, and four ETVs means that the chance that no ETV will be available when one is needed is very slim.

Each of these ETVs has a crew of three for operations and maintenance: a Commander, a Flight Engineer, and a Systems Engineer. All three of these crew members are trained in the basic operation of the ETV, but each is specialized in some of the ETV's systems. The Commander is in charge of maneuvering the ETV and performing course-change burns; they are assisted by the Flight Engineer, whose primary responsibility is engine operation and maintenance. The Commander's duties also include communication with Freyr and with vehicles in LEO to ensure proper orbital alignment and docking approach. As an expert on the propulsion systems of the ETV, the Flight Engineer is responsible for keeping the NTRs running and for balancing reaction mass inside the ETV's tanks. They are also the refueling liaison for the ETV when it docks to Freyr. Finally, the Systems Engineer is responsible for keeping the ETV's non-propulsion systems online, especially communications, light and heating, and life support. They are the resupply liaison at Freyr and sign off on upgrades and repairs to all non-propulsion systems. Together, the three crew members on board and ETV keep it running smoothly; they are housed in the command cabin for the duration of flights.

The command cabin, with a habitable volume of nearly 200 cubic meters, is quite spacious for three crew members, and allows them some space for themselves as well as ample room for running the spacecraft. The larger size also allows for some amenities such as a separate area for human waste removal and some private volumes. For contrast, the International Space Station has a habitable volume of just 388 cubic meters[161] and is inhabited by a crew of six.

2.2.2 LTVs

LTVs, or Lunar Transfer Vehicles, are used to transport products and personnel to and from the Moon's surface. They are similar to the ETV in design, but due to the much smaller ΔV involved in the trip from the lunar surface to lunar orbit, and vice versa, their design can be somewhat lighter and less bulky.

Propulsion

LTVs are powered by gas-core NTR engines, much like the ETVs. These engines are of the same design, 409 kN and an I_{sp} of 1500 seconds. However, the ΔV to involved in the LTV's trip is much lower, only 1.6 km/s (See Appendix D), so the rocket equation says:

$$1600 = 1500 * 9.81 \ln \frac{m_0}{m_1}$$

$$\frac{m_0}{m_1} = e^{1600/14715} = 1.1148$$

This gives a propellant mass % of 10.3%. Because the LTV can be fueled at either end of its trip, it is provided with 15 mass % of fuel at departure to allow for orbital error and is refueled for each trip. Note that because the NTR has a total thrust of 409 kN, it can easily lift up to 225 metric tons from the lunar surface[1]. Again, it is more efficient to use a large mass, as the structural mass becomes less important as compared to the payload mass.

Structure

LTVs travel to and from Freyr and various points on the Moon, in contrast to ETVs, which travel only between Freyr and LEO. This means that a larger fleet of smaller vessels is more appropriate for the LTV program. For this reason, LTVs are smaller and lighter than ETVs and have a simpler design.

As on the ETVs, LTVs have a command module designed for three occupants, a central fuel tank and engine setup, and peripheral cargo volumes. One difference, however, is that the LTVs carry life support inside the command module instead of outside it due to the less stringent life support requirements on LTV systems. Also, the LTV cargo containers are specialized for landing on the lunar surface and feature landing legs to protect the NTR from damage upon landing.

The LTV's command capsule is somewhat different from the ETV's crew cabin, as well. It is arranged on its side so that the crew can be most comfortable when the LTV is parked on the lunar surface, as it must be for some two weeks each time it makes a trip to the lunar surface; by positioning the command capsule on its "side", more floor space is generated when at rest in a gravitational field.

Because the LTV only uses one NTR engine, its structural mass is much smaller - only 50 metric tons. This leaves approximately 140 metric tons for cargo to be lifted from the Moon, a very respectable capacity.

Flight Plan

The specific energies of different phases of the transition from the lunar surface to Freyr's orbit dictate the flight path that the LTV will take. For simplicity, this is divided into two phases: lifting and accelerating. Lifting one kilogram from the lunar surface to the altitude of the orbit takes:

---

[1] $225000 \text{ kg} * 1.622 \text{ m/s}^2 = 364950 \text{ N}$; $409000 \text{ N} / 225000 \text{ kg} = 1.818 \text{ m/s}^2$
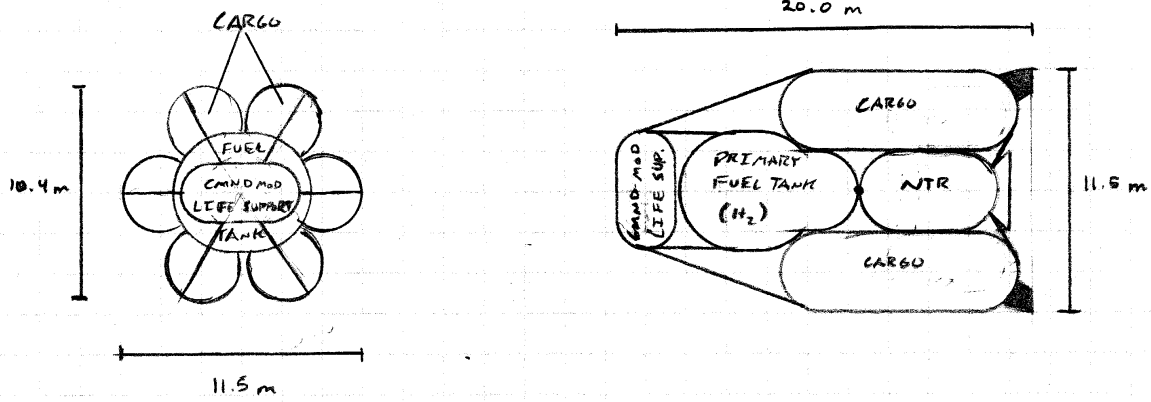
Figure 2.5: LTV Structure

$$\Delta \mathcal{U}_{sp} = \frac{GM_l}{r_1} - \frac{GM_l}{r_2} = 1411223.5 - 1371746 = 39477.0 \, \text{m}^2/\text{s}^2$$

On top of this energy expenditure, the kilogram must be accelerated to the orbital speed of 1651.8 meters per second. This requires a specific energy of:

$$\Delta \mathcal{T}_{sp} = \frac{1}{2} v_o^2 = 0.5 * 2728443.24 = 1364221.62 \, \text{m}^2/\text{s}^2$$

The total specific energy is therefore equal to the sum of these specific energies, or 1403698.6 meters squared per second squared. Because this entire specific energy must at some point belong to the ETV as kinetic energy, we can find the necessary change in velocity to achieve orbit from the lunar surface:

$$\frac{1}{2} v^2 = 1403698.6$$

$$v = 1675.5 \, \text{m/s}$$

The theoretical delta-V for getting an LTV into orbit is therefore just under 1700 meters per second; a buffer of just over 100 meters per second is allowed to account for faster gravitational depletion at low velocities and to provide a safety margin for the vehicles as they ascend to Freyr.

To achieve the desired flight profile, two burns are used. The first lifts the rocket off of the pad on the lunar surface, raises the apoapsis to 100 km, and accelerates the craft to about 90% of orbital velocity. This burn follows a prescribed profile that begins vertically and gradually shifts to a nearly horizontal position to gain more horizontal speed. The second burn is performed just before apoapsis and continues through apoapsis; this burn accelerates the LTV to orbital velocity and matches its orbit closely with Freyr's. The LTV's orbit at this point is slightly faster than Freyr's so that it catches up gradually (within an order of magnitude of 10 meters per second) and does not necessarily have to be launched precisely on time.

155

LTV Specifications

Table 2.2: LTV Specifications

Structural Mass	50000 kg
Recommended Cargo Mass	140000 kg
Recommended Wet Mass	225000 kg
Engine Mass	32000 kg
Total Thrust	409000 N
Acceleration Empty	8.2 m/s^2
Acceleration Fully Fueled	1.8 m/s^2
ΔV With Cargo	2.488 km/s
ΔV With Fuel as Cargo	22.132 km/s
Crew Size	3
Crew Cabin Volume	90.9 m^3 / 3210 ft^3
Length	20.0 m
Width	11.5 m
Height	10.4 m
Std. Cargo Volume	2440 m^3

The LTV's cargo space cannot be enlarged, but the cargo mass can be increased slightly if necessary. Just as on ETVs, the cargo containers are modular and can be switched out for crew modules, specialized containers, or other necessary modules.

Fleet Size and Crew

A fleet of approximately ten LTVs services Freyr and its lunar bases. These craft are designated FR-LTV-01 through FR-LTV-10, and it is not expected that more of them will have to be built, although the possibility does exist and will have to be evaluated depending on circumstance.

The number of LTVs is greater than the number of ETVs because LTVs are required to service a larger number of destinations on shorter notice, requiring a greater number of spacecraft. LTVs must service all of the lunar ISRU facilities to pick up processed materials and then ferry the materials back to Freyr on a bi-weekly basis, so a fairly large number of them are required. With fairly fast turnaround times of just under two weeks, however, and with a substantial cargo capacity of some 50 tons, LTVs are easily able to pick up the slack required.

Just like the ETVs, LTVs have a crew of three, and their crew is also divided into a Commander, a Flight Engineer, and a Systems Engineer, who perform the same roles as they do onboard an ETV. Unlike the ETVs, however, these crew are not expected to remain in the LTV itself during the duration of its stay on the lunar surface. Instead, their cabin is fitted with an airlock that allows egress/ingress operations throughout their two-week stay. This is not only beneficial for the LTV's crew in that it allows mobility and some exercise throughout their stay on the lunar surface,

it is also beneficial to the ISRU personnel, who gain a few helping hands while the LTV is at their ISRU.

2.2.3   Repair Drones

Freyr requires constant maintenance on a minor level. This is not due to any flaw with the station itself, but rather is a symptom of any large space settlement. While it might be possible to employ teams of EVA technicians to perform this maintenance, some of it may be in places difficult for humans to reach, and drones are a thoroughly superior option for most routine work.

These repair drones can move along rails set onto the outside of Freyr's hull to access points on the rotating portion of the station, or can maneuver using high-pressure cold-gas RCS thrusters[162]. These thrusters utilize a yield-before-burst design tank pressurized with gas to an operating pressure of 600 atmospheres. The tank has a total capacity of 40 kg of gas, which varies slightly due to gas composition. The most common gas used for these RCS thrusters is nitrogen due to its relative abundance, but oxygen, carbon dioxide, argon, and other gases can also be used. Obviously, oxygen represents a much greater hazard when dealing with spacecraft components, so efforts are made on Freyr to avoid the use of oxygen where possible. The RCS system has a specific impulse of about 100 seconds, making for fairly poor efficiency, but this lower efficiency is offset by the greater simplicity of the drones without a complex maneuvering system, the low ΔV involved in moving around the non-rotating parts of Freyr, and the lower operational cost. RCS thrusters are positioned on all eight corners of the repair drone to allow translation and rotation in any direction and around any axis simply by firing the thrusters in different combinations and at different power levels.

Drones are powered by an internal nickel-cadmium battery pack. This battery was chosen over a lithium-ion battery for several reasons: longer cycle life, better low-temperature performance, long shelf life, fast charge, and rugged performance[163]. Despite lithium-ion batteries having a higher energy density, their worse low-temperature performance and lower number of charge-discharge cycles means that they are less favorable for long-term use in space.

Repair drones are equipped with materials for patching the exterior of Freyr, including an adhesive for applying patches to small damage sites[164]. They can also be fitted with tools for inspection of hull integrity, reactor service, and spot welding[2]. This allows repair drones to do much of the work that humans would otherwise be required for, reducing strain on human repair workers. The drones, however, do not provide a permanent fix to anything more than a superficial problem; they simply stabilize the situation and make it much easier for the human repair crews to do their jobs.

The repair drone is kept small, with a frontal cross-section of just 2 meters by 1 meter, so that it can reach into most any space on Freyr. Its length is its greatest dimension; grasping arms protrude from the front and underside of the drone. These arms are used to navigate around and grip the outside of Freyr when the drone is maneuvering on a rotating section of the settlement. To move around, the drone uses either one of the lines used by astronauts for maintenance or, in

---

[2]Power is provided through a pulse system that provides a constant draw on internal power while outputting the necessary high-power pulses for spot welding.

many places, protrusions from the surface. It is capable of grasping these and slowly moving itself along; when the drone is moving this way, it keeps its underbelly close to Freyr's hull to minimize torque and keep itself steady.

Note that due to the drone's relatively high delta-V, it can return to Freyr even after having been flung off multiple times on a single mission (depending on how it is loaded with cargo). This adds some safety to the design and means that drones are not lost even if they fall away from the rotating section of Freyr.

Repair Drone Specifications

Table 2.3: Repair Drone Specifications

Structural Mass	90 kg
Recommended Cargo Mass	40 kg
RCS Mass	40 kg
Total Thrust	170 N
Acceleration Empty	1.89 m/s^2
Acceleration Fully Fueled	1.00 m/s^2
ΔV With Cargo	263 m/s
ΔV With Fuel as Cargo	623 m/s
Crew Size	0 (Drone)
Length	3.0 m
Width	2.0 m
Height	1.0 m
Std. Cargo Volume	1 m^3

2.2.4   Why not VASIMR?

At first glance, the VASIMR engines used for Freyr's rotational maintenance seem like a good choice for engines to power the ETVs and LTVs due to their higher specific impulse of approximately 5000 seconds. It is important to note, however, that VASIMR engines, while being very efficient, require large amounts of power to produce low amounts of thrust (200 kW for 5 N)[165]. While this is acceptable on Freyr, where the liquid thorium reactor provides abundant power, it is impractical to provide a small spacecraft with sufficient power: this system would require either extensive solar panels or a large nuclear reactor, both of which are expensive and increase mass greatly. Moreover, thrust of 5 N per engine is not enough to attain a reasonable acceleration, and NASA recognizes that with VASIMR technology, a cargo tug transporting materials to LLO would take six months to make the journey - an impractical amount of time for Freyr, which depends on timely communication and transport with LEO.

As Freyr develops, there may come a time when truly massive amounts of cargo must be moved from LEO to LLO, or from LLO to Mars. In this case, the increased efficiency of a VASIMR engine

would be very helpful, and VASIMR engines could be used at that time for those purposes. At the time of construction and for the first decades, however, Freyr is much better served by its fleet of NTR tugs and exploration ships.

2.3 Earth Launched

It is, of course, necessary that some supplies and materials will have to be launched from Earth. While Freyr has the capability to manufacture most basic commodities and is self-sufficient in terms of food and water, there is no hope of such a small settlement being able to manufacture and process all of the materials required for modern life. For example, the Moon simply does not have large enough quantities of many elements for a modest mining effort to extract them, so metals such as lithium, magnesium, and rare-earth metals (niobium, molybdenum, neodymium, etc.) must be brought from Earth if they are to be used on Freyr - at least until Freyr's mining operations get entirely up to speed. Analysis shows that even when Freyr's ISRUs are operating at full capacity, there will still be some requirement for metal imports.

Naturally, then, these materials must be launched from the Earth's surface. NTR-powered vehicles would be marginally capable of such a feat because the rocket equation states that for a ΔV of 9.1 km/s to reach LEO, with a reduced specific impulse of perhaps 800 seconds due to the reduced efficiency of in-atmospheric flight, the mass ratio must be:

$$9100\,m/s = 800\,s * 9.81\,m/s^2 \ln\frac{m_0}{m_1}$$

$$\frac{m_0}{m_1} = e^{9100/7848} = 3.188$$

This is within the NTR's 7:1 TWR, indicating that the craft could indeed get off the ground. Of course, this could be improved by using a multiple-stage rocket, which leads to a reduction in fuel use over a single-stage rocket. There are, however, problems with using a vehicle powered by NTRs within atmosphere. First, the rocket does use nuclear fuel, and there is no point at which the rocket is more likely to fail than directly at launch or just after - meaning that when the inevitable launch failure occurs, radioactive fallout is scattered all over the launch area. Additionally, the NTR is fairly low-thrust, only giving 409 kN. In Earth's gravity, this is just enough to lift 41.7 tons off of the pad, which is only a little more than the mass of the engine itself. In fact, the NTR does not at this mass carry enough fuel to get itself out of Earth's atmosphere, making it impractical for a launch into orbit.

Based on these concerns, NTR engines are not used to lift payloads from the Earth's surface into orbit. Instead, a chemical booster inserts the payload into orbit. Freyr contracts with private firms to launch payloads into orbit, contracting directly with suppliers to obtain the payload itself. Due to advances in rocket technology, to-orbit costs fall to $5000 per kilogram for bulk heavy lift rockets; Freyr utilizes lifters similar to the Space Launch System (SLS) currently in development by NASA[166]. The rocket used is based on the Block II variant of the SLS and is capable of lifting 130 tons into orbit[167].

Contracting out to another corporation for Earth-to-LEO service provides several advantages for Freyr. It can focus on extra-atmosphere flight, needs no Earth-based branch or subsidiary to launch rockets to LEO, and, critically, avoids the cost of launch facilities construction for infrequent

launches. 130 tons of cargo divided amongst 20,000 people is 6.5 kilograms per person of rare earth metals, lithium, or other items that absolutely cannot be produced on Freyr; 6.5 kilograms should not be necessary more than once or twice a year. Commercial launch facilities are constructed for more traffic than this; for Freyr, construction of a launch facility would result in many billions of dollars spent initially, plus millions in maintenance on a regular basis, for a twice-a-year savings of perhaps some dozens of millions of dollars.

2.3.1   Ultra-Heavy Lift Candidates

Potential candidates for the launch vehicle include a Falcon Heavy derivative, Long March 9, SLS Block I, SLS Block IB, SLS Block II, Saturn V/4-260, and other rockets as private space corporations may develop[168].

<div align="center">

Table 2.4: Earth-to-LEO Heavy Launch Vehicles

Launch Vehicle	Launch Mass	Payload to LEO	m_0/m_1
Falcon Heavy[169]	1462836 kg	53000 kg	27.6
Long March 9[170]	4100000 kg	130000 kg	31.5
SLS Block I[171]	2650000 kg	70000 kg	37.9
SLS Block II[172]	2950000 kg	130000 kg	22.7
Saturn V/4-260[173]	10351050 kg	362700 kg	28.5

</div>

Depending on the eventual needs of Freyr, any of these heavy-lift rockets could prove to be the optimal choice, although the Falcon Heavy and SLS Block II show particular promise. It could also be that at certain times, not as much material is needed at a time, and so launches of smaller rockets (Delta IV Heavy, Ariane V, Falcon 9, etc.) may be preferable. In this case, Freyr would contract for these smaller rockets instead of the larger ones for a time - another advantage of contracting for launch services as opposed to Freyr providing its own Earth-to-LEO capability.

One particularly interesting vendor at the present time is SpaceX due to its greater efficiency, reusability, and independence from any government. Additionally, SpaceX utilizes an innovative fuel crossfeed system that keeps its central booster near full during flight until the outer boosters are depleted, increasing ΔV by effectively splitting the first stage into two separate stages. This will allow SpaceX to offer its launches at a lower price, resulting in cost savings for Freyr and a larger market share for SpaceX.

Of course, the more cargo can be launched into orbit at a time, the more efficient the rocket tends to be in terms of payload % mass. The problems with this are transporting the cargo out to Freyr once it is in LEO, the fact that Freyr simply does not need or want a payload of 362700 kg, such as the Saturn V/4-260 could deliver, at one time, and the much more complicated logistics surrounding the launch of such a massive rocket. Ultimately, a balance must be struck between the greater efficiency of a larger payload and the greater ease of launch, transport, and general operations when dealing with a smaller payload (small is relative; these payloads are still dozens of metric tons).

It is also possible that new rockets will be developed that are more attractive for Freyr to use. For example, advances in nuclear rocket technology may make it practical to launch from Earth using an NTR-style engine. This engine could provide much increased I_{sp} for launch to orbit, along with a corresponding decrease in cost, and advances in the thrust provided by such systems could make it attractive for Freyr to use them as a heavy-lift platform. On a more unlikely note, fusion reactions could be harnessed to power rockets ascending to orbit, or a railgun-style launch system could be provided to launch massive payloads. either of these solutions would be more reasonable on the Moon, and are not seriously considered here.

Based on some combination of advances in rocket technology and volume of cargo to be shipped to Freyr, it may end up making economic sense for Freyr to build its own heavy-lift vehicle. At this point in Freyr's design and not making excessive predictions about the future, however, this is considered unlikely.

2.3.2   Contracting

Freyr's contracts with Earth-based launch corporations include several stipulations on payload-to-orbit. Freyr pays in advance for the rocket launch, but the contract is for the materials in orbit; launch failure is the responsibility of the contractor with the exception of the payload itself, which Freyr is responsible for replacing. The payment provided is for the service of launching the payload to orbit, so payload-related problems are Freyr's concern unless the contractor's rocket performed at a less-than-expected level.

In general, the contracts are written so that Freyr is responsible for the payload, and the contractor is responsible for the rocket. An example contract appears on the following pages.

CONTRACT

Paragraph 1. Between Freyr Inc. ("Freyr") and Orbital Launch Systems Company ("Orbital"), for the delivery of a mass of non-living materials, not to exceed 75,000 (seventy-five thousand) kilograms, to Low Earth Orbit ("LEO") in an orbit with both periapsis and apoapsis between 200 (two hundred) and 250 (two hundred fifty) statute miles as measured from mean sea level (MSL) at an inclination of between 27.0 (twenty-seven point zero) and 30.0 (thirty point zero) degrees with respect to Earth's equator on a semiannual basis (a "delivery"), deliveries to take place at specific times to be agreed on by Freyr and Orbital not less than 2 (two) Earth standard years (twenty-four months) prior to launch.

Definition 1. Contract Duration

Contracting for the delivery of 20 (twenty) deliveries over the period of 10 (ten) Earth standard years, with the option for extension as determined by both parties.

Definition 2. Delivery Margins

The final orbit shall have both an apoapsis and a periapsis of between two hundred and two hundred fifty statute miles as defined in Paragraph 1. Deliveries are to be completed within 30 (thirty) days of scheduled date. Deliveries consist of a payload specified by Freyr, which may vary from one delivery to the next.

Definition 3. Payload Specifications

The mass of any payload to be delivered shall not exceed 75,000 (seventy-five thousand) kilograms, but may be specified as less than 75,000 (seventy-five thousand) kilograms at Freyr's discretion.

Definition 4. Orbital's Responsibilities

Orbital is responsible for the successful delivery of the payload specified by Freyr to the designated orbit, as defined in Paragraph 1. Orbital is therefore responsible for:

1. Development and Construction of the Launch Vehicle;

2. Fueling of the Launch Vehicle;

3. Obtaining launch clearance with the appropriate and necessary authorities;

4. Launch Vehicle Operations (see Paragraph 2);

5. Successful orbital insertion per guidelines in Paragraph 1;

6. Adequate protection of payload during launch.

Definition 5. Freyr's Responsibilities

Freyr is responsible for obtaining the payload and delivering it to Orbital for Launch Vehicle construction and stacking. Freyr is therefore responsible for:

1. Procuring the payload;

2. Securing transportation for the payload to Orbital's construction facilities;

3. Providing full payload specifications to Orbital;

4. Specifying payload environmental and handling requirements.

Definition 6. Catastrophic Launch Failure

Catastrophic launch failure occurs if the payload does not reach a stable orbit.

Definition 7. Non-Catastrophic Launch Failure

Non-catastrophic launch failure occurs if the payload reaches a stable orbit but the orbital parameters as defined in Paragraph 1 are violated.

Paragraph 2. Launch Vehicle Operations include:

1. Construction of the Launch Vehicle;

2. Launch Vehicle Stack assembly;

3. Transport of completed Launch Vehicle to launch site;

4. Operation of all preflight procedures, including but not limited to:

        a. Fueling,

        b. Component checkouts,

        c. Avionics certification,

        d. Engine gimbal tests.

5. Operation of flight control devices during launch and orbital insertion.

These functions and all other operations required for successful launch and insertion are to be carried out by Orbital. Freyr is not responsible for any of the above activities.

Paragraph 3. Once the payload has been delivered to orbit, Orbital shall relinquish control of the payload and any remaining sections of the Launch Vehicle. Control shall be handed over to Freyr at the time of orbital circularization main engine cutoff ("MECO"). All materials remaining attached to the payload at the time of MECO become the property of Freyr.

Paragraph 4. In the event of a catastrophic launch failure, Orbital is not compensated for the loss of the Launch Vehicle. Freyr is responsible for the loss of the payload, while Orbital is responsible for the loss of the Launch Vehicle. An investigation is to be conducted, composed of a joint effort between Orbital and Freyr, to determine the cause of the launch failure. If this investigation finds that the payload was directly responsible for the launch failure and that Orbital was not reasonably notified of the characteristic of the payload that caused the launch failure, Freyr shall be held accountable for the launch failure and Orbital shall be paid in full for the delivery.

In the event of a non-catastrophic launch failure, Orbital shall be required to either correct the orbital parameters or to reimburse Freyr for the expense of recovering the payload from an orbit outside the designated parameters.

Paragraph 5. Compensation will be provided to Orbital in the form of United States dollars upon the delivery of each payload to orbit. Freyr shall pay $7000 per kilogram of payload delivered into orbit, with a bonus of $100 per kilogram for launch within six hours of the time specified jointly by Freyr and Orbital (see Paragraph 1).

Paragraph 6. The time and date of each launch shall be decided upon independently by Freyr administration, but shall not deviate by more than one month from the semiannual schedule. Launches shall be carried out within one month of September 1 and within one month of March 1, as Freyr sees fit to request. Consultation meetings shall be help to confirm the date chosen by Freyr not more than one month after Freyr's announcement of the chosen date. If Orbital is unable to complete the launch on that date due to circumstances beyond their control, Freyr is obligated to select another date. This process shall continue until a launch date is found on which Orbital is capable of launching.

Paragraph 7. Once a time and date have been chosen for launch, they cannot be changed except with the joint permission of Freyr and Orbital.

Paragraph 8. This contract may be extended at the agreement of both parties.

By signing below, I understand that I irrevocably commit my employing company to the full completion of this contract, and I affirm my authority to make this decision. I hereby approve and confirm the terms and conditions above, and I understand that this action is binding.

Freyr Signature:_____

Title:_____

Date:_____

Orbital Signature:_____

Title:_____

Date:_____

END OF DOCUMENT

Freyr holds contracts with multiple suppliers Earthside to maintain some measure of independence. The contract that appears on the preceding pages is with a fictitious company named "Orbital Launch Systems Company" that provides the service of delivering payloads to orbit, but Freyr could just as easily contract with another private ground-to-space transport firm. Present-day examples include Orbital Sciences[174] and SpaceX[175], both of which hold U.S. government contracts for the development of spacecraft and the delivery of materials to the ISS.

This ability to contract with multiple companies helps to drive Freyr's cost down through market competition. Further benefits include a wider commercial base for spaceflight, the development of new technologies as spacecraft manufacturers compete for contracts.

Chapter 3

Construction and Operations

3.1 Phases of Construction

Freyr is built as a work in progress, not as a single-step space colony. It is, of course, necessary to launch the initial components of the settlement from the Earth's surface, but once these are assembled in orbit Freyr can begin to process materials from the Moon and take its first steps on the road to self-sufficiency.

3.1.1 Stage 1. Earth Dependence

The first parts of Freyr will be the most expensive. Because it is necessary to build up the infrastructure on the Moon and for transfer between LEO and LLO, the first several deliveries will include the cost of launching massive amounts of supplies into LEO, driving up the cost of construction. As is mentioned earlier, by the time Freyr is being constructed the cost of launching to LEO has fallen to $5000 per kilogram, and bulk rates in the early stages of Freyr ensure an incurred cost of $5800 per kilogram rather than the $7000 per kilogram that is later contracted for.

First Launches

The first several launches to LEO are used to build up a fleet of ETVs and LTVs. The high specific impulse and reusability of these spacecraft means that further costs will be greatly defrayed, and that transportation to LLO is much easier and cheaper than it would otherwise be. The ETVs remain in LEO to provide service when heavy transport to LLO is required, while the LTVs are given a payload of materials for ISRU construction and flown remotely into LLO.

After these very initial lunches, the materials for construction of basic ISRUs are launched to LEO and transported to LLO by ETVs. Unfortunately, during this time period the ETVs are reliant on fuel launched from Earth, which places limits on operations.

The first ISRUs constructed are (1) water processing, (2) titanium extraction and refining, and (3) iron extraction and processing. Multiple ISRUs of each type are constructed to speed manufacturing and produce usable products. These ISRUs obtain their power from nuclear reactors, so those must also be launched; these missions are classified as hazardous cargo and cost $6500 per kilogram. The reactors are initially fueled on Earth with U-233 or U-235 and are then launched and tugged to the Moon by ETVs, where they are lowered to the surface by LTVs and set up to provide power to the ISRUs under construction.

After these initial ISRUs, a thorium extraction ISRU is constructed on the lunar surface and begins to produce thorium for use in Freyr's LFTR.

This stage is expected to take about six years for completion, and will cost $42.2 billion (this includes the cost of the space station, described in the next section).

Habitation

In this stage of Freyr, most personnel live on the lunar surface, in ISRU facilities. This allows rapid development of lunar industrial and manufacturing capacity while not requiring extensive unsupported operations on the Moon: ISRUs provide the resources to build more ISRUs, which results in an exponential growth of processing capability.

During this stage, another source of habitation is the orbiting space station that occupies the orbit Freyr will eventually inhabit. This station has a capacity of twelve astronauts and a mass of about 1000 tons; this makes it 2.5 times as massive as the ISS while housing twice as many astronauts. The station is constructed in the same way as the ISS (that is, in a modular fashion), with modules slightly larger than the modules on the ISS and more comparable to the main body of Skylab, which massed a little over 76 tons[176]. Several modules of this size are coupled together, with the result that the station as a whole can be isolated from any individual section, and the station can be kept from experiencing a total failure. The total habitable volume of the station is about 1500 cubic meters; power is provided by a very small, 500 kWt nuclear reactor with an S-CO_2 Brayton cycle for power conversion. Back-up power is provided by a 50 kW solar array. One of the advantages of this reactor is that it allows Freyr's personnel to learn the necessary touch for working with the reactor and iron out any kinks in the design before it is used in Freyr itself, minimizing the possibility of a system failure by providing a long testing period beforehand.

As the ISRUs proliferate on the lunar surface, materials are shipped into orbit on LTVs to begin the construction of what will become Freyr. As the station becomes airtight, people begin to move into it so that construction operations can continue at a faster pace.

Initial Construction

With materials now flowing from the ISRUs in place on the lunar surface, construction is begun on Freyr itself. The titanium backbone is cast in several pieces on the Moon and launched using LTVs; all construction of segments larger than 20 meters is completed on-orbit. This does present one limitation: the LTVs are not designed to work with such an unwieldy piece of cargo as a 15-meter piece of backbone for the settlement proper, so payload capacity is reduced and the LTVs must make more trips to account for the same mass being transported to orbit. This early in Freyr's development, this places limits on the rate of materials transfer; once the settlement's production capacity has increased, this would be a minor inconvenience, but so early in Freyr's construction cycle it is debilitating.

The first pieces of Freyr to be constructed are the Spaceport and the core. Once the reactor area is checked out and cleared for power generation, the reactor is installed and begins breeding U-233 fuel from its supply of Th-232 from the Moon. Naturally, an initial supply of U-233 is required; once more, a hazardous cargo mission is launched from Earth and the seed uranium is delivered to Freyr to begin the breeder reactor's operations.

To simplify construction operations, what will become the core of Freyr is built around the existing space station. This allows transfer of the reactor to Freyr to hold over the station until the new

reactor can be installed and means that while the initial sections of Freyr are under construction and no part of it is airtight, the construction crew still has a spacious place to go to when not actively working on Freyr's exterior. Additionally, it provides a source of some of the specialized components that Freyr must eventually integrate into its own systems and provides an emergency shelter system in the event of partial or complete depressurization of Freyr.

Once the reactor is operational, construction of Freyr becomes much easier. The large amount of power on hand causes problems with heat dissipation, but also provides an ample supply of electricity for making hard welds between individual pieces of titanium shipped up from the lunar surface. This helps to create a sturdier structure and provides reinforcement for Freyr's structural load.

The next most important components for Freyr are the various parts of the life support system. In the core, Freyr has a single SCWO capable of a throughput of 1.875 tph of water (just under 100 kg of waste per hour). This provides the water recycling services for up to 600 people, plus the wastes from their aeroponic activities. This particular SCWO is operated somewhat differently from the average SCWO on Freyr because it must be operable in microgravity; this adds an interesting engineering challenge but is relatively easily done. In addition to the SCWO, Freyr installs about 110 cubic meters of algae culture to provide oxygen for the inhabitants and 1100 square meters of aeroponic cultivation. These facilities provide the food and oxygen that the current inhabitants of Freyr require to survive and continue constructing the settlement. The large capacity of these systems allows for up to 600 inhabitants at this point in time, which provides a huge amount of manpower for the continued construction of Freyr, with about 250 man-days per 24-hour cycle (the workday during these early periods is kept to 10 hours per day).

Because Freyr is not yet rotating at sufficient angular velocity to simulate gravity, it is necessary for inhabitants to maintain their muscle mass on a daily basis through exercise programs. To facilitate this, Freyr makes use of resistance bands, pneumatic resistance devices much like NASA's ARED (Advanced Resistive Exercise Device)[177], and a few cardio training machines (exercise bikes and treadmills with weight-simulation devices). Additional cardio training is provided by high intensity interval training (HIIT) using exercises specific to a microgravity environment. The goal of all these measures is to help reduce muscle and bone loss while Freyr is in a state of microgravity, as continued exposure to microgravity has been shown to result in loss of muscle mass and bone structure.

During this phase, launch of materials from the Earth diminishes greatly as Freyr gains more and more capacity to generate its own resources from the lunar ISRUs. Construction costs fall sharply and are now determined by the amount of time that is being lost as Freyr is constructed. Naturally, Freyr is always somewhat dependent on Earth for some resources, but it is during this phase that Freyr really begins to be self-sufficient.

The most important development in this phase is the setup of ISRU operations on the Moon. It is because of these ISRU operations that Freyr will eventually be built, and getting them in place early means that the materials for Freyr can mainly be harvested from the Moon instead of having to be lifted all the way from Earth. Over the lifetime of Freyr, this corresponds to a savings of more than twenty trillion dollars ($20,000,000,000,000), not counting the cost of the materials

themselves.

This stage is expected to take about four years for completion, and will cost $42.2 billion ($42,200,000,000).

Summary Statistics

These give information on the basic state of Freyr at the end of this period.

Table 3.1: Summary Statistics After Stage 1

Property	Value	Unit
Radius	50	m
Diameter	100	m
Height	250	m
Angular Velocity	± 0	rad/s
Rim Velocity	0	m/s
Structural Mass	1.797E7	kg
Total Mass	2E7 - 4E7	kg
Moment of Inertia	2.264E8	kg-m^2
Loaded Moment of Inertia	2.519E8 - 5.040E8	kg-m^2
Habitable Volume	9.36E6	m^3
Habitable Floor Area	4.97E4	m^2
Population Capacity	500	persons
Life Support Capacity	600	persons
Recommended Population	450	persons

3.1.2 Stage 2. Fledgeling Steps

Once Freyr is self-sufficiently producing its own materials and food (using aeroponic facilities on the lunar surface), it is possible to begin construction of the larger settlement. These construction operations begin with the Industrial torus and then proceed to the Storage torus; the Life Support/Habitation torus is not yet built.

It is during this stage that Freyr begins to generate artificial gravity for the comfort and well-being of its residents. Also during this time period, Freyr's population expands to about 2000, allowing for faster progress on the construction of the Life Support/Habitation torus and allowing for faster progress on the lunar surface in terms of ISRU construction.

During Stage 2, Freyr's LFTR is brought up to full power as more manufacturing systems come online. This happens mainly as the Industrial torus is completed, which is the first major project of Stage 2.

Docking and Null-G Spaces

During Stage 2, Freyr's docking spaces are expanded, and the Spaceport is readied to be a fully micro-gravitational space. At the same time, the other parts of Freyr are prepared for spinning up and construction is continued on the Industrial and Storage tori.

Freyr's six major docking ports are constructed and installed, with four new ports augmenting the two that were already in position on the Spaceport's walls. In addition, the airlock complex at the end of the Spaceport is installed, giving Freyr the capability to export pieces made inside the settlement to the outdoors (in space). This alleviates the need for the LTVs to carry bulky payloads, which in turn leads to greater efficiency in materials transport and allows for a faster rate of metals processing and construction.

These docking spaces are what allow Freyr to really start doing business. Now that the core and Spaceport are properly outfitted to receive any type of vessel (thanks to the IDSS), Freyr is capable of beginning to do trade with parties on Earth. For example, Freyr can now begin to work on contracts from Earthbound space agencies to launch probes, manned missions, and others, as well as perform other services, and it is capable of setting up a shipping operation with its multiple docking ports. For example, given some time to get its aeroponic system working, Freyr could supply food to a LEO space station at just a fraction of what it would cost to bring the food up through Earth's atmosphere. All of these services are made possible by the versatility that these new docking ports allow Freyr, and all of them contribute to the overall economic diversity and health of the settlement. The earlier Freyr can begin to establish itself as a player in the space market - and a player that is willing to work with customers and take full advantage of its position while offering affordable options - the better off the settlement will be in the long run.

Torus Construction

With the core and Spaceport completed, work on Freyr now focuses on the Industrial torus and then on the Storage torus. These tori are constructed from components cast on Freyr from raw materials imported from the Moon, as opposed to sections cast on the Moon and imported to Freyr in their final form. This development is made possible by the completion of the core, which means that industrial processes can be carried out easily on board the settlement and greatly reduces the hassle of actually constructing additional parts of Freyr.

Sections of the Industrial and Storage tori are cast as large as will fit through the airlock at the end of the Spaceport - that is, plates of the required thickness (7.5 cm for the Industrial torus, or 1.6 cm for the Storage torus) that have a length of 28 meters and a width of 20 meters. Turned on their edges, these plates will just fit through the major airlock with a couple of centimeters to spare - the righter the fit, the better, in this case. These sections are then moved to where they are needed for the construction of the torus.

Actually securing the plates together is extremely difficult. The plates must be load-bearing, and they must be joined very firmly, which leaves but one option: directly welding the plates together. This requires massive amounts of power to do correctly, because it requires actually melting an

entire face of the plate to join it to the one adjacent, but Freyr has 100+ MWe to play with, conceivably up to 125 MWe without too much trouble. Because the vacuum of space is also a quite good insulator, this makes heating the surfaces to the required temperature easier than it would be on Earth - and, because there are no air currents in space to cause uneven cooling, the entire weld cools slowly and uniformly, resulting in increased strength and a lower possibility of failure.

Hard welding two adjacent plates together solves several problems. First, it means that there is a continuous metal structure about the entire outside of the torus, which increases its strength. Second, it eliminates any potential leaks by getting rid of all the seams between plates and ensuring that there are no gaps for air to escape through. Finally, a hard weld can actually be stronger than the metal surrounding it, further increasing the structure's strength. The primary problem with this version of hard welding is that the power requirement for heating an entire edge of one plate to the point where it can be welded is immense - as mentioned before, however, this is okay because Freyr has a large amount of power at its disposal. It is also possible that Freyr could make use of ISRU nuclear reactors for on-site power at the welding sites, which would provide an immediate and massive source of power (on the order of 10^7 watts).

It is estimated that construction of the Industrial torus will require 1322 such plates[1]. Due to the relatively slow cycle time of such a large airlock, and the fact that raw materials must also be brought in through the airlock, it is estimated that the time between plate deliveries will be approximately two hours (one hour for the airlock operations, one hour to position each ingoing/outgoing cargo piece within the airlock to prepare for cycling). This means that, given another hour per plate for delays, time lost due to unavoidable circumstances, etc, delivery of all the plates to the exterior of Freyr will take about 4000 hours, or half a year. Because this is not Freyr's only operation at any given time, however, and because the plates must also be constructed exactly to fit onto the outside of the torus, the entire process will likely take more like two years. Working at a fast pace with 500 workers, it is believed that construction of the Industrial torus within two years is feasible.

During construction of the Industrial torus, the equipment that will be used in the torus is also manufactured, and typically installed before the shell is completed. This allows easier installation opportunities and reduces the hassle required in setting up the torus's interior operations; by placing the industrial equipment directly into the torus while the shell is not yet completed, pieces as large as 20 m by 20 m by 10 m can be affixed to the inside of the Industrial torus, while the same piece of equipment installed after the torus was completed would have to be broken down into over 40 different pieces, clearly much more of a pain.

Once the Industrial torus is structurally sound, it is pressurized with helium to 30 kPa, which is its final operating pressure, and checked for leaks. When all leaks are sealed, the industrial torus is connected to the core by a set of five 3x3 meter access points, which consist of an airlock 10 m long and 3 m on a side. These allow for easier transfer of materials and personnel between the Industrial torus and the core without allowing the two atmospheres to mix and while maintaining the isolation of the two pressurized spaces so that a depressurization event does not empty both of them. In addition to these access points, the Industrial torus is joined to the core by a single large airlock of length 20 meters, width 10 meters, and height 5 meters. This airlock is used for the passage of

---

[1] $\frac{740220}{28*20} = 1321.8$

bulky materials between the two pressure shells and is capable of fitting most components that are too tricky to assemble in the Spaceport.

After this, the Storage torus is constructed. The method of construction is very similar to that used for the Industrial torus, with the plates being oriented circumferentially with respect to their length around Freyr' axis of rotation. This increases the usable area of each plate (because they have to be curved significantly due to the smaller minor radius of the Storage torus). Due to the far smaller size of the Storage torus, it is estimated than only 425 plates will be required for construction; due to increased industrial output after the construction of the Industrial torus, these plates can be completed and transported to site in just 900 hours, leading to a total construction time of just half a year for the (admittedly much smaller) Storage torus.

Once construction on this smaller torus is completed, it is joined to the Industrial torus by six 3x3 meter access points, which allow the passage of materials to be stored. There is no major airlock between these two tori due to the small minor radius of the Storage torus and because no piece of material or equipment too large to pass through a 3 meter square access point needs to be stored. The Storage torus is initially pressurized with an atmosphere of 30 kPa of oxygen and 30 kPa of nitrogen; this extreme fire and explosion risk is necessary because the Storage torus must be habitable for Freyr's personnel while the Life Support/Habitation torus is constructed.

ISRUs

Throughout this period, ISRUs on the Moon continued to proliferate. As more and more of them developed across the Oceanus Procellarum region of the Moon, they began to specialize, choosing sites optimal for the processing of certain metals found in high abundances at that specific point on the surface.

This specialization allowed greater efficiency in the processing of materials. When each ISRU was concerned with the extraction and purification of all ores, the process was lengthy, more difficult, and generally not a very efficient method of obtaining materials. Under the new method, each ISRU could quickly and efficiently harvest one or two minerals from the lunar regolith and discard the rest of the regolith as waste, leading to more discarded regolith but also faster and more efficient production of the materials Freyr needs to continue development.

For example, an ISRU located in a particularly good site for titanium might extract the ilmenite portion of the lunar regolith and discard the rest - and then, depending on the exact economics of the situation and what metals Freyr needed at the time, could choose to either process out all of the metals present in the ilmenite or just separate out the titanium, leaving the rest of the ilmenite as unwanted waste. Because of the ease of extracting iron from ilmenite, however, it is anticipated that with relatively little extra effort, a titanium extraction ISRU could easily also purify iron as a metal and achieve greater oxygen production. Iron is not particularly useful to Freyr, but its applications on the Moon - and, to a limited extent, on Freyr - make it a useful metal to have around. At the very least, it could be used to provide basic fittings, utensils, and etc. for the ISRU's crew.

In much the same way, an ISRU dedicated to the extraction of silicon might discard the titanium

in its regolith samples because it lacks the infrastructure to efficiently process that metal, gaining 10 or 20% efficiency in the production of silicon just by choosing to focus on its extraction over the extraction of all other minerals.

Note that this is only possible because of the large number of ISRUs that can be constructed during this stage and time period. With only a few ISRUs, it is necessary that each of them use the lunar regolith to the best ability of the technology and extract all useful materials from it; when there are many ISRUs involved in the lunar mining process, each individual one can focus on a particular material because, as a whole, they can still provide enough of each material for Freyr and have redundancy in the system.

Habitability

When the Industrial and Storage tori are structurally sound and the major pieces of internal equipment have been placed, ETVs and LTVs dock to the outside edge of the storage torus and begin to accelerate the station. These craft collectively provide a total of 7362 kN at a radial distance of 320 m, which gives a torque of 2.356E9 N-m. The vehicles are attached to the Storage torus by locking grippable bars; these bars are embedded in the Storage torus's shell and are designed to spread out a load of up to 5 million newtons over a large area of the shell of the torus, alleviating the stress of having a large spacecraft hanging off of the outside of the torus.

Based on an assumption that the moment of inertia of the parts of Freyr that currently exist is 2.9E13 kg-m^2 (see 1.3.9), the angular acceleration due to this torque is:

$$\Gamma = I\alpha$$

$$\alpha = \frac{2.356E9}{2.9E13} = 8.1E - 5$$

8.1E-5 radians per second squared. Based on these calculations, it takes about 1850 seconds to attain Freyr's normal rotation velocity of 0.1476 radians per second:

$$0.1476 = 8.1E - 5 * t$$

1850 seconds is just over half an hour, indicating that the total amount of fuel expended to spin up Freyr is about 926 tons of hydrogen propellant. While this is a large expenditure of propellant, it is more than paid for by the benefits of having a rotating settlement and can be paid back in weeks or a couple of months with the by-products from helium-3 extraction (one day of helium-3 extraction, coupled with a little electrolysis, results in over 25 tons of hydrogen propellant).

Once the ETVs and LTVs are finished spinning up the tori, they drop off of the outside of the Storage torus, falling away from the structure. This removes them from the rotating reference frame. At this point, they fire their engines once more to cancel out their velocity with respect to Freyr and begin to move back towards the docking ports on the Spaceport.

Spinning up the Industrial and Storage tori enables Freyr to provide an environment for its personnel in which there is not a constant danger of bone degradation and muscle loss - or, at least, not such a great danger as before. Because Freyr's angular velocity is designed for generation of 1 g at a larger radius, namely 450 meters, and the Storage torus has an outer radial distance of just 320 meters, the gravity felt by Freyr's personnel at this point during the settlement's development is only 6.98 meters per second squared, or 0.71 g. While it is expected that this will be sufficient to counteract most of the harmful effects of low gravity, and it is certain that a partial gravitational environment will be less detrimental to Freyr's personnel than a microgravity environment, it is not certain how this specific level of gravity will affect the human body, and this stage of Freyr's development can help to fill in some medical holes in the understanding of the human body's response to a low-gravity environment.

During Stage 2, Freyr's personnel by and large live in the Storage torus. With a habitable volume of 2.37 million cubic meters, much greater than the core's volume of 229000 cubic meters, Freyr's population can expand to about 1000 persons in comfort. To deal with the larger population size, a more advanced and more capable life support system is installed in the Storage torus. Some of the equipment is moved from the core, such as much of the aeroponic growing system, but some of it is constructed fresh for this application, such as a new SCWO unit and a new set of algae culture tanks. It is important that the core retain their tanks, separated as they are from the rest of Freyr's life support by the Industrial torus. Based on these improvements, each of Freyr's crew is assigned their own area, and basic rooms are constructed within the Storage torus to help alleviate some of the oppression of sharing a relatively confining space with a thousand neighbors for a lengthy amount of time (until the Life Support/Habitation torus is completed).

To help with feelings of confinement, certain areas inside the Storage torus are set out as clear paths, where Freyr's current population can have a direct line of sight along the torus and thereby gain some minor sense of freedom.

Additionally, the first civilian government on Freyr is initialized during this phase of construction. While before authority was wielded by a few authority figures who planned the development of the settlement, now governance of Freyr's long-term situation was handed over to part-time politicians (part-time because everyone still had to work a full job to make sure the settlement was completed on time). This helped Freyr's population feel that they had a voice in the long-term development of the settlement. While this first civilian government is not a fully functioning one, it does have certain powers and it can make decisions about the general state of the settlement, provided that the operations team still has priority in the day-to-day operations of Freyr. This is the same system that is implemented in the final iteration of Freyr, once construction is complete.

Summary Statistics

Statistics about Freyr at the end of Stage 2.

Table 3.2: Summary Statistics After Stage 2

Property	Value	Unit
Radius	320	m
Diameter	640	m
Height	325	m
Angular Velocity	+0.1476	rad/s
Rim Velocity	47.2	m/s
Structural Mass	2.592E8	kg
Total Mass	3.5E8 - 5E8	kg
Moment of Inertia	9.017E12	kg-m^2
Loaded Moment of Inertia	1.353E13 - 2E13	kg-m^2
Habitable Volume	5.80E7	m^3
Habitable Floor Area	1.027E6	m^2
Population Capacity	1250	persons
Life Support Capacity	1500	persons
Recommended Population	1000	persons

3.1.3 Stage 3. Independence

Finally, during Stage 3, Freyr begins to breathe on its own. It moves away from the influence of Earth in its operations and, instead, looks within itself for completion. During this phase, all but the most difficult to manufacture materials are produced directly on Freyr or in a lunar ISRU; even fluoridated toothpaste can be produced using fluorine bound in the lunar regolith, then recycled after passage through an SCWO. There are very few things that Freyr cannot do for itself at this point.

Moving away from lifelines with Earth does, by necessity, present some challenges of its own. For example, Freyr must be ready to be truly self-sufficient if it intends to reduce imports from Earth drastically enough to really matter, and Freyr now has to set up a complete and functional government. Before any of this can happen, however, the construction of the Life Support/Habitation torus must be undertaken and completed.

Construction

The Life Support/Habitation torus is the largest of them all, and the most difficult to construct. This is due to several reasons: the thicker plates used in its construction, the fact that some of Freyr is already rotating, and the simple size of the torus. These difficulties are addressed below.

Firstly, the thicker nature of the plates necessary for this torus makes it more difficult to complete the necessary welds and provide a thorough link between two adjacent plates. 20 centimeters is simply a huge amount of metal to weld, and were the project not in a vacuum this venture would be impossible.

To complete the weld, two teams work on heating the plate's edge at the same time, working from opposite sides of the plate. That is, one of the teams is "inside" the final structure, and the other is "outside" it. This means that each team must weld as if they were working on a 10 cm segment instead of a 20 cm segment. The welding is conducted in the same manner as it was for the other tori, with one of the plates' edges being melted and then the two being fixed to each other and being allowed to cool passively. Because of the thicker nature of these plates, however, this cooling happens at a slower rate and is actually more uniform, which helps to increase the strength of the weld and reduces the possible of structural deformities within the metal[2].

Nevertheless, welding these plates together is much more difficult than welding the thinner plates used for the Industrial and Storage tori. Another complication is added by the silica glass used in the material of the Life Support/Habitation torus, which takes extra care to join properly. When done correctly, however, this material forms an even stronger bond than the metal it is mixed with, helping to reinforce the joints between plates. It melts at a temperature just higher than that at which the titanium-aluminum alloy melts, but because it is so embedded in the metal, it acts as a heat sink of sorts while being heated, which means that the titanium alloy and the silica glass melt at approximately the same time. At this point, the two plates can be joined, and the slow passive cooling process that ensues ensures that the silica forms a strong bond across the joint.

Another aspect of the thicker plates used for this torus is that they must be slightly smaller to fit through the airlock - 27 meters by 20 meters. This is still a very large area, and the plates are only smaller than those used for the other two tori by 20 square meters, but the difference is still palpable in that it increases the number of difficult welds to be made during the construction of the torus.

Secondly, some of Freyr's structure is already rotating. This leads to a dilemma: construct the Life Support/Habitation torus while it is rotating, or construct it in a non-rotating frame and then maneuver it into position and spin it up?

The correct answer, it is believed, is to construct the torus in a non-rotating reference frame so that the welding is easier and the internal structure can be laid out more easily, then to move the torus to its final position and spin it up to the same angular velocity as the rest of Freyr[3]. This provides several advantages over the other method: the construction process is easier, the torus can be spun up all at once, and the different decks of the torus can be fabricated and pre-installed. Additionally, it is possible to get at spaces this way that might otherwise be obstructed by the Storage torus. Once the Life Support/Habitation torus is complete, the Storage and Industrial tori are spun down to facilitate attachment of the Life Support/Habitation torus; attempting to keep those sections of Freyr rotating while attaching the final torus introduces numerous catastrophic failure modes.

To facilitate this method of construction, the unfinished Life Support/Habitation torus is constructed in a sort of drydock, a ring around the Spaceport. It is constructed at its final radius but in a non-rotating frame, which allows the finished product to be moved easily to its final position but still allows all the advantages of non-rotating construction. During the drydock period, the

---

[2]This is because a slower cooling rate leads to larger crystal size, among other factors.
[3]Note here the difference between angular velocity and angular speed...get it?

unfinished torus is held in the proper position by lightly tensioned cables attached to several points along the Spaceport's surface. These cables, by providing a force of tension against the incompressible metal of the torus, result in a compressive force in the torus and keep it in the proper alignment.

As a requirement, then, the first part of the torus to be constructed is an inner ring at a radius of 321 meters. This ring is what the cables are attached to, and provides a backbone for the construction of the rest of the torus. Once this backbone is in place, the rest of the torus can be constructed in an outwardly direction and the interior can be filled in as the exterior grows. Note that if this construction were attempted while the beginnings of the torus were rotating, not only would the construction crews constantly be battling simulated gravity while holding onto 440-ton panels of the shell, the rotation of the entire settlement would begin to slow as more and more pieces were added, and it would become very difficult to maintain the rotation given that the torus to which the rotation-maintaining VASIMR engines are attached is not yet complete.

Finally, the size of the Life Support/Habitation torus is a challenge that stands in the way of constructing it. The torus requires a staggering 3100 panels, and because they are so much thicker, each one may take up to three hours, even with the increased crew size, to fabricate, export, and then attach to the growing structure. Additionally, this particular torus requires like neither of the others that the interior be filled out as the torus is constructed, which slows down the actual construction process to as much as six hours per panel.

Still, 3100 panels at four hours a panel leads to 12.5 thousand hours of work to complete the structure of the Life Support/Habitation torus. Based on a 24-hour workday with about 300 in each shift of eight hours, plus some extra time working on the other workings of the settlement, this still comes out to a year and a half just for the construction itself. To complete the interior to a satisfying degree, an estimate of four years is likely more reasonable, which includes a crew of 1000 people building and not doing much else. The only thing saving the project is the microgravity the torus is being constructed in, which makes it easier to handle large pieces of equipment and material. If this construction were being conducted in normal gravity, it would doubtless take a much larger crew to complete a similar task in the same amount of time.

On the other hand, those four years include the installation of the necessary life support systems, including the water, air, and waste processing systems. Essentially, all non-biological components are installed at this point as long as they can handle vacuum. If they cannot, then they are installed later, once the torus is complete and pressurized.

Near the end of the construction of the Life Support/Habitation torus, large fuel tanks are installed around the rim of the torus. These tanks hold hydrogen fuel for the NTRs used by ETVs and LTVs, which is used to spin up the torus.

Fuel Requirements Note that this requires a productive capacity of about 77 tons per hour, necessitating a massive amount of fuel for LTV trips, which must be conducted, on average, every 109 minutes. Because each LTV trip requires 35 tons of fuel, fuel must be produced at an average rate of 20 tons per hour. Because the fuel is simply hydrogen, this is easier than it might otherwise be, but still the fuel requirement is not trivial. Helium-3 mining results in the production of 3.4

tons of hydrogen per hour, clearly not enough to meet the demand. To make up the difference, water processing ISRUs dedicate all excess power and water to electrolyzing hydrogen, which for an assumed capacity of 10 water processing ISRUs generates another 336 kg per hour, but even this step is not sufficient to deal with the sudden requirement for high volume transfer and high fuel usage. Fuel depots established on the Moon could have a total capacity of perhaps four or five kilotons of hydrogen; this store will last for between 13 and 14 weeks and take about 79 weeks to replace. The balance of fuel usage during Stage 3, then, must come from some source other than hydrogen. This leads to the use of oxygen, nitrogen, helium, carbon dioxide, or pretty much any gas in the NTR engines. Even water could be used, if necessary. The NTR becomes less efficient as the molecular mass of the fuel increases, which is why hydrogen is the preferred choice of fuel, but to get the job done and use up excess volatiles most any fuel can be used. This has the advantage of utilizing higher molecular weight fuels, such as oxygen gas, which allows the contribution of water processing ISRUs to jump to about 10 tons per hour and means that fuel production due to helium extraction is as high as 9 tons per hour. With these production rates, the draw on fuel stockpiles can be as low as one ton per hour, which means that to last 18 months said stockpile must contain a minimum of 13 kilotons of fuel. Because of the acceptance of fuels other than hydrogen, however, these stockpiles are fairly easy to accumulate, taking only four or five weeks to accumulate.

Spinning Up

Once the structure of the Life Support/Habitation torus has been finished, the torus is moved to its final location and then joined to the Storage torus before the entire settlement is spun up as a complete unit. The ETVs and LTVs complete both of these tasks, using their NTR propulsion systems to move the bulky and massive torus.

Based on the torus's shell mass of 1.62 million tons, plus a multiplier of perhaps 1.2 for existing interior fixings, the ETVs and LTVs can effect a linear acceleration of 4.54E-3 meters per second squared, which is by any accounts a safe enough speed for the torus to be well controlled on its path to its final location.

$$a = \frac{F}{m} = \frac{7362000\,\text{N}}{1620000000\text{kg}} = 0.00454\,\text{m/s}^2$$

While en route, the torus is first accelerated to about 0.1 meters per second (which takes just over 20 seconds) and then left to drift. The trajectory of the moving torus is constantly monitored by computer systems in the core of Freyr, and the cables holding it in the correct configuration help to keep it steady as it travels. While no deviations from straight-line movement are expected, these measures are put in place to be absolutely certain that construction disasters do not strike at this point in the construction of the settlement. Even a minor mistake could be absolutely devastating, resulting in massive destruction and pressure loss.

Once they have accelerated the torus to the desired speed, the ETVs and LTVs position themselves on the opposite side of the torus. At the rate at which the torus is moving, it takes approximately 1000 seconds to travel to the desired location; when it is 100 seconds away, the ETVs and LTVs

slow its velocity to just 0.05 meters per second, doubling the amount of time remaining. The last 30 meters of the procedure are conducted at the tiny pace of 0.01 meters per second; at this speed, it only takes 2.2 seconds to slow to a stop. The slow approach used here is for safety; while a faster approach would be easier to pull off using the ETV and LTVs' engines, it is necessary to ensure that the vehicles have enough time to arrange themselves properly and that the torus is oriented properly; going too fast invites disaster to strike.

Altogether, the translation of the torus from its position around the Spaceport to its final position takes about 45 minutes (during the acceleration and deceleration phases), which does not count the amount of time spend preparing for the transfer.

Once the torus is in position it is attached to the Storage torus with both hard welds and attachment cables. At this point, it is necessary to spin up the settlement and restore artificial gravity. To provide fuel for this operation, which is more more fuel-intensive than spinning up the Industrial and Storage tori due to the much greater moment of inertia of the Life Support/Habitation torus, fuel lines are run from the interior of the Life Support/Habitation torus directly to the fuel tanks of the ETVs and LTVs spinning up the torus. The fuel depots placed inside the torus were placed there for exactly this purpose. While it is somewhat more difficult to use tanks located inside the torus simply because they must be placed there, consider that no other part of Freyr will be co-synchronously rotating with the Life Support/Habitation torus while it is in the process of being spun up.

The ETVs and LTVs provide more torque during this operation than they did while spinning up the Industrial and Storage tori, because of the larger lever arm of the force they apply, but the moment of inertia of this torus is also much greater. Based on reasonable assumptions about the amount of mass in the Life Support/Habitation torus and its distribution, which leads to a moment of inertia for the torus of 4.00E14 kg-m^2, the angular acceleration due to the force applied at $r = 525$ meters by the ETVs and LTVs is:

$$\Gamma = I\alpha$$

$$\alpha = \frac{3.865E9}{4.00E14} = 9.66E - 6$$

This angular acceleration is 0.12 times the angular acceleration of the Industrial and Storage tori when they were spun up, and indicates that the process will take 15,275 seconds. This corresponds to 4 hours and almost 15 minutes, much longer than the time it took to accelerate the Industrial and Storage tori.

Based on the equation for fuel consumption:

$$\dot{m} = \frac{F_T}{I_{sp} * g_0} = \frac{7362000}{1500 * 9.81} = 500.3$$

The total use of fuel is 500.3 kilograms of fuel per second. Multiplied by the burn time of the

accelerating force, this comes out to 7,642 tons of fuel expended[4]. Clearly, this is a huge expenditure of fuel, but it provides such huge advantages that it is immediately justified by the presence of a large habitable volume and of Earth standard gravity in the residential areas.

7642 tons is about the amount of hydrogen propellant gained from the processing of 2 tons of helium-3, which takes several years to build up but is clearly not impossible. Alternatively, it could be produced from the electrolysis of 68,175 tons of water, but this doesn't seem like a terribly attractive or practical solution. It could be possible to use some sort of electrical motor - but consider that the amount of power evolved by the engines is in excess of 285 MW, which means that Freyr is incapable of providing such an angular acceleration. Additionally, after scaling down the power consumption to something suitable for Freyr's reactor - say, 100 MW - there would be additional losses, not to mention the difficulty of setting up a system for transferring the energy to the torus. Using ETVs and LTVs, by contrast, allows the re-use of several of Freyr's components, putting them to a new use and finding new applications for old technology. This not only makes use of existing methods, it also reduces infrastructure costs and maintenance issues.

As before, once the acceleration is complete the ETVs and LTVs drop off of the outside of the torus and return to the Spaceport. After this, the VASIMR rotational maintenance engines are fired up as necessary to maintain the settlement's rotation.

Interior Finishing

Once the Life Support/Habitation torus has been spun up, its interior is outfitted to be a permanently habitable place for humans. The hydrogen propellant tanks are removed, making space for life support systems on the Lower Life Support deck, while the other decks are set up for their particular functions.

The first step is installing the life support systems of the torus. These systems are described in 1.4, and the descriptions are not repeated here. Note that all of the life support systems can be throttled up or down depending on capacity, for example by using more or less of the capacity available, meaning that the same life support systems can remain in place throughout the torus's life cycle.

At this point in Freyr's construction, it is not necessary to use more than a small fraction of the available life support capacity because the settlement's population is only about one thousand persons. This begins to change in Stage 3, as the life support systems are installed. Once all of the life support systems are in place and functional for 1000 persons, the entire populace of Freyr is moved into the Life Support/Habitation torus, freeing up space in the Storage torus. Of course, before this happens, there are safety checks conducted on the interior of the torus by workers in MCP suits as if they were on EVA. These inspections ensure that the atmospheric composition, temperature, and other characteristics of the Life Support/Habitation torus are all as they should be before the population of Freyr is allowed in without suits on.

Buildings are installed as Freyr's populace begins to inhabit the Life Support/Habitation torus,

---

[4]$500 * 15275 = 7642171$

being constructed mainly following one plan but with some small customization. It is expected that during this phase, the Life Support/Habitation torus will feel much too large, as the population is currently only 5% of the population the space was designed for. While the colonists are split evenly between the two habitation decks, then, they are otherwise not limited in their choice of housing location. This means that those who wish to be part of a closer community have the opportunity to do so, while those who wish to be alone also have that ability. Since, however, the greatest distance between any two people on the habitation decks is not greater than 1500 meters, the separation distance is not really so great as it seems. Still, after the close confines of the Storage torus, endured for years, the open areas of the Life Support/Habitation torus are incredibly spacious.

Population Growth

After the completion of the Life Support/Habitation torus, it is possible for Freyr's population to begin growing. This requires lifting people into orbit, generally, because increasing the population via in vitro fertilization and surrogate mothers is impractical on Freyr's timescale.

Lifting people out of Earth's atmosphere and gravity well requires a lot of energy. A single launch of a people-containing vessel from Earth to LEO could cost around $600 million dollars and could transport 30 people, for a to-orbit cost of some $20 million. The economies of scale involved in launching thousands of people, along with improvements to the launch vehicle and partial recovery of the booster stage, could conceivably reduce this amount to $7 to 10 million, and at an ideal level of recovery the cost of launching a person to LEO could be as low as $2 million.

Once these people are in LEO, they are met by an ETV that transports them to Freyr. After launch, their capsule itself is attached to the ETV, meaning that they must carry provisions and supplies for a relatively long stay without resupply. A single ETV can conceivably transport up to 120 people at a time, taking five days to make the trip and perhaps two days in LEO to attach the capsules correctly.

Freyr's population is increased in this way and by encouraging inhabitants to have children at a slightly higher-than-sustainable rate. The first method leads to linear population growth, while the latter leads to exponential and then logistic population growth; eventually, the logistic model becomes more important in modeling Freyr's population dynamics.

Population growth is kept relatively slow, perhaps a thousand people per year at first, to help ease Freyr into a state of higher life support production and to ensure that the number of new people arriving on Freyr is not overwhelming and that at any given time, almost all of Freyr's population knows their way around the settlement and knows what to expect. This helps keep Freyr running smoothly even as its population steadily increases.

Full Capability

At the end of Stage 3, Freyr is structurally complete. It contains all the facilities, mechanisms, and trappings that the settlement will need. All that remains is for Freyr's residents to set up a social

structure, elect their leaders, and continue work on the industrial and manufacturing capacity of the settlement. These are processes that may never be complete.

Once Freyr has reached its full population of 20,000 persons, it ceases bringing people up from Earth for permanent habitation. Despite this, there is still the option for a vacation trip for Earth's very rich, who can make their way out to Freyr and spend a week or a month exploring the settlement and gawking at outer space.

At its full capacity, Freyr can now begin to focus on less tangible goals: developing strong relationships with Earthbound entities, producing skilled manufacturers and workers for the industrial applications of life on board Freyr, and other such pursuits.

Summary Statistics

These statistics summarize Freyr after Stage 3 is complete.

Table 3.3: Summary Statistics After Stage 3

Property	Value	Unit
Radius	525	m
Diameter	1050	m
Height	325	m
Angular Velocity	+0.1476	rad/s
Rim Velocity	77.5	m/s
Structural Mass	1.88E9	kg
Total Mass	3.76E9 - 5.64E9	kg
Moment of Inertia	3.140E14	kg-m^2
Loaded Moment of Inertia	6.281E14 - 9.421E14	kg-m^2
Habitable Volume	5.186E7	m^3
Habitable Floor Area	7.86E5	m^2
Population Capacity	24000	persons
Life Support Capacity	25000	persons
Recommended Population	20000	persons

These statistics correspond to the complete picture of Freyr as outlined in 1.3.9. At the end of Stage 3, then, Freyr is structurally complete and capable of pursuing all endeavors intended of the settlement.

3.1.4   Stage 4. Further Development

After Stage 3, there is not much left to do in the official development plan for Freyr. Industrial capacity can be brought online, community can be built, ISRUs can proliferate across the lunar surface, but in general Freyr is remarkably complete.

At this point, then, Freyr diverges from the development plan laid out for it and travels down one of several roads. The foreseeable options are as follows:

1) Provide a source of raw materials for further space stations or settlements;
2) Expand its own structure on the opposite side of the Spaceport (most likely) or attached to the reactor end of the core;
3) Focus on building new space stations of settlements under its own guidance; or
4) Conduct some other choice that makes sense based on the specific situation at the time.

Raw Materials

If Freyr decides to act as a source of raw materials for new space stations or settlements, it will begin to focus primarily on industry, paying the most attention to acquiring as much material as possible so that it can sell that material to other entities.

Ideally, Freyr would like in this case to become a monopoly on readily available metals, ceramics, and other materials vital for construction in space. While certainly any other entity could start from scratch like Freyr and develop its own mining industry, it is much easier and potentially more cost-effective to acquire materials after they have been extracted and refined. This is especially true of such rare materials as the radioisotopes required for a nuclear reactor, which are scattered in relatively low concentrations across the lunar regolith - or the regolith of any other planet or asteroid.

Essentially, by making use of the infrastructure that Freyr already has in place because of its development of resource utilization from scratch, Freyr could dedicate its productive capacity to producing goods to be sold to other settlements or stations. While Freyr would have to be careful to avoid exceeding the cost for import from Earth, and would also be wise to keep prices low enough that buyers aren't tempted to produce their own goods from the regolith, this scheme would provide a tidy income for Freyr and establish strong trade relationships with other developing space powers.

Expansion

Going another route, Freyr could expand its structure through the addition of another microgravity module, adding further industrial, manufacturing, and habitation capacity. This would allow faster progress towards any other goals while making Freyr an even more imposing force in space exploration and development.

Freyr could attach more sections to itself just about anywhere, but one obvious choice is to duplicate its structure so that the two Spaceports face away from each other and the reactors are close. This provides several disadvantages, of course. Another option is to build further on the existing structure, possibly adding specialized industrial tori between the Industrial and Life Support/Habitation tori, above and below the Storage torus[5]. This could have interesting implications

---

[5]The Spaceport points upward, away from the rotational plane.

for Freyr's uses. Alternately, additional storage spaces could be constructed, or microgravity areas could be expanded in any shape desired.

This route would likely be the one chosen if there are no forthcoming space stations or settlements to sell to, in which case Freyr's manufacturing base would simply be producing parts that could not be stored up forever: building more stuff with them is simply the easiest way to get rid of these spare parts.

An expansion of Freyr would also increase all sorts of manufacturing capability, increasing Freyr's revenue and giving it more leverage to continue development of vital systems and further desired systems.

New Settlements/Stations

Freyr could also choose to build its own settlements and stations, whether in the Earth-Moon system or somewhere else. These settlements would be loosely affiliated with Freyr and would likely be set up under some sort of profit-tithing system, allowing Freyr to maintain some control without stifling development and overburdening itself.

If Freyr chooses to develop its own settlements in space, it stands to gain much: either a vast store of scientific knowledge, if that is the purpose of the station/settlement, or a large amount of profit, if profit is the motive of the settlement or station. By binding these new stations and settlements to it, Freyr will also effectively have the power to determine the laws of the use of outer space, making it an important political and legal player in the space game rather than simply a solitary settlement in lunar orbit.

What's more, Freyr could so easily provide the materials to get these settlements started that they could begin operations with hundreds of inhabitants nearly immediately. As Freyr began, a station would be sent ahead with basic life support systems and the larger station or settlement would be built around it. Freyr's rate of industrial output indicates that a massive amount of material could be shuttled quickly to even distant locations; this is one case where the increased efficiency of a VASIMR system is very helpful, especially on the initial robotic missions that set up basic living conditions.

Freyr is not limited, in this, to orbital settlements. It could also choose to set up planetary bases, which would most likely be bound to Freyr in the same way that any orbital settlement would be. The ability to start these planetary settlements is, of course, due to Freyr's established capabilities, which allow broad-base support for settlements as they start out and provide a sort of safety net or rescue mechanism for the inhabitants of these new settlements.

Another Option

It is also very possible that the option that makes the most sense for Freyr is not included in the above list. This could be due to any number of factors that could arise between Freyr's founding and its completion. It is impossible to know exactly what these factors will be, and thus it is

impossible to conclude what possible paths Freyr may consider. Several good guesses are given above, but only in the broadest of terms; the specific situation and response will be unique to Freyr when the necessary time arrives.

3.2   Cost Estimate

The brilliance of Freyr is that, after the initial investment for the fleet of ETVs, LTVs, and basic support ships, and the first of the lunar ISRUs, there is no cost to lifting most of Freyr whatsoever. That's because Freyr mines and processes the vast majority of its own materials from lunar resources. Once the fist water and metals ISRU sites are complete, they can produce most of the materials needed for further expansion, production of more ISRUs, and the processing and fabrication of materials for Freyr.

The downside of this approach, of course, is that it results in longer construction times and a more difficult construction process, but the savings of trillions of dollars of lifting supplies to lunar orbit more than offsets these costs.

3.2.1   Initial Costs

It is, however, necessary that for a while, anyhow, Freyr will depend on Earth for some materials. Despite its processing and industrial capabilities, Freyr cannot hope to provide a substitute for some of the advanced electronics, machinery, and equipment that must be specially manufactured even on Earth. Until Freyr gets a computer chip facility operational, for example, it has to import hard drives, processors, RAM, and other computer components. Other materials will simply take time before Freyr can get a production system up and running, and so must be imported as well. It is estimated that throughout Freyr's lifespan, it will have to import some 500 tons of materials per year, at a cost of up to $7000 per kilogram for launch to LEO and transport to Freyr. Importing about 500 tons annually thus corresponds to a cost of $3 billion per year.

Additionally, the initial ETV and two LTVs that must be launched mass a total of 190 tons, plus 425 tons of initial fuel for the ETV and one LTV to make the trip to the Moon and set up the fuel production system. At a cost of $6000 per kilogram to LEO, this adds $3.69 billion to Freyr's price tag. The lunar ISRUs each mass some 500 tons, and three of them are set up before materials are being produced from the Moon, for a total launch of 1500 tons to LEO. Assuming, again, $6000 per kilogram, the initial three ISRU units tack on $9.00 billion. Finally, the station put into orbit around the Moon for initial operations control and to serve as a sort of nucleation site for Freyr has a mass of about 1000 tons, adding $6.00 billion onto Freyr's budget.

The materials and construction for these facilities is also costly. It is assumed that about 30% of the budget for the development of each facility will go into planning and design, leaving 70% to actually build the craft. Given that the pieces of these various facilities must be individually designed at this point saves money in the long term, but results in costs in the short term, with a development cost of perhaps $2 billion for the LTV and ETV, $4 billion for the ISRUs, and $10 billion for the space station. The use of COTS components saves money in the design phase of all these facilities, making the development cost much smaller than it would be for a facility designed from scratch - for example, some old ISS module designs are used for the space station, and empty upper-stage fuel tanks can be repurposed into cargo containers for the ETVs and LTVs. The use of pre-existing components in this way means that less development cost has to go into each component of the early

launches and launch systems, driving down some of the single greatest costs of the project. The most expensive vehicle components to design for their mass are the ETV and LTV components, and these are produced in large enough quantities to offset these somewhat greater development costs. The higher cost of ETV and LTV development is driven by the need to integrate life support systems into a new package, developing fail-safe systems that can be used effectively in the event of a system failure, and the development of the required electrical/programming/hardware subsystems.

Freyr must also launch its personnel. Over the construction timeline of the settlement, it is expected that about 10000 of Freyr's residents will need to be lifted out of Earth's atmosphere. Because there is no need for them to return through that atmosphere, they do not need the kind of heat-shielded capsule used by today's astronauts; instead, they can make use of a less cramped, more spacious design. Development costs for this launch configuration could run as high as $1-2 billion, and launches would include the mass of the container as well as that of the colonists. A reasonable to-orbit payload could be around 100 tons, depending on the rocket used, so the cost for bringing about 30 inhabitants to Freyr, as well as one passenger-suitable cargo module, runs about $600 million.

The initial setup cost, then, is approximately $42 billion, plus or minus up to five billion dollars. Freyr has budgeted $50 billion for this cost so that it can be sure to have enough funds; excess capital goes towards offsetting the continued cost of launching vital supplies to LEO.

Table 3.4: Initial Setup Costs

Item	Cost
ETV and LTV Design	$2 billion
1 ETV	$0.540 billion
2 LTVs	$0.600 billion
Fuel	$2.55 billion
ISRU Design	$4 billion
3 ISRU Stations	$9.0 billion
Lunar Station Design	$10 billion
1 Lunar Station	$6.0 billion
Launch Vehicle (Cap. 30) Design	$1.5 billion
10 (Cap. 30) Launches	$6.0 billion
Total	**$42.2 billion**

Once this expense of $42 billion has been made, Freyr is well on its way to being operational. It has a crew of up to 300 individuals working on the Moon and in lunar orbit to begin the construction of Freyr, and it has three ISRU facilities extracting minerals for further development. After this point, other than incidental launches from Earth, the primary expense that Freyr incurs is the import of supplies it cannot produce itself. The cost of this import comes to $3 billion per year, clearly not an insignificant cost to Freyr. At this point, however, Freyr can begin contracting with space agencies to conduct missions, launch probes and vehicles, and conduct other business to offset the cost of importing these items. As it grows steadily more self-sufficient, also, the cost of importing items that cannot be constructed on Freyr drops as fewer items need to be imported, and due to

Freyr's small initial population the cost then is much smaller as well.

3.2.2 Main Body

Some of Freyr's technologies have to be imported from Earth even once it is operational. These, as mentioned above, run to about $3 billion per year. These expenses cover all of the physical items that Freyr requires per year - 500 tons is really quite a lot of material for a population of 20,000 to be importing on an annual basis, and is equivalent to somewhere around 200,000 laptops every year.

Other non-physical items may also require payment. These include the salaries of ground-based individuals working for Freyr or interfacing with Freyr as their primary responsibility, the costs of communicating through existing networks with contractors and representatives, and other costs. The annual sum of these costs is not yet known, but is expected to be up to $5 million per year. Compared to Freyr's other expenses, then, these costs are insignificant.

As circumstances require, there may also need to be one-time purchases of large equipment: for example, another ETV delivered to LEO or a set of particular components that Freyr does not include in its annual $3 billion for materials purchases. These purchases are not expected to exceed $50 million per year, but it may come about that they do exceed this amount. In any case, the scale of these expenses can be reasonably estimated to be between 10^6 and 10^8 dollars per year (one million to one hundred million dollars). Again, use of COTS components can help to drive down these costs.

3.2.3 Balancing the Books

Based on Freyr's capacity for helium-3 production following the curve:

$$P(t) = \begin{cases} 0.6 + 0.1 \ln(t), & t \leq 10 \\ 0.807 + 0.1(t - 10), & t \geq 10 \end{cases}$$

Where P is in tons per year and t is in years. This curve represents the beginning of helium-3 production at $t = 2$ years and models a steady but slow rate of growth from there, with a capacity of one ton per year reached at $t =$. Assuming a market value of $5.7 billion per ton, we perform the integration of $f(x) = A + B \ln(x)$ from 0 to x' and find that the result is:

$$F(x) = \begin{cases} Ax' + Bx'(\ln(x') - 1), & t \leq 10 \\ Ax_c + Bx_c(\ln(x_c) - 1) + Ct - DEt + \frac{D}{2}t^2, & t \geq 10 \end{cases}$$

Plugging in our own values, it is clear that Freyr's cumulative revenue from helium-3 production can be given by the function:

190

$$R(t) = 5.7E9 \begin{cases} 0.6t + 0.1t(\ln(t) - 1), & t \leq 10 \\ 7.302 - 0.193t + 0.05t^2, & t \geq 10 \end{cases}$$

Note that $R(t)$ is in dollars and t is in years. With a 5% interest rate on the initial investment of $42 billion, the balance after 14 years is negative. This indicates that from the time Freyr's initial components are launched, it will take about 14 years to pay off the debt incurred from the launches. While the model used certainly becomes invalid at some point, it remains reasonably valid through 20 years, meaning that we can expect to have Freyr's launch costs fully paid off in between 12 and 18 years.

This analysis does not include the contribution due to other materials and services that Freyr can provide to the Earth, which could help to pay off the debt faster, or the annual cost of importing materials to the settlement, which could add to the debt and cause it to be paid off more slowly. Based on the combination of these two uncertainties, a wide time range is allowed for the assumed pay-off of Freyr's debt.

3.2.4 Ongoing Payments

Freyr's ongoing financial responsibilities are surprisingly small. They consist solely of the cost of lifting new materials out of the Earth's atmosphere and the purchases mentioned above under 3.2.2. This is because Freyr constructs itself from materials extracted from the lunar regolith.

Inherent in this assumption is that Freyr can obtain the mineral rights to those portions of the Moon it wants to mine. Lunar mineral rights are not exactly clearly defined, but existing laws and treaties suggest that Freyr may very well be able to acquire the rights to limited portions of the Moon for its use. If this is not the case, some of Freyr's profits may be diverted to developing countries[178] or Freyr may have to pay royalties for the use of the property to its owners. These are both eventualities that would cause a large increase in the long-term cost of Freyr.

Despite these considerations, it is entirely possible that because there is not other reasonable authority with a use for lunar regolith, Freyr may inherit the minerals rights of the Moon by placing its ISRUs on the surface.

3.2.5 Human Costs

Apart from importing the materials for Freyr's initial construction, the colonists for Freyr must all be lifted from the Earth's surface. Again assuming a launch cost of $6000 per kilogram and an average mass of 65 kg (145 lm), the cost of importing 20,000 colonists, which is a little more than will actually be lifted from Earth due to natural population increase on Freyr, is estimated to be $7.8 billion. Including the mass of whatever vehicle is used to carry them, a more reasonable number is around $200 billion if all colonists are lifted from the surface of Earth. To offset this cost some, Freyr takes a slightly longer time to develop and chooses instead to provide the necessary

materials for human life using materials from the Moon. By only actually lifting 10,000 individuals out of Earth's gravity well, Freyr saves up to $100 billion over its lifetime.

While the settlers themselves may help to offset some of this cost, it is estimated that each settler would not be expected to pay more than $100,000 due to their continued involvement with life on board Freyr, and an average payment might be more like $50,000 (estimated). While this is a very large amount of money, it buys transport to Freyr, and then job security, housing, and food for the rest of their life. Based on this average payment, 10,000 colonists could conceivably contribute up to $500 million, and at $100,000 per person they could contribute up to $1 billion. Clearly, simply charging potential colonists for the ability to live on Freyr will not pay for the lifting operations; in fact, only 0.5% to 1% of the costs are covered.

Lifting human inhabitants, in fact, is Freyr's greatest single expense, greater even than lifting the initial materials required for staring the settlement and ISRU facilities. This is because 10,000 people have a mass of 650 tons, not huge in and of itself, but also require extremely expensive protective equipment, which drives the cost and mass of a launch up.

It is possible that the development of a re-usable launch vehicle for large numbers of human occupants could drop this cost by half or more, but still, $50 billion is no small amount of cash.

To acquire these funds, Freyr continues to produce valuable economic opportunities for entities on Earth. Thus the ability to lift the human occupants of Freyr out of the Earth's gravity well is gradually acquired, and along with this trend Freyr's population is gradually increased through periodic launches instead of all at once.

Given a population growth rate of 8%, which is sustainable based on existing world statistics and Freyr's large material capability, Freyr's population will double in about 9 years, which yields a reasonable timeframe for Freyr's population growth. Based on an annual population import rate of around 270 people per year, and an initial population of 1000 persons after Stage 2, the population as a function of time in years is:

$$P(t) = P_0(1 + r)^t + D\frac{(1 + r)^t - 1}{r}$$

$$P(t) = 1000(1.07)^t + 270\frac{(1.07)^t - 1}{0.07}$$

Evaluating for $P(t) = 20000$, we find that:

$$20000 = 1000(1.07)^t + 270\frac{(1.07)^t - 1}{0.07} = 1000(1.07)^t + 3857(1.07)^t - 3857 = 4857(1.07)^t - 3857$$

$$t = \log_{1.07} 4.911880 = 23.5 \, \text{years}$$

This model finds that Freyr will be fully populated after 23.5 years, with the total cost of bringing humans to Freyr totaling up to $70 billion.

3.2.6 Final Cost Estimate

Based on the analysis here, it is clear that the base cost for Freyr is, at the very least, $140 billion. Adding to this the cost of $3 billion per year for maintenance and import of essential parts or personnel, and Freyr's total cost over a 50-year lifetime (the lifetime of the settlement is explored more fully in 3.4) comes to around $300 billion.

To account for some expenses that I have either forgotten, neglected to include, or am not correctly foreseeing, I multiply this number by three to find a more reasonable estimate for the lifetime cost of Freyr: around $900 billion.

Note, however, that based on helium-3 production of around four tons per year on average across Freyr's lifetime, and at a cost of $5.7 billion per ton of helium-3, the net cost of Freyr drops until it actually turns a lifetime profit of $240 billion. This profit does not take into account any other services or materials that Freyr sells across its lifetime.

Based on these (admittedly not very precise) analyses, the net lifetime cost of Freyr should be very much in the black.

3.3 Operational Capabilities

Freyr, once operational, is a very capable space settlement. With its population of 20,000, and the vast lunar mining facilities that were set up to provide it with raw materials, Freyr is capable of producing vast amounts of industrial output and services to the people of Earth.

It's important to understand the productive capacity of Freyr to get an idea of its development timeline and its capability for economic prosperity after completion. Nevertheless, this section is intended as an overview of manufacturing capabilities; for a more detailed look, please see 1.7 (Industry)

3.3.1 Raw Materials

Freyr's post important items of production are its raw materials, shipped to the settlement from the Lunar surface. These materials provide the basis for all of Freyr's production, and allow all of its economic activity.

After Freyr's construction is complete, the number of ISRUs on the lunar surface is allowed to decrease, and many of the remaining ISRUs are allowed to idle. This means that while a stockpile of refined raw materials may be kept at the ISRU on the Moon, further extraction is not necessarily required.

Water production is limited to two ISRUs, both active. Each ISRU contains a storage pool of about 400 tons of water, and replenishes this store as necessary. If lots of water is required on Freyr for some purpose, water production can reach 0.6 tph, or 101 tons per week. This amount of water production could completely replace Freyr's water supply in a little over a year - if all of Freyr's water were to escape from the settlement, it could be replaced in 59.5 weeks. Production of water is typically reserved for fuel production by electrolysis. The rate of extraction of 0.6 tph that a these two water processing ISRUs can provide yields a supply of hydrogen fuel of 67.2 kg per hour, or 11.2 metric tons per week. Electrolyzing the 400-ton reserve in each ISRU can then provide an additional 89.6 metric tons of fuel.

Fuel is also produced as a by-product of helium-3 extraction. At Freyr's operational capacity, it can produce at least 5 tons of helium-3 per year, which leads to a profit of $28.5 billion dollars and the production of 30,500 tons of hydrogen fuel. On an hourly basis, then, helium extraction leads to the production of 3.4 metric tons of hydrogen fuel for NTR engines. This is by far the larger source of fuel for Freyr, though the production of fuel by water-processing systems allows the LTVs to refuel at the ISRU instead of having to ship in hydrogen for the NTRs to burn.

While fuel is one of the most important consumables for Freyr because, once used, it cannot be recycled but is instead lost to space, other raw materials are even more important to Freyr's function. To get an idea of the scale of some of these materials, the amounts of several volatile gases procured during helium extraction are given here.

This is frankly an almost obscene amount of material. Just the LTV flights to move them up to Freyr from the Moon's surface would be 578 in number - although, if the hydrogen were used as

Table 3.5: Annual Volatiles Production, Tons

Volatile	Production
Helium-3	5
Helium-4	15500
Hydrogen	30500
Nitrogen	1860
Methane	8060
Carbon Dioxide	8525
Water	16430

fuel on the Moon, the total number of flights becomes 360, or about one per day. This is probably do-able, based on the scale of LTV flights during Freyr's construction, but on the other hand Freyr simply doesn't want or need the addition of 8,525,000 kilograms of carbon dioxide on a yearly basis. A possible use for these volatiles is as fuel for NTRs: although the specific impulse is slightly lower than if hydrogen were used, use of lower-quality fuel for cargo transfers allows higher-quality fuel for interplanetary missions or for sale to other parties.

The mineral production of Freyr's ISRUs is even more startling. Based on the industrial capacity required to complete Stage 3 of Freyr's construction, the ISRU network has a capacity of some 115 tons per hour. For obvious reasons, this output is restricted under normal conditions. Large stockpiles of purified raw materials can be obtained on the Moon, on the order of megatons, in the time to spare (one megaton of material can be accumulated in just over a year.

These materials can then be processed as needed, whether to build further space stations, ship materials to Earth, fabricate spacecraft, or other purposes. Note that 115 tons per hour means that enough thorium for an entirely new breeder reactor can be harvested in about three weeks, meaning that nuclear fission power on Freyr and on the Moon can proceed smoothly and without interruption through almost any demand or rate of breeder reactor production.

The carbon and nitrogen flux into Freyr from the lunar surface allows production of excess food, which can then be exported to other settlements or spacecraft or stored for later use.

3.3.2 Structural Capability

Based on the production of raw materials by Freyr's lunar facilities, Freyr has the capability to produce new structures for habitation, transport, and structural components. These can be used for a variety of purposes, but most commonly they are used for building additions to Freyr, construction of new spacecraft, of building new lunar structures. Based again on manufacturing capacity during Stage 3, Freyr can produce a total of 115 tons per hour of new material.

Clearly, this rate of production is unsustainable: as seen before, it requires an LTV launch from the Moon every hour or two, which exceeds Freyr's fueling capability rapidly and is generally just not a good idea due to sustained workload. Just as clearly, however, it is very possible to achieve production of, say, 50 tph of finished products, which could then be used to construct objects in

space. At this rate of production, another Freyr could be built in about 11.5 years using solely materials from the existing settlement.

These products could not, most likely, be assembled this fast. It's difficult to keep up a 50 tph production rate for years on end. Some of this difficulty can be alleviated with robotic and automated machinery, but some of it is simply the stress on Freyr itself and on the human inhabitants of the settlement. It is probably more reasonable to count on 35 tph of basic structural production. Note, however, that the materials produced here are strictly simple structural members - large sheets of titanium-aluminum alloy, for example. This production rate does not account for construction times, but rather simply for turning out material to be attached directly to a structure, without too much alteration or specification.

3.3.3   Complex Components

Any electronics - and, to a lesser extent, any complicated structural members - must be produced individually, and are therefore manufactured at a slower rate than bulk components. For example, cross-braced struts can be used to connect different parts of a spacecraft more efficiently than a solid block of material, both in terms of mass and in terms of manufacturing difficulty, but they take more time to make than an equivalent mass of bulk material.

Many of these parts are produced by a 3-D printing method, but some have to be painstakingly assembled manually, piece by piece, and others must be constructed separately so that they can be detached and replaced. These manufacturing methods are capable of producing extremely detailed and precise parts, but they do take much longer than the fabrication of a bulk material. Without detailed analysis of each process, which is not feasible here due to limited time, a precise estimate of this manufacturing capability cannot be made, but it is estimated that Freyr's capability for producing these complex parts is on the order of 0.5 tph. For such components as microchips, integrated circuits, etc. Freyr's manufacturing capability may be as low as 0.001 tph or even lower.

3.4 Lifetime

Freyr's lifetime is a matter paramount to its design. Analysis of systems on the ISS indicates that while repairs may be frequent, major structural damage is not common. In fact, because Freyr is in orbit around the Moon, it can start with a blank slate and never introduce orbital debris, which results in a clear flight path for Freyr and means that FOD to Freyr will be incredibly rare or nonexistent. Thus the vast majority of maintenance to Freyr will be in the form of interior maintenance - there just aren't that many things on the exterior to be damaged.

If Freyr's interior and whatever portions of the exterior require maintenance (communication arrays, etc.) can be well maintained, there is no theoretical limit to Freyr's lifespan. An analogy is centuries-old castles or houses that have been cared for and so are still in use. As components wear, however, it becomes more and more difficult to maintain Freyr at full capacity, and Freyr will begin to deteriorate. A reasonable-seeming timeline for Freyr's operational lifetime is perhaps 50 years from the time of completion. Note that this is completely arbitrary; it is currently unknown what the wear and tear may be on the settlement and it could conceivably last for far longer than this (or far shorter) depending on what those conditions turn out to be. Additionally, Freyr's lifetime could be extended for centuries with enough of an effort, an effort which may or may not be justifiable depending on the economic situation of the settlement and of space colonization in general.

With that said, it is also expected that Freyr will become obsolete as better technologies are developed - it's more cost-effective at some point to simply construct a new settlement than it is to retrofit Freyr with the new technologies; at this point, Freyr becomes largely un-useful. As a platform utilizing older technologies, Freyr is expected to lie by the wayside and gradually become derelict, falling gradually out of use.

While Freyr will become economically obsolete, its structure will likely still be useful. A large, rotating settlement is not something that can be easily recycled, which seems to indicate that Freyr will remain in orbit around the Moon for quite some time (it doesn't make sense to destroy the settlement, either). Thus the settlement could still be used as a platform for low-level manufacturing, research, or other basic capabilities. The fundamental difference between an orbital settlement and any existing vehicle or structure is that the settlement is all but self-sufficient, which allows it to be a nearly maintenance-free platform for years to come. The self-sufficient nature of such a settlement means that no matter how dated it becomes, it will still be available and still have the technology required to support life, which could become important or may simply be desirable for some group to acquire secondhand.

3.4.1 Risk Analysis

The risks associated with Freyr are not small. The number of ways in which a settlement can fail are more than the number of ways most other systems can fail due simply to the difficulty of maintaining live-able conditions on board the settlement. If any of several subsystems fails completely - air, water, food, power, containment - the settlement will die along with most or all of the people on it.

Because of the vastly increased risks associated with life on a settlement, steps have been taken to minimize the risks faced by optimizing Freyr's systems for avoidance of complete failure of any individual system. This capability is provided by very sturdy systems, redundant subsystem components, storage of critical supplies, and over-engineering to ensure compliance with requirements.

Note that there are other risks associated with Freyr than those addressed here, but that most of these are covered in Section 1.4.9. A comprehensive list of risks, along with specific methods to avoid them, must be reserved for a more in-depth study and cannot be included here for lack of time and detail.

A final note about the risks associated with Freyr: to attempt to minimize these risks, in general, experimental technologies are not preferred for Freyr and are used only when necessary for the success of the settlement. The more is known about a particular system, the better its risks are understood and the easier it is to mitigate those risks with preventative measures.

Table 3.6: Summary of Risk Analysis and Mitigation

Risk	Analysis and Mitigation
Structural Burst	The predominant mechanism for structural failure is "bursting." This involves the shell giving way to internal pressure at some particular failure mode. To prevent this, Freyr's shell was engineered to minimize the risk of such an event. Steps taken include: circular cross section for improved uniformity of stress distribution around the walls of a torus, use of high-tensile strength materials, and allowing a stress safety factor of >10 in shell design. A shell burst would result in nearly complete destruction of the settlement.
Point Puncture	A point puncture is not a terribly large immediate risk to a structure as large as Freyr due to the large volume of air and the relatively small likely hole size. That is to say, the relative flow rate is low enough that steps can be taken to mitigate the damage before the situation becomes critical. The risk of loss of human life is mitigated by the installation of emergency shelters in the Storage and Industrial tori and by the thick shell of the Life Support/Habitation torus, but there are not effective ways to shield against a general puncture by a high-velocity impactor. Fortunately, Freyr's small size means that such an impact is expected over multiple centuries. A point puncture could have very little effect on Freyr or cause total decompression, depending on the size of the puncture.
Magnet Failure	A magnet failure in the ferrofluidic bearing between the Spaceport and the central core could destabilize the joint, leading to air loss and increased drag on the joint; such a failure could be caused by de-Gaussing of the magnet or fracture damage, although complete disablement of the magnet is unlikely. To mitigate these effects, multiple magnets are used for each seal and multiple layers of ferrofluid are used in series so that any individual failure does not compromise the entire seal. Thus, this risk does not carry very severe consequences for Freyr as a whole or even for the ferrofluidic joint.
Spacecraft Impact	If a spacecraft such as an ETV or LTV crashed into Freyr, the settlement could conceivably sustain significant damage. This damage would be caused by the impact itself and might be especially concerning on the outer edge of the settlement, where there is a large tangential velocity. To avoid these collisions, constant communication is maintained between incoming vehicles and Flight Control, and ETVs and LTVs are fitted with collision avoidance algorithms that recognize the shape of Freyr and avoid all parts of the settlement except the Spaceport by default.

Technology Delay	A delay in the implementation of a particular technology could have long-lasting effects on Freyr. For example, if NTR engines are not developed to the required capacity for some years after they are required for ETV and LTV flights, Freyr will be delayed for those same years at great cost. Similarly, a delay in life support technology implementation could lead to large incurred costs as Freyr becomes dependent once again on materials brought from Earth. In order to minimize these risks, Freyr uses COTS parts wherever possible and technologies that are already being developed to ensure readiness.
Launch Failure	A launch failure could have various impacts on Freyr, depending on the particular launch that fails. If the launch is a routine supply launch (once Freyr has been well established for some time) the effect will be very slight, but a failure while launching components for the first ETVs or the initial space station in lunar orbit could have much more serious repercussions. Freyr obtains launch insurance prior to these vital launches and, of course, contracts with corporations that have excellent safety records.
Launch Delay	A launch delay has very little impact on Freyr other than a delay of two or four weeks in transit from LEO. This is because Freyr's schedule is not typically time-constrained to the degree of weeks, at least not for the parts provided by a standard supply mission. While a launch of vital supplies could, again, have a larger impact if delayed, there is no practical way to protect against a delay in a rocket launch.
Industrial Accident	An industrial accident on Freyr needs to be taken very seriously. In the Industrial torus, large amounts of molten metal, silicates, and other materials are processed in relatively close proximity. The spill of a dozen tons of molten metal could have disastrous effects on Freyr's interior and anyone working in it. To reduce the possibility of these accidents, Freyr personnel inspect equipment at regular intervals and replace parts that show signs of wear. Processes or materials that could combine explosively are also separated by distance (for example, oxidizers and fuels). Freyr's personnel are required to wear personal protection equipment (PPE) at all work sites, with the level of protection corresponding to the work being done, and all oxygen in the Industrial torus is provided through a closed personal supply.
Algal Tank Failure	A failure involving Freyr's oxygen-generating algae tanks could jeopardize the entire settlement's oxygen supply if not prevented and handled properly. To prevent a large-scale disaster, several tanks of algae are maintained separately, reducing the likelihood that a large amount of oxygen generating capability will be lost. Additionally, pressure release valves are installed on the carbon dioxide inlet and oxygen outlet valves to ensure that excessive pressure does not fracture the tanks.

SCWO Failure	If one of Freyr's SCWO units goes offline for some reason, barring a catastrophic deconstruction of the unit as a whole, the effect on Freyr will generally be slight. Because SCWO units are arranged in redundant and complementary ways, the loss of any individual SCWO only reduces the total amount of water throughput available to Freyr, and does not knock any vital systems offline. The main consequence of SCWO failure is that showers may be somewhat more restricted. Additionally, because SCWO feeds are cross-linked between different units, no section of Freyr will be without water processing capability.
LFTR Failure	An LFTR could fail in one of two ways: through simple mechanical failure or through nuclear failure. In the event of a nuclear failure, the entire assembly is detached from Freyr and its tangential velocity draws the malfunctioning reactor safely away from Freyr. In either case, another LFTR is brought online as soon as possible - either the second primary LFTR, also on the Industrial torus, or the backup LFTR in the central core. The risk of such a reactor failure, which could cause unacceptable interruptions in the power supply to industrial or residential areas, is reduced by regular inspections of LFTR components.
NTR Malfunction	The NTR engines used by ETVs and LTVs are their sole means of propulsion besides a feeble in comparison RCS unit. The loss of an NTR on either spacecraft could be catastrophic. Again, maintenance is the key to avoiding these problems, but in the event that one does occur, the commander is to use the RCS unit to move into a stable orbit if possible and await rescue.
Atmospheric Mixing	Because the two primary atmospheres on Freyr are both at different pressures and composed of different gases, allowing them to mix could introduce dangerous situations to various parts of the settlement. Mixing of the atmospheres is precluded by airlock-style sealing techniques implemented at the boundary between the Storage torus and the Life Support/Habitation torus.
Internal Unrest	It is realized that at some point Freyr's inhabitants may become disgruntled with the administration and that riots or other large-scale internal disturbances. The preliminary governmental structure described herein limits the likelihood of a large-scale disturbance, but in the event that one does occur the various pressure doors that separate Freyr's tori are engaged, preventing vertical movement within the settlement, and Freyr's small police force restricts access to vital equipment (such as SCWO units, the air processing facility, et cetera).
Delay in Fusion Development	Freyr's economy depends mainly on the export of helium-3 for use is fusion reactors, so a delay in the development of large-scale fusion power could have a significant economic impact on the settlement. Because a greater store of helium-3 allows for faster development, however, the impact on Freyr is not all too drastic in the long term. To help ensure timely development, Freyr could assist with financing the first reactor to stimulate further development.

Chapter 4

Conclusion

4.1 Summary

Freyr is humanity's first orbital space settlement, with space for 20,000 people. It exists in a near-polar (86°) 100 km lunar orbit and is economically supported by materials harvested from the lunar surface.

Structurally, Freyr is composed of a central core and three concentric tori, containing respectively industrial facilities, storage areas, and habitation areas. These tori are all sealed off from one another by airlock-style separations to create a structure that is both whole and composed of distinct parts. The total radius of Freyr's tori is 525 meters, and the settlement spins at 0.1476 radians per second to generate artificial gravity. A non-rotating section of the settlement is provided fro vehicles to dock to; this section is isolated from the rotation of the rest of the settlement by a ferrofluidic seal that contains the atmosphere while allowing the two sections to slip freely past each other.

The structural parts of Freyr are primarily constructed from a titanium-aluminum alloy made from metals extracted from the lunar regolith. This alloy is both strong and lightweight, and since its materials are available in huge amounts on the lunar surface, it is ideal for the structural components of Freyr's shell. In some cases, quartz fibers are mixed into the alloy structure to decrease the use of hard-to-work titanium, which also increases the strength.

Freyr's power is provided by nuclear fission in a liquid fluorine thorium salt reactor, which breeds fissile uranium from stable thorium that is more abundant in the lunar regolith. Reactors on Freyr are redundant and the primaries are located on the exterior of the rotating structure so that they can be easily jettisoned in an emergency. Nominal power output from the reactors is 215 MWt/100 MWe, but can be boosted to a theoretical maximum of 645 MWt/300 MWe with all reactors operating at full power.

At a power output of 215 MWt/100 MWe, the interior temperature of Freyr is just over 4 degrees Celsius everywhere except the Life Support/Habitation torus, which experiences temperatures of about 22 degrees Celsius. At higher power outputs, this temperature scales non-linearly because power radiated is a function of T^4.

Life support systems on Freyr operate on a fundamentally closed-loop design, with minimal losses, and are designed to recover waste products for future use. Notable components of this system are aeroponic cultivation, biological oxygen maintenance via algae culture, supercritical water oxidation for wastewater recovery, and the atmospheric containment system that isolates the atmospheres of the different tori that make up Freyr.

Within the Life Support/Habitation torus, residential spaces are provided for 20,000 individuals. Houses and other day-to-day facilities are located on two separate decks, while a less constricted "outdoor" space is provided on a third deck. This allows 12-hour offset day/night cycles for the two halves of Freyr's population, helping to level out workloads and power demand. Residents spend most of their time in a nominal-g environment to avoid excessive muscle loss and bone decalcification, which also assists in childhood development.

It is currently unknown what Freyr's community and population dynamics will be, because it is

unknown what conditions may arise on an orbital settlement and it is also unknown what the specific composition of Freyr's populace will be. It is, however, expected that Freyr will mirror Earth reasonably well, and it is hoped that Freyr's inhabitants will find ways to work productively with each other instead of being antagonistic. Along the same lines, Freyr's government can be sketched out but not fully determined at this time, and its currency can be described but not accurately implemented.

It is estimated that Freyr's money will take the form of "credits" equivalent to a certain share of Freyr's profits. This system allows internal consistency while no requiring Freyr to print its own currency and providing a fair method of compensation for work. In addition, directly distributing Freyr's profit to its inhabitants in the form of these credits makes Freyr, fundamentally, an employee-owned company or a citizen-owned government, making the administration more attuned to the needs of its citizens. This attitude is reinforced by the lack of professional politicians: even individuals in public office are required to obtain and hold a job of some sort.

Freyr's most important justification for existence lies in its industry. Freyr has the capability for metal processing, volatiles extraction and shipment, construction of various types of high-grade or advanced ceramics, and more. Its versatile capabilities, located primarily in the Industrial torus, include refining aluminum, iron, silicon, and titanium, alloying metals, fabrication of large-scale near-perfect crystals, He isotope separation, silicate composite construction, ceramics development and implementation, and even highly technical and difficult processes such as circuit board construction. In addition, a major component of Freyr's industry is spacecraft fabrication.

Freyr, as a lunar orbital platform with extensive manufacturing capability, can construct spacecraft to specification at much lower cost than any Earth-based organization. This is because it can use lunar materials and launch spacecraft from energetically favorable lunar orbit rather than having to launch entirely out of Earth's gravity well. This can save money on satellite deployment or manned vehicle construction; the only part of such a spacecraft that Freyr cannot provide is the crew, which is relatively inexpensive compared to the cost of lifting an entire spacecraft up the gravity well.

Industrial activity is also provided, at a fee, to other spaceborne entities. For example, an asteroid mining vessel might need a place to process their materials because it is not economically favorable for them to process their own materials yet; Freyr provides the equipment needed in exchange for a service fee or possibly a levy on the materials processed.

While industrial activity on Freyr is a large-scale endeavor, only helium-3 extraction and processing is Freyr's main source of income. Most materials processed on Freyr are used on the settlement itself or on the Moon's surface because transporting them to Earth is not often worth the cost of transportation and then safe descent through the atmosphere. As mentioned previously, the exception to this is helium-3, which is worth the expense of safe transport to Earth's surface.

A by-product of the production of so much material on Freyr is that very little material needs to be brought up to Freyr from Earth. Just as Freyr has no need to export things to Earth, its diverse manufacturing and recycling capabilities mean that it has no reason to import goods from Earth, with a very few exceptions that are simply very difficult to produce on Freyr or do not exist in sufficient quantities on the Moon. There are very few materials in this last category; even Rare

Earth metals are available in the lunar regolith.

Freyr is not a standalone platform. It is assisted by several facilities on the lunar surface, as well as several vehicles that transport materials and people between Freyr, the lunar surface, LEO, and other destinations. These supplemental vehicles and structures include Earth Transfer Vehicles (ETVs), which move cargo and passengers between Freyr and LEO, Lunar Transfer Vehicles (LTVs), which shift cargo and passengers between Freyr and the lunar surface, and ISRUs, In Situ Resource Utilization units, which harvest materials from the lunar regolith and begin to process them before they are transferred to Freyr and processed in the Industrial torus. ETVs and LTVs utilize nuclear thermal rockets (NTRs) that pass hydrogen fuel across a high-temperature quartz barrier heated by nuclear fission. These engines allow good performance with relatively low cost and ease of propellant manufacturing.

Freyr provides a platform for further exploration of and expansion into the Solar System. The energetically favorable orbit it occupies puts Freyr a mere 0.7 km/s from Earth escape, and makes it possible to launch large-scale interplanetary missions - not just probes, but also manned spacecraft - at much reduced cost and effort. Additionally, Freyr acts as an incubator and proving ground for technologies that will be used on subsequent orbital settlements, paving the way for settlements orbiting Mars, in the asteroid belt, and at other locations in the Solar System.

Based on a rough timeline, it is estimated that Freyr could be completely constructed in about 20 years after mining operations were started on the Moon. These mining operations could conceivably be begun in 15 years if Freyr were completely funded overnight. As mining capacity develops, Freyr will be constructed piecemeal, beginning with the interior sections and ending with the exterior tori. At every step of the process, steps will be taken to ensure that rotating and non-rotating sections of Freyr have no possibility of coming into contact.

The lifetime over which Freyr is useful and habitable after construction is estimated to be in excess of 50 years. This is a low-end estimate; Freyr could conceivably remain for centuries if well-maintained and deemed useful. This could happen if there are not massive advances in certain areas of technology or if Freyr's manufacturing capability is still useful and outweighs the use of thousands of people to operate and maintain the settlement - but since it is all but entirely self-sufficient, this seems likely.

The total cost of the settlement could be as much as $900 billion invested, but a simple calculation assuming that Freyr's only profit comes from sales of helium-3 indicates that the settlement will turn a $240 billion profit over its lifetime (for a total lifetime income of $1.14 trillion). In all likelihood, the actual cost of Freyr's construction will be lower than the cited $900 billion; perhaps $500 billion is a more likely number. This is unknown as of now and would require a more in-depth analysis of the settlement design and construction parameters and time frames.

4.2 Further Exploration

The Freyr Project is not, of course, an end product in and of itself. Instead, it is a stepping stone to other destinations and towards permanent colonization of space on a massive scale. Freyr can provide several resources to humanity as it expands into the universe, and allows intensive research on the effects of microgravity and on human life in space.

4.2.1 Next Steps

Using Freyr's spacecraft manufacturing capabilities, exploration missions can easily be sent to Mars, Venus, Saturn and its moons, and other Solar System destinations. Coupled with probes that Freyr manufactures and sends of cheaply, these exploration missions pave the way for permanent bases and research stations on a small scale. For example, based on orbital measurements of Mars, inexpensive probes could be sent there to evaluate landing sites to be visited by a human exploration team: with a lander mass of one ton, allowing for sophisticated experiments but not extensive trans-surface motion, Freyr can launch a single transit vehicle carrying as many landers as desired, using less than 200 kg of fuel per lander. Compare this to the 900 kg Curiosity mission, which used an Atlas V-541 launch vehicle with a fueled mass of 540 tons.

$$2470 = 1500 * 9.81 \ln \frac{m_0}{m_1}$$

$$\frac{m_0}{m_1} = e^{2470/14715} = 1.183$$

Additionally, a similar tactic could be used for exploration of Titan, a moon of Saturn, or Europa, a moon of Jupiter, which are both promising in terms of liquid water and hydrocarbons: a spacecraft launched from Freyr can carry many probes at lower cost, allowing thorough investigation of either moon or of the planets themselves.

4.2.2 Permanent Settlements

With materials shipped from Freyr, it will not be difficult to construct a permanent settlement, either in Mars orbit or on the surface, that can sustain human life. At that point, further settlements can be constructed out near Saturn (as in Maui, the contest winner from 2013), in Venus orbit, or at other Solar System destinations. Support for these stations will be made possible from Freyr and other settlements near Earth with access to lunar minerals and an existing mining complex.

Using the materials Freyr mines from the moon, it will become more cost-effective to mine asteroids and other planets. This will allow further expansion into space as the materials become available to build further space settlements, whether in lunar orbit, Martian orbit, or elsewhere in the Solar System.

Freyr sets up each new settlement in just two launches. Vital components that cannot be manufactured on Freyr are launched from Earth, of course, but Freyr itself only launches two spacecraft for each new settlement. The first craft consists of a small crew section (relative to the size of the station) of 50 members and cargo units; it contains all the materials necessary for the establishment of ISRUs on the new planetary surface and the initial components of the new settlement. Propellant tanks are recycled into the first modules of the settlement, ISRUs are established and begin producing materials, and the colony is born as a simple orbital station. Eventually, the station is spun up and work is completed; at this point, the second ship is launched carrying 450 colonists. These few initial settlers set up the station, finish the interior, and manage the station's operations for a time.

Depending on the size of the station, additional inhabitants may be launched to it in the years following initial setup. Some targets, such as Titan, Europa, or large mineral-rich asteroids, will house a greater number of inhabitants, while others, such as a research station in orbit around Venus, will remain at the population of 500.

Just as the populations of various settlements are different, their purposes are very different. Some settlements, like Freyr, provide an industrial, manufacturing, and materials base, while others are used for research on specialized topics. Some others are intended for exploration and have greater capabilities for landing, rover operations, and probe establishment. Together with Freyr, they form an interplanetary network of space settlements that collectively make themselves self-sustaining.

4.2.3   Final Goals

Eventually, the advances allowed by Freyr's unique launch point and the settlements that have come from Freyr will allow the development of interstellar travel, and the human race will spread to the stars. This is an advancement that will not occur for quite some time, on the scale of millennia, but Freyr is nonetheless the next step towards an interstellar human race. Technologies, techniques, and propulsion methods discovered on Freyr and other settlements will combine to allow much further exploration.

Freyr provides the initial spark that the human race needs to truly begin its exploration of space. It is possible that discoveries made because of The Freyr Project will lead to the materials required for a space elevator, to more advanced rocket techniques allowing for currently unattainable velocities, to small-scale fusion power, to a whole range of scientific and engineering marvels, and it all begins here.

4.3   Afterword

The Freyr Project is a proposal for a sustainable and mostly self-sufficient space settlement that could be constructed within the next century. It is a home for 20,000 individuals beyond Earth's surface and provides resources for technological development, microgravity research, solar system exploration, development of lunar minerals and resources, and human grown in general.

Freyr's structure, economy, industry, government, and support systems have all been designed for maximum benefit, practicality, and efficiency. The settlement contains a closed-loop life support system, facilities for industrial development, and all the mechanisms required for self-sufficiency. It derives raw materials from the surface of the Moon, and its unique position in a polar lunar orbit allows Freyr to act as a powerful catalyst for further development. Its technological developments also lay the groundwork for newer and better space-based systems and ensure human safety in a space environment.

The Freyr Project's cost is admittedly high, at up to $900 billion invested over its initial 50-year lifetime. The economic, technological, and political benefits of Freyr are worth the investment, however, and The Freyr Project provides an excellent ROI that can be used for expansion of Freyr or further solar system development.

With The Freyr Project, we take our next and greatest step into the future.

Chapter 5

Appendices

5.1 Appendix A. Lagrangian Points.

The Lagrangian points, used in Freyr's Comsat network and useful for other purposes in the solar system, are points where the forces on an object in a constrained three-body system balance and a stable orbit can be attained without the use of propellant for thrusting. These points are especially useful because they move with the rotating system, and therefore do not move with respect to the Moon or the Earth.

5.1.1 Collinear Lagrangian Points

The positions of the three linear Lagrangian points can be found by solving a relation involving the gravity of each body and the centrifugal "force" felt by a body in a rotating reference frame. The assumptions made here are that $M_1 >> M_2$, that orbits are circular, and that there are no external perturbations (there are, of course, but this lets us avoid dealing with the Coriolis force).

We know that, for a body in between the two masses,

$$\vec{F} = m \left(\frac{M_1 G}{r^2} - \frac{M_2 G}{(r_2 - r)^2} - \frac{G M_1}{r_2^2} \right)$$

Assumptions have been brought into play here: note that if $M_1 >> M_2$, then $r_1 \approx 0$ and so $(r_1 + r)^2 \approx r^2$. Also, $M_1 + M_2 \approx M_1$, and so according to Kepler's periodic law (derived below), $\omega^2 = \frac{G M_1}{r_2^3}$.

Because the force must be zero in equilibrium conditions, then,

$$\frac{M_1 r_2^2 (r_2 - r)^2}{r^2 r_2^2 (r_2 - r)^2} - \frac{M_2 r^2 r_2^2}{r^2 r_2^2 (r_2 - r)^2} - \frac{M_1 r^2 (r_2 - r)^2}{r^2 r_2^2 (r_2 - r)^2} = 0$$

Defining $r_2 = 1$ for unit equality within the system, this reduces to

$$M_1 (r^4 - 2r^3 + 2r - 1) + M_2 r^2 = 0$$

This can be solved using the method of approximation for any particular two-body system. The Earth-Moon system gives the value of 0.833, meaning that EML1 lies at a distance from Earth of about 0.833 times the distance to the Moon.

Similarly, the Lagrangian points that do not lie between the two bodies are given by the equation

$$M_1 (r^4 - 2r^3 + 2r - 1) - M_2 r^2 = 0$$

This is also solved via the method of approximation, and for the Earth-Moon system returns the values of -1.002 and 1.200, meaning that EML2 and EML3, respectively, are 1.2 times as far as the Moon and 1.002 times as far as the Moon on the opposite side of Earth.

5.1.2 Noncollinear Lagrangian Points

The remaining two Lagrangian points are not solved for so easily. The derivation follows, modeled off of a derivation found on Phy6.org[179].

Consider a triangle of three masses, rotating about its center of mass O in period Γ. Then the centrifugal force felt by each mass is as follows:

$$F_1 = m_1 r_1 \frac{4\pi^2}{\Gamma^2}\hat{r}_1, \ \ F_2 = m_2 r_2 \frac{4\pi^2}{\Gamma^2}\hat{r}_2, \ \ F_3 = m_3 r_3 \frac{4\pi^2}{\Gamma^2}\hat{r}_3$$

Now add in the gravitational force on each mass from the other two masses and set the net force equal to zero:

$$0 = m_1 r_1 \frac{4\pi^2}{\Gamma^2}\hat{r}_1 + F_{1,2} + F_{1,3}$$

$$0 = m_2 r_2 \frac{4\pi^2}{\Gamma^2}\hat{r}_2 + F_{2,1} + F_{2,3}$$

$$0 = m_3 r_3 \frac{4\pi^2}{\Gamma^2}\hat{r}_3 + F_{3,1} + F_{3,2}$$

Thus the total sum of the forces is:

$$0 = m_1 r_1 \frac{4\pi^2}{\Gamma^2}\hat{r}_1 + F_{1,2} + F_{1,3} + m_2 r_2 \frac{4\pi^2}{\Gamma^2}\hat{r}_2 + F_{2,1} + F_{2,3} + m_3 r_3 \frac{4\pi^2}{\Gamma^2}\hat{r}_3 + F_{3,1} + F_{3,2}$$

$$0 = (m_1 r_1 \hat{r}_1 + m_2 r_2 \hat{r}_2 + m_3 r_3 \hat{r}_3)\frac{4\pi^2}{\Gamma^2}$$

Now consider the sides of the vectors as triangles pointing towards mass 1: $\vec{r_2} + \vec{r_{2\to1}} = \vec{r_1}$ and $\vec{r_3} + \vec{r_{3\to1}} = \vec{r_1}$. Multiplying each expression for r_1 by m_1, m_2, or m_3 as appropriate, we find that:

$$\vec{r_1}(m_1 + m_2 + m_3) = (m_1 r_1 \hat{r}_1 + m_2 r_2 \hat{r}_2 + m_3 r_3 \hat{r}_3) + m_2 \vec{r_{2\to1}} + m_3 \vec{r_{3\to1}} = m_2 \vec{r_{2\to1}} + m_3 \vec{r_{3\to1}}$$

This implies that $r_1 = \frac{m_2}{M}\vec{r_{2\to1}} + \frac{m_3}{M}\vec{r_{3\to1}}$. Now, because these two vectors must be proportional to the mass they point from, we can write that $\frac{\frac{m_2}{M}\vec{r_{2\to1}}}{\frac{m_3}{M}\vec{r_{3\to1}}} = \frac{m_2}{m_3}$. This simplifies as:

$$\frac{m_2 \vec{r_{2\to1}}}{m_3 \vec{r_{3\to1}}} = \frac{m_2}{m_3}$$

It's clear that $\vec{r_{2\to1}} = \vec{r_{3\to1}}$. Because we could have chosen any vertex to perform this analysis on (not just m_1), it is obvious that:

$$r_{2\to1} = r_{3\to1} = r_{2\to3} = \cdots$$

Therefore the triangle that results in equilibrium is an equilateral triangle, and so the Lagrangian points are set off at an angle of 60 degrees from the parent body.

5.1.3 Stability

The stability of the Lagrangian points hinges on the action of the Coriolis force. A derivation is not provided here of the stability of the Lagrangian points, but the effect is clear in a potential plot calculated taking Coriolis force into account[180]:

;

Figure 5.1: Potential Plot of the Restricted Three-Body System

The L1, L2, and L3 points are unstable and appear as saddles on the potential plot, while the L4 and L5 points are stable and appear as hills.

5.2 Appendix B. Orbital Mechanics.

Derivations of equations and principles used in this report, to a reasonable extent.

5.2.1 Keplerian Orbits

The problem discussed here is the two-body problem wherein two objects are interacting with each other in the absence of external forces. The two objects are attracted for each other by a force $F = \frac{Gm_1m_2}{r^2}$ so that the force on one of the objects due to the other is

$$\vec{F}_{1,2} = -\frac{Gm_1m_2}{r^2}\hat{r}$$

We can easily derive several facts from this.

Background

1. $\vec{r} \times \vec{a} = 0$

$$\vec{a} = \frac{\vec{F}}{m} = -\frac{Gm_2}{r^2}\hat{r}$$

$$\vec{r} \times \vec{a} = (\vec{r} \times \hat{r})\left(-\frac{Gm_2}{r^2}\right) = 0$$

2. When discussing this system, we define $\vec{L} = \vec{r} \times \vec{p}$. Note that in a non-relativistic coordinate system, $\vec{p} = m\vec{v}$ and thus $\vec{L} = m(\vec{r} \times \vec{v})$.

$$\dot{\vec{L}} = \frac{\mathrm{d}}{\mathrm{d}t}m(\vec{r} \times \vec{v})$$

Since $\frac{\mathrm{d}m}{\mathrm{d}t} = 0$ in this frame,

$$\dot{\vec{L}} = m(\vec{r} \times \frac{\mathrm{d}\vec{v}}{\mathrm{d}t} + \vec{v} \times \frac{\mathrm{d}\vec{r}}{\mathrm{d}t}) = m(\vec{r} \times \vec{a} + \vec{v} \times \vec{v}) = 0$$

This problem makes use of cylindrical coordinates rather than rectangular coordinates. This coordinate system has dimensions r, θ, k, related in the following manner: $\hat{k}$ is the same as $\hat{k}$ in rectangular coordinates, $\hat{r} = \cos(\theta)\hat{i} + \sin(\theta)\hat{j}$, and $\hat{\theta} = -\sin(\theta)\hat{i} + \cos(\theta)\hat{j}$.

Note that cylindrical coordinates are not the same as the spherical coordinates r, θ, ϕ. Upon examination, it is found that $\hat{r} \times \hat{\theta} = \hat{k}$ and so on, following the rules of rectangular coordinates.

It can easily be found that $\dot{\hat{r}} = (-\sin(\theta)\hat{i} + \cos(\theta)\hat{j})\dot{\theta}$ and $\dot{\hat{\theta}} = (-\cos(\theta)\hat{i} - \sin(\theta)\hat{j})\dot{\theta}$.

Elliptical Orbits

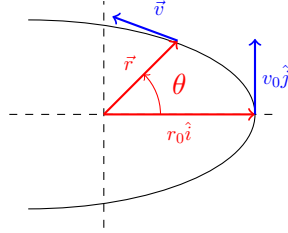This information can be used to solve Kepler's orbital motion problem.

Figure 5.2: Reference diagram for Kepler's problem.

We already know that $-\frac{GM}{r^2}\hat{r} = \ddot{\vec{r}}$ from Newton's gravitational formulation.

$$\vec{v} = \dot{\vec{r}} = \frac{\mathrm{d}\vec{r}}{\mathrm{d}t} = r\frac{\mathrm{d}\hat{r}}{\mathrm{d}t} + \hat{r}\frac{\mathrm{d}r}{\mathrm{d}t}$$

If $\vec{b} = \frac{\vec{L}}{m}$, then

$$\vec{b} = \vec{r} \times \vec{v} \text{ and } \vec{b} = \vec{r} \times \dot{\vec{r}}$$

$$\vec{r} \times \dot{\vec{r}} = r\hat{r} \times \left(r\frac{\mathrm{d}\hat{r}}{\mathrm{d}t} + \hat{r}\frac{\mathrm{d}r}{\mathrm{d}t} \right) = r^2\hat{r} \times \frac{\mathrm{d}\hat{r}}{\mathrm{d}t} + r\frac{\mathrm{d}r}{\mathrm{d}t}(\hat{r} \times \hat{r}) = r^2\hat{r} \times \dot{\hat{r}}$$

We already computed $\dot{\hat{r}}$ earlier: observe that $\dot{\hat{r}} = \dot{\theta}\hat{\theta}$ (see that $\dot{\hat{r}} = \hat{\theta}$). In physics, we set $\dot{\theta} = \omega$, so that $\dot{\hat{r}} = \omega\hat{\theta}$. Given this and the definition of the coordinate system, we can say that

$$r^2\hat{r} \times \dot{\hat{r}} = r^2\omega\hat{r} \times \hat{\theta} = r^2\omega\hat{k}$$

This gives us $\vec{b} = r^2\omega\hat{k}$.

Moving back to an earlier expression, we say that

$$\ddot{\vec{r}} \times \vec{b} = -\frac{GM}{r^2}\hat{r} \times \left(r^2\omega\hat{k} \right) = GM\omega(-\hat{r} \times \hat{k}) = GM\omega\hat{\theta} = GM\dot{\hat{r}}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(\vec{v} \times \vec{b}) = \vec{v} \times \frac{\mathrm{d}\vec{b}}{\mathrm{d}t} + \ddot{\vec{r}} \times \vec{b}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(\vec{v} \times \vec{b}) = GM\dot{\hat{r}}$$

Integrating this, we find that

$$\vec{v} \times \vec{b} = GM\hat{r} + \vec{C}$$

When we solve for the initial condition (remember that $\vec{b} = \vec{r} \times \vec{v}$), we find that

$$r_0 v_0^2 \hat{i} = GM\hat{i} + \vec{C}, \text{or } \vec{C} = \left(r_0 v_0^2 - GM\right)\hat{i}$$

Substituting in, we find that

$$\vec{v} \times \vec{b} = GM\hat{r} + (r_0 v_0^2 - GM)\hat{i}$$

Considering $\vec{r} \cdot (\vec{v} \times \vec{b})$, we find that it evaluates to $\vec{b}^2 = r_0^2 v_0^2$. This finally gives the result

$$r_0^2 v_0^2 = \vec{r} \cdot \left[GM\hat{r} + (r_0 v_0^2 - GM)\hat{i}\right]$$

$$r_0^2 v_0^2 = GMr + (r_0 v_0^2 - GM)r\cos(\theta) = GMr\left(1 + \left(\frac{r_0 v_0^2}{GM} - 1\right)\cos(\theta)\right)$$

$$r = \frac{\frac{r_0^2 v_0^2}{GM}}{1 + \left(\frac{r_0 v_0^2}{GM} - 1\right)\cos(\theta)}$$

This is the polar equation for an ellipse with eccentricity $\frac{r_0 v_0^2}{GM} - 1$ and semi-latus rectum $\frac{r_0^2 v_0^2}{GM}$.

Equal Areas in Equal Times

$$\vec{v} = \frac{\mathrm{d}\vec{r}}{\mathrm{d}t} = \frac{\mathrm{d}r\hat{r}}{\mathrm{d}t} = \hat{r}\frac{\mathrm{d}r}{\mathrm{d}t} + r\frac{\mathrm{d}\hat{r}}{\mathrm{d}t} = \dot{r}\hat{r} + r\omega\hat{\theta}$$

$$\frac{1}{2}r^2\,\mathrm{d}\theta = \text{area}$$

$$\vec{L} = mr^2\omega\hat{k} = mr^2\frac{\mathrm{d}\theta}{\mathrm{d}t}\hat{k}$$

Since $\dot{\vec{L}} = 0$, the area swept out is always the same per unit time.

Period/Semi-Major Axis Relationship

Several other facts follow easily from the above derivation. For example, we can show that

$$\vec{v} \times \vec{b} = GM((e + 1)\cos(\theta)\hat{i} + \sin(\theta)\hat{j})$$

Additionally, note that since $\dot{\vec{L}} = 0$, we can set $||\vec{L}|| = mv_0 r_0$. This allows us to find an interesting result. Since the area of an ellipse is πab, and the area swept out per unit time is $\frac{L}{2m}$,

$$\Gamma = \frac{\pi ab}{\frac{L}{2m}} = \frac{2\pi mab}{L}$$

B-3

Because, in an ellipse, $b^2 = a^2(1 - e^2)$, we can say that

$$\Gamma = \frac{2\pi m a^2 \sqrt{1 - e^2}}{L}$$

Additionally, note that $a(1 - e^2) = \frac{L^2}{GMm^2}$, which lets us say that

$$\Gamma^2 = \frac{4\pi^2 m^2 a^4 (1 - e^2)}{a(1 - e^2)GMm^2}$$

$$\Gamma^2 = \frac{4\pi^2 a^3}{GM}$$

That is, the square of the period of an elliptical orbit is proportional to the cube of its semi-major axis. Note that if $a = \frac{r_1 + r_2}{2}$, as in a Hohmann transfer orbit, then this expression becomes:

$$\Gamma^2 = \frac{\pi^2 (r_1 + r_2)^3}{2GM}$$

$$\Gamma = \pi \sqrt{\frac{(r_1 + r_2)^3}{2GM}}$$

This can easily be manipulated into the form given in 2.2.2 "Flight Path".

5.2.2   Tsiolkovsky Rocket Equation

This equation governs the behavior of a rocket by giving an expression for the total ΔV, or change in velocity, available to a spacecraft based on the efficiency of its engine and ratio of fueled mass to empty mass.
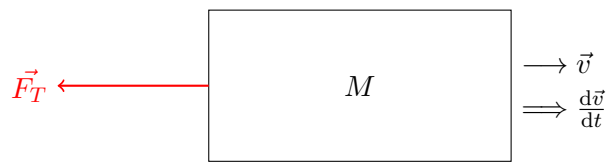
Free-Body Diagram

Figure 5.3: Free-Body Diagram for the Tsiolkovsky Problem

Definitions

Specific Impulse, I_{sp}, is defined as:

$$F_T = I_{sp} * \dot{M} * g_0$$

Effective velocity, v_e, is defined as:

$$v_e = I_{sp} * g_0 = \frac{F_T}{\dot{M}}$$

The instantaneous mass of the spacecraft is denoted M, and its velocity is denoted v.

Calculation

From Newton's Second Law, it is clear that

$$\dot{p} = M\dot{v} = -F_T = -v_e * \dot{M}$$

$$M(t) = M_i - \dot{m}t$$

$$\dot{v} = -v_e * \frac{\dot{M}}{M}$$

$$\int_{t_i}^{t_f} \dot{v} = -v_e \int_{t_i}^{t_f} \frac{\dot{M}}{M}$$

$$\Delta v = -v_e \left[\ln(M)\right]\Big|_{M_i}^{M_f} = v_e \ln \frac{M_i}{M_f}$$

$$\Delta v = I_{sp} * g_0 * \ln \frac{m_0}{m_1}$$

This is the completed Tsiolkovsky rocket equation.

5.2.3 Hohmann Transfers

The Hohmann transfer is a maneuver that uses two engine firings to transition between two orbits. The first burn puts the spacecraft on an elliptical orbit with a periapsis on the lower orbit and apoapsis on the higher orbit (lower and higher in the gravity well of the primary). The characteristics of a Hohmann transfer can be calculated using the conservation of energy and the assumption of instantaneous impulses, which is reasonable for most Hohmann transfers unless low-thrust engines are used.

Using the Vis-Viva equation[181] , it is possible to determine the ΔV at each burn to carry out a Hohmann Transfer. Starting from a low circular orbit of radius r and adding velocity until the apoapsis touches the higher target orbit of radius r_f, it is clear that:

$$v_f^2 - v_i^2 = \mu \left(\frac{2}{r} - \frac{1}{a_f} \right) - \mu \left(\frac{2}{r} - \frac{1}{r} \right) = \mu \left(\frac{1}{r} - \frac{1}{a_f} \right)$$

$$v_f^2 - v_i^2 = \mu \frac{a_f - r}{r a_f}$$

Since $a_f = \frac{r+r_f}{2}$, this can be written as

$$v_f^2 - v_i^2 = \mu \frac{\frac{r+r_f}{2} - r}{r \frac{r+r_f}{2}} = \mu \frac{\frac{r_f - r}{2}}{r \frac{r+r_f}{2}}$$

$$v_f^2 = \mu \frac{\frac{r_f - r}{2}}{r \frac{r+r_f}{2}} + \mu \frac{1}{r} = \frac{\mu}{r} \frac{2r_f}{r_f + r}$$

$$v_f = \sqrt{\frac{\mu}{r}} \sqrt{\frac{2r_f}{r_f + r}}$$

The change in velocity is then given by

$$v_f - v_i = \sqrt{\frac{\mu}{r}} \sqrt{\frac{2r_f}{r_f + r}} - \sqrt{\frac{\mu}{r}} = \sqrt{\frac{\mu}{r}} \left(\sqrt{\frac{2r_f}{r_f + r}} - 1 \right)$$

To insert from this orbit into the target orbit, a circular orbit at r_f, another burn must be made. This time,

$$v_f^2 - v_i^2 = \mu \left(\frac{2}{r_f} - \frac{1}{r_f} \right) - \mu \left(\frac{2}{r_f} - \frac{1}{a_f} \right) = \mu \left(\frac{1}{a_f} - \frac{1}{r_f} \right)$$

$$v_f^2 - v_i^2 = \mu \frac{r_f - a_f}{r_f a_f}$$

Because, again, $a_f = \frac{r+r_f}{2}$, this can be written as

$$v_f^2 - v_i^2 = \mu \frac{r_f - \frac{r+r_f}{2}}{r_f \frac{r+r_f}{2}} = \mu \frac{\frac{r_f - r}{2}}{r_f \frac{r+r_f}{2}}$$

$$v_f^2 = \mu \frac{\frac{r_f - r}{2}}{r_f \frac{r+r_f}{2}} + \mu \frac{2r}{r_f + r} = \frac{\mu}{r_f} \frac{r_f - r + 2r}{r_f + r} = \frac{\mu}{r_f}$$

$$v_f = \sqrt{\frac{\mu}{r_f}}$$

The change in velocity is then given by

$$v_f - v_i = \sqrt{\frac{\mu}{r_f}} - \sqrt{\frac{\mu}{r_f}} \sqrt{\frac{2r}{r + r_f}} = \sqrt{\frac{\mu}{r_f}} \left(1 - \sqrt{\frac{2r}{r_f + r}} \right)$$

The total ΔV for a Hohmann transfer is the combination of these two burns, which comes out to:

$$\Delta V = \sqrt{\frac{\mu}{r}} \left(\sqrt{\frac{2r_f}{r_f + r}} - 1 \right) + \sqrt{\frac{\mu}{r_f}} \left(1 - \sqrt{\frac{2r}{r_f + r}} \right)$$

This gives the total ΔV for a Hohmann transfer with instantaneous impulses; real impulses such as those used by the ETVs and LTVs are not instantaneous, resulting in in increase in ΔV requirements.

5.3   Appendix C. Inflatable Structures.

Our lunar structures consist, essentially, of an inflatable structure. We make use of two envelopes, an outer envelope to provide structure and an inner envelope to provide a living space. The inflatable setup allows for quick setup and arrangement, while maintaining a light-weight package and allowing extreme versatility.

A further benefit of inflatables is that, with no continuous solid connections between different locations within the structure, machinery operating will not cause unwanted vibrations, either in the industrial section of the structure or in the crew quarters. Finally, any required repairs are made easy by having a fabric skin instead of a metal skin; a fabric skin may be easily mended, while metal requires more involved repairs and specialized tools.

Insulation will be provided by two layers of metallized polyethylene terephthalate (MPET)[182], in conjunction with the air gap between the two envelopes and the aluminized nylon used in the envelopes themselves.

The floor of our base is composed of polymer concrete, which allows us to level out remaining discrepancies in the underlying surface and provides a strong, durable floor layer without enormously increasing initial setup mass requirements.

5.3.1   Outer Envelope

The outer envelope of our structure consists of woven ballistics grade kevlar (K-29) fabric[183] surrounding a closed-cell neoprene (CCN) membrane. The K-29 fabric has a thickness of 1.22mm, and a breaking strength of more than 5.4e5 N/m in each direction[184].

The superior tensile strength of K-29 fabric (one single strand of yarn can support more than 300 N[185]) and the fact that it shows practically no change with wide variations in temperature, down to -195 C[186] indicate fantastic structural characteristics, and its light weight of 0.45 kg per square meter[183] will reduce costs and make setup easier. Additionally, ballistic kevlar shows great resistance to abrasion and puncture, further reducing the possibility of a breach in the envelope.

On the interior side of the K-29 fabric is a layer of MPET insulation, which reflects up to 90%[183] of radiated heat while adding hardly any weight. We chose not to put MPET insulation on the exterior of the kevlar fabric because of the fragility of the insulation. The interior layer of MPET in turn surrounds a layer of 5mm CCN, which is the main air-seal[187] and has a per-area mass of 0.75 kg per square meter. This neoprene sponge sheet operates well at temperatures as low as -40 C and is inside a sheet of MPET insulation, so its function will not be impaired by the Martian environment. CCN is an ideal substance for this application because it allows no passage of air or water, and although neoprene has a relatively low Young's modulus, it is contained and protected by our exterior layer of K-29, which takes up the stress on the CCN and limits the strain endured. Finally, CCN sponge sheet will not degrade over time, but rather maintain its structural integrity and flexibility, making it an excellent choice for a long-term lunar processing station.

The various components of both envelopes are connected to each other by DuPont Vertak DBS3000

Figure 5.4: Expanded view of exterior envelope structure.
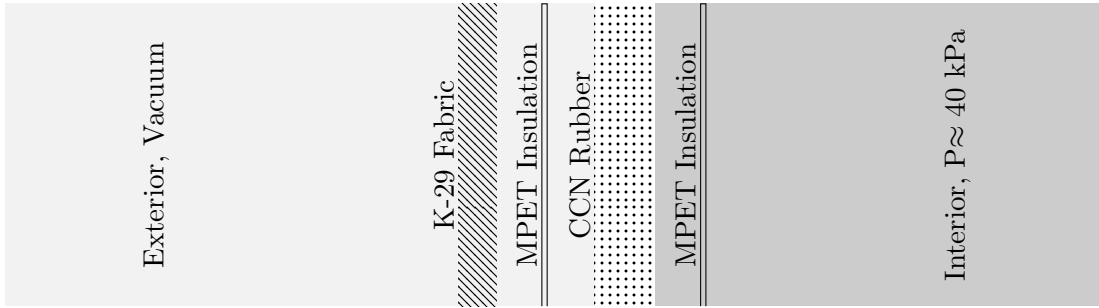
adhesive[188]. The high tensile strength of this adhesive, 76.8 psi (530 kPa), combined with its relatively low hardness of <20 (Shore O) means that the resulting bonded layers will still be flexible, but will not come apart under any reasonable conditions, much less under the expected conditions. The total thickness of the exterior envelope is approximately 1.7 cm.
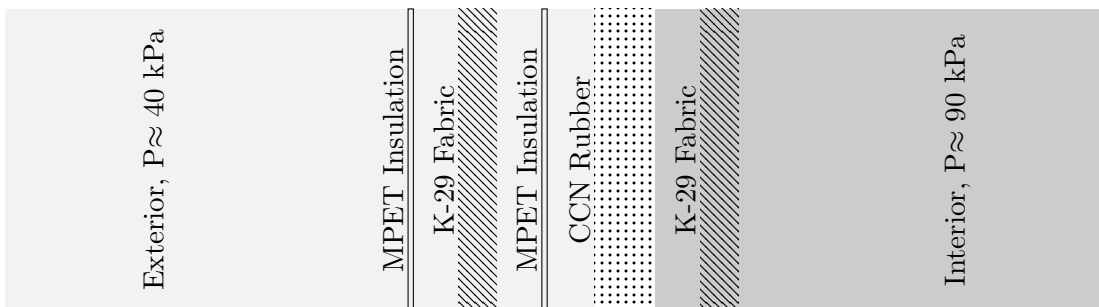
The pressure outside the exterior envelope is hard vacuum, effectively 0 Pa. Inside the exterior envelope, we will maintain a pressure of 40 kPa, about 40% of Earth's atmosphere. This allows us to have an intermediate pressure between exterior and habitable pressures, and reduce the stress on both envelopes.

5.3.2   Inner Envelope

The inner envelope of our structure consists of another layer of K-29 fabric with a CCN liner. For the inner envelope, however, there is a layer of MPET on each side of the K-29, because there is a much reduced danger of abrasion and multiple layers will provide more thermal protection.

The structure of the interior envelope is otherwise identical to that of the exterior envelope, with one exception: there is an additional layer of K-29 inside the CCN liner, which is embedded with aluminum fasteners to facilitate interior setup of equipment and living areas. The total thickness of the interior envelope is approximately 2 cm.

Figure 5.5: Expanded view of interior envelope structure.

The interior envelope separates a region of 40 kPa outside the membrane and a region of 90 kPa inside the envelope, which is a little under 90% of Earth normal. Again, this is a step up in

pressure to ease the stress on each envelope and facilitate better performance of the CCN liner in air sealant.

The two envelopes are separated by approximately 16 cm of air space.

5.3.3 Floor

The floor of our base station is composed of several layers. The outermost layer is simply a continuation of the exterior envelope, which serves as abrasion protection from the ground and helps to even out the surface. Above this membrane is a layer of sprayed polyurethane, which completely levels the floor and provides further insulation and shock absorption. Finally, the top layer of the floor is a layer of polymer concrete with a rubber coating, which is affixed at its edges to the interior envelope.

Polyurethane foam is sprayed over the exterior envelope. We have allocated 80 L of polyurethane liquid for this purpose, which produces a 3 cm coating over 200 square meters of floor space[189]. The mass of this polyurethane liquid is about 150 kg. Polyurethane foam is structurally very strong[190], adding strength to structures it is incorporated into, so we are not worried about its material properties. Additionally, polyurethane foam does not degrade under cold temperatures, UV radiation, or most chemical reactions, and is fire retardant.

The primary purposes of the polyurethane coating are to provide insulation for the floor and to improve its structural stability. Another use, however, arises because of the sprayable nature of the foam. We use the polyurethane foam to even out any non-level areas of the floor (within reason, of course). This helps the polymer concrete to sit better and allows for a more uniform floor.

On top of the polyurethane, we deposit a layer of polymer concrete to provide a durable surface that will not be damaged by years of continuous use, a problem with other inflatable structures. This polymer concrete (PC) is formed by mixing a prepared chemical mixture with lunar regolith aggregate to produce a concrete structure. We use styrene, with methyl methacrylate and a peroxide catalyst, as the binding agent, which forms a concrete with a compressive strength in excess of 15,000 psi within one Earth day[191]. The concrete requires 10-15 wt.% binding agent; the balance of the mass is provided by local aggregate, making this solution not just durable but also very lightweight.

Additionally, a layer of isobutylene isoprene rubber (IIR)[192] is applied to the surface of the floor. This rubber is chosen for several reasons: it is impermeable to air, is not affected by water, acids, bases, or oxygenated solvents, and has excellent capability for vibration dissipation due to elastic hysteresis. This leads to a floor that is already good at absorbing vibration, is airtight, and will not deteriorate if agents are spilled on it. It is important to note that IIR is not very resistant to degradation by hydrocarbon solvents, but since we will not be working extensively with hydrocarbons, this is not a problem.

The exterior and interior membranes have a thickness of about 4 cm, the polyurethane foam is about 3 cm thick, and we add to that 6 cm of PC and 5 mm of IIR. This means that the floor has a depth of 11.5 cm. Note that, at the floor, the interior and exterior membranes are collapsed

Figure 5.6: Expanded view of floor construction.

IIR Coating
Polymer Concrete
Polyurethane
Exterior and Interior Envelopes
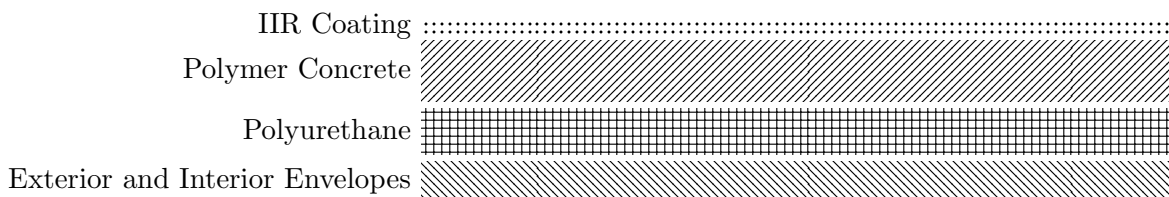
together, with no air space between them. Since neither membrane moves in this case, abrasion between them is not a problem.

The mass of the floor is 135 kg per square meter, but only 21 kg per square meter has to be transported to the lunar surface; the balance is made up by local aggregate used in the PC.

There are distinct advantages to using a floor set up in this format. First, since both envelopes will have already been inflated, pressure can be maintained inside the habitat while the polyurethane and PC are setting, which helps us to predict their behavior. Second, by placing the exterior envelope on the surface instead of a layer of PC or even polyurethane, we ensure that the structure could be moved if necessary and avoid forward contamination of the lunar environment.

5.3.4 Insulation

Insulation on the base is provided by multiple layers of MPET, plus the insulating effects of the other envelope components and polymer concrete. The energy loss calculations are complicated, but making certain reasonable assumptions, we find that the rate of heat loss from the structure is approximately 1 kW during the lunar night. This is a highly efficient structure at maintaining heat, as we can see from the low heat loss rate.

5.4 Appendix D. Volume of a Toroidal Section.

This appendix contains calculations that were tedious enough to be excluded from the primary report text.

5.4.1 Method 1

This derivation is a little bit annoying, but it is presented here as I derived it. The final result has been checked at the extrema and appears correct.
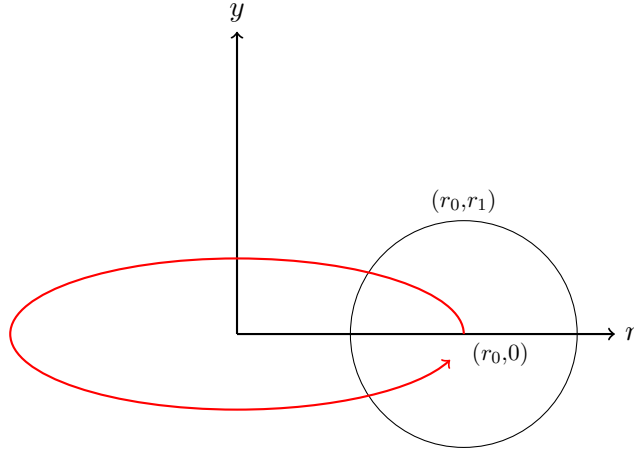
To find the volume of the torus, we integrate in cylindrical shells from $r = r_0 - r_1$ to $r = r_0 + r_1$. The expression for a small section of the volume is:

$$\mathrm{d}V = \left(4\pi\, r \sqrt{(r_1^2 - r_0^2) + 2r_0 r - r^2} \right) \mathrm{d}r$$

Integrating this to find an expression for V and defining $f(r) = \sqrt{-r^2 + 2r_0 r + (r_1^2 - r_0^2)}$, we find that:

$$V = 4\pi \frac{1}{48} \left(-2f(r)(4r_0^2 + 4r_0 r + 8(r_1^2 - r^2)) - 24(r_0 r_1^2) \tan^{-1}\left(\frac{r_0 - r}{f(r)} \right) \right) + C_1$$

Solving for the case $r = r_0 + r_1$ and setting the result equal to zero, we find an expression for C_1:

$$f(r_0 + r_1) = \sqrt{-(r_0 + r_1)^2 + 2r_0^2 + 2r_0 r_1 + r_1^2 - r_0^2} = 0$$

$$0 = 4\pi \frac{1}{48} \left(0 - 24(r_0 r_1^2) \tan^{-1}\left(\frac{-r_1}{0} \right) \right) + C_1 = 4\pi \frac{\pi}{4}(r_0 r_1^2) + C_1$$

$$C_1 = -\pi^2(r_0 r_1^2)$$

With this, the more general formula is:

$$V = 4\pi \frac{1}{48} \left(-2f(r)(4r_0^2 + 4r_0 r + 8(r_1^2 - r^2)) - 24(r_0 r_1^2) \tan^{-1}\left(\frac{r_0 - r}{f(r)} \right) \right) - \pi^2(r_0 r_1^2)$$

D-1

Note that when this expression is evaluated at $r = r_0 - r_1$, it simplifies to:

$$f(r) = \sqrt{-(r_0 - r_1)^2 + 2r_0(r_0 - r_1) + r_1^2 - r_0^2} = 0$$

$$V = 4\pi \frac{1}{48} \left(0 - 24(r_0 r_1^2) \tan^{-1} \left(\frac{r_1}{0} \right) \right) - \pi^2 (r_0 r_1^2) = -2\pi^2 r_0 r_1^2$$

This is, in fact, the volume of a complete torus of circular cross-section. The negative sign is due to the fact that integration was performed from the center of rotation outwards. Frankly, in practice we can just assume that all volumes are positive.

5.4.2 Method 2

While the above is a precise answer, it is tedious to derive and an approximation is likely good enough. Such an approximation for finding the volumes assumes that the centroid of each portion is located at the midpoint of the area, which is reasonable for these shapes and is likely to be a good approximation.

This method makes use of Pappus's theorem to say that, if point c represents the centroid of the shape's radial cross-section, then the volume is given by:

$$V = 2\pi * r_c * A$$

where A is the cross-sectional area. Because the sections of a torus are pretty close to uniform, it's a decent approximation to say that their centroid is at their geometric center, indicating that, for a given toroidal section between radii r_1 and r_2, the volume can be found by:

$$V = 2\pi * \left(r_0 + \frac{r_1 + r_2}{2} \right) (r_2 - r_1) \left(2\sqrt{r^2 - \left(\frac{r_1 + r_2}{2} \right)^2} \right)$$

This equation is significantly simpler than the other form and can be found much more easily. It becomes more accurate for smaller sections, over which the curvature of the torus's walls is negligible. Note that in this equation, r indicates the minor radius of the torus.

5.5   Appendix E. The Rotating Ring.

The derivations presented here are the various possibilities for the contributing factors to stress in a rotating ring. It is assumed that (1) the ring is uniform, (2) the tension is uniform, (3) the ring's thickness is insignificant as compared to its radius, and (4) external loads are evenly distributed over the ring. A system diagram for a small section dl of a rotating ring appears below.

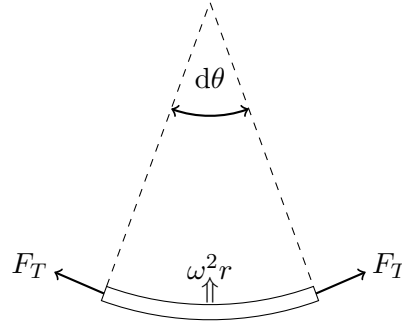
Figure 5.7: System Diagram for a Section of a Uniform Rotating Ring

Defining the cross-sectional area of the ring as A, the density of the ring as ρ, and its angular velocity and radius as ω and r respectively, we can write an equilibrium statement for the system. Note that in a rotating system, it is necessary to include the centripetal acceleration of the system as a result of the tensional force.

$$2F_T \sin\left(\frac{\mathrm{d}\theta}{2}\right) = A\rho\,\mathrm{d}l * \omega^2 r$$

Because $\sin(\mathrm{d}\theta/2) \approx \mathrm{d}\theta/2$, we can then write this equation as:

$$F_T\,\mathrm{d}\theta = A\rho\omega^2 r\,\mathrm{d}l$$

Knowing that $r\,\Delta\theta = \Delta l$ and therefore that $r\,\mathrm{d}\theta = \mathrm{d}l$, the above equation can be rewritten:

$$F_T = A\rho\omega^2 r\,\frac{\mathrm{d}l}{\mathrm{d}\theta} = A\rho\omega^2 r^2$$

$$F_T = A\rho\omega^2 r^2$$

Since, of course, the stress T is simply the force per unit area, it can be written very simply as:

$$T = \rho\omega^2 r^2$$

Note that this derivation is only valid if the thickness of the ring is insignificant compared to the ring's radius - but that, within that constraint, the shape of the ring and its cross-sectional area

do not matter. Also note that any two rings with equal density will experience an equal strain at the same angular velocity and radius.

5.5.1 Ring with Equivalent Load

To evaluate the stress in a ring with a load on it (that is, a ring that also has to accelerate a mass towards the center of rotation), I modeled the added mass as an increase in the density of the ring, so that the new density is $\rho + \Delta\rho$ such that $\Delta\rho = \frac{m}{A\,\mathrm{d}l}$. In this equation, m is the mass per $\mathrm{d}l$ such that $m\omega^2 r$ is equal to the additional weight supported by the length $\mathrm{d}l$. This means that when the system equilibrium expression is written, it comes out to:

$$2F_T \sin\left(\frac{\mathrm{d}\theta}{2}\right) = A(\rho + \Delta\rho)\,\mathrm{d}l * \omega^2 r = (A\rho\,\mathrm{d}l + m)\omega^2 r$$

This makes sense. When solving the system equation, the same process as before is used and it is easily found that:

$$T = (\rho + \Delta\rho)\omega^2 r^2$$

$$T = \rho\omega^2 r^2 + \frac{m}{A\,\mathrm{d}l}\omega^2 r^2$$

A more useful form in this case is a previous step:

$$F_T = \left(A\rho + \frac{m}{\mathrm{d}l}\right)\omega^2 r^2$$

$$T = \frac{\left(A\rho + \frac{m}{\mathrm{d}l}\right)\omega^2 r^2}{A}$$

This allows the use of the effective mass per unit length, which is more easily determinable than the effective increase in density of the ring.

5.5.2 Ring with Pressure Differential

A ring of width w that separates two regions of different pressure has a pressure P_1 on the inside of the ring and P_0 on the outside of the ring. The net force due to pressure on a small section of the ring is therefore given by:
$$\mathrm{d}F = (P_1 - P_0)w\,\mathrm{d}l$$
Defining $\Delta P = P_1 - P_0$, this simplifies to

$$\mathrm{d}F = \Delta P * w\,\mathrm{d}l$$

This force adds to the centrifugal force that must be overcome to constrain the ring itself, meaning that the tension can be written as

$$F_T \, d\theta = (A\rho\omega^2 r + \Delta P w) \, dl$$

$$F_T = A\rho\omega^2 r^2 + \Delta P w r$$

Dividing by the cross-sectional area to determine the stress, it is easily found by assuming a rectangular cross section of height h that

$$T = \rho\omega^2 r^2 + \frac{\Delta P \, r}{h}$$

Note, then, that adding a pressure differential adds a term $\frac{\Delta P \, r}{h}$ to the stress in the ring.

5.5.3   Ring with Both Equivalent Load and Pressure Differential

Based on the equations derived for a ring with equivalent load and a ring with a pressure differential, it becomes clear that when both an equivalent load and a pressure differential are applied to a rotating ring, the stress in the ring must be:

$$T = \rho\omega^2 r^2 + \frac{m}{A \, dl}\omega^2 r^2 + \frac{\Delta P \, r}{h}$$

Again, the assumptions inherent in these equations are: (1) the ring is uniform, (2) the tension is uniform, (3) the ring's thickness is insignificant as compared to its radius, and (4) external loads are evenly distributed over the ring. These assumptions must be true for the equations to be completely accurate, and they are more accurate the closer the assumptions are to being true.

5.5.4   The Torus

A torus is considered as a special case of the rotating ring wherein the rotational radius is not the same as the pressurized radius. This has the effect of reducing the stress, as will shortly be seen.

The cross-section of a torus is, of course, a circle. This circle contains the pressurized atmosphere and thus carries a stress

$$T_1 = \frac{\Delta P \, r}{h}$$

The radius used in this equation, however, is the radius of the torus and not the rotational radius.

A torus also carries a stress along its length, equal to the stress that would be exerted were the torus capped. The atmospheric pressure pushes along the length of the torus and exerts a force

$$F = A_T P = \pi r^2 P$$

E-3

This force is distributed over the entire area of the torus's shell if we consider the torus to be sufficiently large, meaning that the stress, which is the force divided by the area it acts on, is

$$T_2 = \frac{F}{A_S} = \frac{\pi\,r^2\,P}{2\pi\,r\,h} = \frac{\Delta P\,r}{2h}$$

$$T = \frac{\Delta P\,r}{2h}$$

The total stress on the torus's shell, then, must be

$$T_1 + T_2 = \frac{\Delta P\,r}{h} + \frac{\Delta P\,r}{2h} = \frac{3\Delta P\,r}{2h}$$

Note that for this stress to be equal to the stress in a ring supporting that much tension, the radius of the torus would have to be 2/3 the radius of the ring - which makes the tori overlap over the axis of rotation and encloses much more volume than a simple rotating disk.

Notes

[1] McCoy, Dan. *Freyr*. Norse Mythology for Smart People, 2015. Web. http://norse-mythology.org/gods-and-creatures/the-vanir-gods-and-goddesses/freyr/

[2] Freyr. http://en.wikipedia.org/wiki/Freyr

[3] Commercial Protein Crystal Growth. http://www.nasa.gov/mission_pages/station/research/experiments/252.html

[4] Delta-V Map. http://i.imgur.com/SqdzxzF.png

[5] Lunar Mining Possibilities. http://www.thelivingmoon.com/43ancients/02files/Moon_Mining.html

[6] The Troubled Fate of the International Space Station. http://www.huffingtonpost.com/dr-sten-odenwald/the-troubled-international-space-station_b_5341339.html

[7] Plasma Propulsion for Geostationary Satellites. http://www.nipne.ro/rjp/2011_56_Suppl/0003_0014.pdf

[8] Bizarre Lunar Orbits. http://science.nasa.gov/science-news/science-at-nasa/2006/06nov_loworbit/

[9] Konopliv, A. S.; Asmar, S. W.; Carranza, E.; Sjogren, W. L.; Yuan, D. N. Recent Gravity Models as a Result of the Lunar Prospector Mission. Icarus, Volume 150, Issue 1, pp. 1-18 (2001)

[10] Bizarre Lunar Orbits. http://science.nasa.gov/science-news/science-at-nasa/2006/06nov_loworbit/

[11] New Moon Map. http://www.space.com/8644-moon-map-shows-uranium-short-supply.html

[12] New Moon Map. http://www.space.com/8644-moon-map-shows-uranium-short-supply.html

[13] Thorium Processing. http://www.britannica.com/EBchecked/topic/593298/thorium-processing/81620/Conversion-to-uranium-233

[14] Lunar Mining Possibilities. http://www.thelivingmoon.com/43ancients/02files/Moon_Mining.html

[15] Liquid Fluoride Thorium Reactor. http://en.wikipedia.org/wiki/Liquid_fluoride_thorium_reactor

[16] Closed Loop Brayton Cycle at Sandia National Laboratory. http://energyfromthorium.com/2014/04/04/closed-loop-brayton-cycle-sandia-national-laboratory/

[17] Hydrogen-Cooled Turbo Generator. http://en.wikipedia.org/wiki/Hydrogen-cooled_turbo_generator

[18] The Closed-Loop Brayton Cycle at Sandia National Laboratory. http://energyfromthorium.com/2014/04/04/closed-loop-brayton-cycle-sandia-national-laboratory/

[19] Carnot Cycle. http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/carnot.html

[20] Coopersmith, Johnathan. *DISPOSAL OF WGH-LEVEL NUCLEAR WASTE IN SPACE*. Texas A&M University, n.d. Web. http://www.nss.org/settlement/manufacturing/SM12.111.DisposalOfHighLevelNuclearWasteInSpace.pdf

[21] No author, *Energy Density Calculations of Nuclear Fuel*. What is Nuclear, 2014. Web. http://www.whatisnuclear.com/physics/energy_density_of_nuclear.html

[22] ASM Inc. Aluminum 6061-T6; 6061-T651. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6

[23] ASM Inc. Titanium Ti-6Al-4V (Grade 5), Annealed. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MTP641

[24] Iron - Fe. Lenntech, 2014. Web. http://www.lenntech.com/periodic/elements/fe.htm

[25] ASM Inc. AISI Type 302 Stainless Steel, cold rolled to 986 MPa tensile strength. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MQ302AE

[26]Properties of Normal Strength Portland Cement Concrete. The Engineering Toolbox, 2014. Web. http://www.engineeringtoolbox.com/concrete-properties-d_1223.html

[27]Vinidex: Polyethylene Properties. http://www.vinidex.com.au/technical/material-properties/polyethylene- properties/

[28]Mechanical Properties of Carbon Fibre Composite Materials, Fibre / Epoxy resin (120C Cure). Performance Composites, 2014. Web. http://www.performance-composites.com/carbonfibre/mechanicalproperties_2.asp

[29]6AL-4V Titanium Bar. Aerodyne Alloys, 2014. Web. http://www.aerodynealloys.com/products/titanium/specs/ams-4928.php

[30]Rask, Jon; Vercoutere, Wenonah; Navarro, Barbara J; Krause, Al. *Radiation Educator Guide.* NASA: George C. Marshall Space Flight Center, n.d. Web. http://www.nasa.gov/pdf/284273main_Radiation_HS_Mod1.pdf

[31]ASM Inc. Aluminum 6061-T6; 6061-T651. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6

[32]ASM Inc. Titanium Ti-6Al-4V (Grade 5), Annealed. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MTP641

[33]ASM Inc. AISI Type 302 Stainless Steel, cold rolled to 986 MPa tensile strength. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MQ302AE

[34]Wikipedia: Lead. http://en.wikipedia.org/wiki/Lead

[35]Vinidex: Polyethylene Properties. http://www.vinidex.com.au/technical/material-properties/polyethylene- properties/

[36]WebElements. Tantalum: Physical Properties. http://www.webelements.com/tantalum/physics.html

[37]ThomasNet: Materials Used in Radiation Shielding. http://www.thomasnet.com/articles/custom-manufacturing-fabricating/radiation-shielding-materials

[38]Vinidex: Polyethylene Properties. http://www.vinidex.com.au/technical/material-properties/polyethylene-properties/

[39]Atwell, Rojdev, Aghara, and Sriprisan. Mitigating the Effects of the Space Radiation Environment: A Novel Approach of Using Z-Graded Materials. AIAA SPACE 2013 CONFERENCE AND EXPOSITION

[40]NDT Resource Center. *Exposure Limits.* National Science Foundation, n.d. Web. https://www.nde-ed.org/EducationResources/CommunityCollege/RadiationSafety/safe_use/exposure.htm

[41]*Albedo Coefficient.* No author given, 2015. Web. http://files.pvsyst.com/help/albedo.htm

[42]Titanium. http://en.wikipedia.org/wiki/Titanium

[43]Carbon on the Moon. http://www.asi.org/adb/m/08/08/lunar-carbon.html

[44]Associated Press. *Washington's Blueberry Crop Growing to 45,000 Tons.* The Oregonian, 10 July 2014. Web. http://www.oregonlive.com/pacific-northwest-news/index.ssf/2014/07/washingtons_blueberry_crop_gro.html

[45]N.a. *Low Productivity May Increase Sri Lankan Rice Imports and Prices in 2014, Says FAO.* Orzya, 5 OCT 2014. Web. http://www.oryza.com/news/rice-news-asia-pacific/low-productivity-may-increase-sri-lankan-rice-imports-and-prices-2014

[46]How Astronauts are Affected by Space Exploration. http://www.nasa.gov/externalflash/HRP_Feature/

[47]NASA Technical Reports Server. http://ntrs.nasa.gov/search.jsp?R=19760013392

[48]The Benefits of Using a Ferrofluidic Seal. Ferrotec, 2014. https://seals.ferrotec.com/technology/seal-benefits

[49]Korotev R. L., Jolliff B. L., Zeigler R. A., Gillis J. J., and Haskin L. A. (2003) Feldspathic lunar meteorites and their implications for compositional remote sensing of the lunar surface and the composition of the lunar crust. Geochimica et Cosmochimica Acta 67, 4895-4923.

[50]Double Row Ball Bearings. SKF Group: 2014. http://www.skf.com/group/industry-solutions/cars-and-light-trucks/engine/engine-block/double-row-ball-bearings/index.html

[51]Glover, Tim. *VASIMR: Express Flight to Mars*. MarsWeek Conference, MIT, April 10, 2004. Web. http://web.mit.edu/mars/Conference_Archives/MarsWeek04_April/Speaker_Documents/VASIMREngine-TimGlover.pdf

[52]Wilhelmsen Ships Service. Handling Dangerous Gases - Oxygen. http://www.wilhelmsen.com/services/ maritime/companies/buss/BUSS_Pressroom/Documents/Understanding%20Oxygen.pdf

[53]Richard E. Fairfax, *Standard Interpretations: Standard Number 1910.134; 1910.134(d)(2)(i)(A); 1910.134(d)(2)(i)(B); 1910.134(d)(2)(iii)*. United States Department of Labor, Occupational Safety and Health Administration, 2 April 2007.

[54]Exponential Functions and the Atmosphere. http://spacemath.gsfc.nasa.gov/astrob/7Page15.pdf

[55]Apollo Command Module LiOH Canister. http://www.space1.com/Artifacts/Apollo_Artifacts/LiOH_Canister/lioh_canister.html

[56]Human Needs in Space. http://settlement.arc.nasa.gov/75SummerStudy/Chapt3.html#Small

[57]Artificial Gravity. http://en.wikipedia.org/wiki/Artificial_gravity#cite_note-12

[58]The Coriolis Effect. https://stratus.ssec.wisc.edu/courses/gg101/coriolis/coriolis.html

[59]Radioactivity in Nature. http://www.umich.edu/ radinfo/introduction/natural.htm

[60]Space Radiation Threat to Astronauts. http://www.space.com/21353-space-radiation-mars-mission-threat.html

[61]Health Threat from Cosmic Rays. http://en.wikipedia.org/wiki/Health_threat_from_cosmic_rays

[62]CO_2 Separation. http://www.cslforum.org/publications/documents/CO2_Separation_from_Pressurized_Gas_Stream.pdf

[63]Simultaneous Measurement. http://www.plantphysiol.org/content/57/4/659.full.pdf

[64]Advanced Life Support. http://ston.jsc.nasa.gov/collections/trs/_techrep/CR-2004-208941.pdf

[65]*Carbon Dioxide Comfort Levels.* The Engineering Toolbox, 2014. Web. http://www.engineeringtoolbox.com/co2-comfort-level-d_1024.html

[66]Turbosystems Engineering. *Overview of Supercritical Water Oxidation (SCWO)*. Turbosystems Engineering Inc., 2014. Web. http://www.turbosynthesis.com/summitresearch/sumscw1.htm

[67]Moen. *Moen Chrome One-Function Eco-Performance Showerhead.* Moen Inc., 2015. Web. http://www.moen.com/ moen/chrome-one-function-eco-performance-showerhead/_/R-CONSUMER%3A6313

[68]Essentials of Vegan Nutrition. http://www.happycow.net/vegan_nutrition.html

[69]Iowa Corn and Soybean. http://www.extension.iastate.edu/agdm/crops/pdf/a1-14.pdf

[70]Tango III. http://settlement.arc.nasa.gov/Contest/Results/96/winner/seis.html

[71]Blue-Green Algae. http://www.fitday.com/fitness-articles/nutrition/vitamins-minerals/blue-green-algae-myths-and-facts.html#b

[72]BG Algae FAQs. http://www.dep.state.fl.us/water/bgalgae/faq.htm

[73]Spirulina (dietary supplement). http://en.wikipedia.org/wiki/Spirulina_(dietary_supplement)#Nutrient_and_vitamin_content

[74]At Which Wavelength. http://scienceline.ucsb.edu/getkey.php?key=1668

[75] *Aerofarms Aeroponic Farming Compared to Other Methods.* AeroFarms, 2015. Web. http://aerofarms.com/why/comparison/

[76] An Introduction to Materials for Use in Vacuum. http://www.southern-pvd.com/vk/evkbasics3.htm

[77] Gordon, J. *Dissolving Our Dead Bodies in Lye: a Good Idea, But is it Going Far Enough?* Science Buzz, 10 MAY 2008. Web. http://www.sciencebuzz.org/blog/dissolving-our-dead-bodies-lye-good-idea-it-going-far

[78] Nelson, Stephen A, *Meteorites, Impacts, and Mass Extinction.* Tulane University, 01 DEC 2014. Web. http://www.tulane.edu/s̃anelson/Natural_Disasters/impacts.htm

[79] Volokh, Eugene. What Percentage of the U.S. Population is Gay, Lesbian, or Bisexual? Washington Post, 15 July 2014. Web. http://www.washingtonpost.com/news/volokh-conspiracy/wp/2014/07/15/what-percentage-of-the-u-s-population-is-gay-lesbian-or-bisexual/

[80] Index Mundi: World Demographics Profile 2014. 23 August 2014. Web. http://www.indexmundi.com/world/demographics_profile.html

[81] Birth Rate, Crude (Per 1000 People). The World Bank Group, 2014. Web. http://data.worldbank.org/indicator/SP.DYN.CBRT.IN

[82] The Global Religious Landscape. Pew ResearchReligion & Public Life Project, 2014. Web. http://www.pewforum.org/2012/12/18/global-religious-landscape-exec/

[83] Virtual Keyboard. http://www.brookstone.com/laser-projection-virtual-keyboard

[84] Completely Fair Scheduler. Wikipedia. http://en.wikipedia.org/wiki/Completely_Fair_Scheduler

[85] Advantages of Distributed Data Processing. Houston Chronicle. http://smallbusiness.chron.com/advantages-distributed-data-processing-26326.html

[86] Wireless Standards - 802.11a, 802.11b/g/n, and 802.11ac. http://compnetworking.about.com/cs/wireless80211/a/aa80211standard.htm

[87] Asymmetric Cryptography (Public-Key Cryptography): TechTarget. http://searchsecurity.techtarget.com/definition/asymmetric-cryptography

[88] NSBRI: The Body in Space. http://www.nsbri.org/DISCOVERIES-FOR-SPACE-and-EARTH/The-Body-in-Space/

[89] Wikipedia: Apollo 17. http://en.wikipedia.org/wiki/Apollo_17

[90] Ursula Schneider, *Fusion: Energy of the Future.* International Atomic Energy Agency, 2001. Web. https://www.iaea.org/newscenter/news/fusion-energy-future

[91] Lunar Mining Possibilities. http://www.thelivingmoon.com/43ancients/02files/Moon_Mining.html

[92] Schmitt, H. H. and Kulcinski, G. L. Fusion Power from Lunar Resources. Fusion Technology, Vol. 21, p. 2221-2229 (July 1992)

[93] Concentrating Solar Power: Energy From Mirrors. National Renewable Energy Laboratory, March 2001. DOE/GO-102001-1147 FS 128. Web. http://www.nrel.gov/docs/fy01osti/28751.pdf

[94] Williams, Dr. David R. Moon Fact Sheet. NASA Goddard Spaceflight Center, 25 April 2014. Web. http://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html

[95] Boiling Points of Some Common FLuids and Gases. The Engineering Toolbox, n.d. Web. http://www.engineeringtoolbox.com/boiling-points-fluids-gases-d_155.html

[96] Greatbatch, W. Extraction of Helium-3 Gas From Ilmenite Ore Utilizing Radiant Solar Energy. US Patent App. 09/861,085. Web. http://www.google.com/patents/US20020066288

[97]Thermal Properties of Fused Quartz. Momentive, 2014. Web. http://www.momentive.com/Products/Main.aspx?id=20352

[98]Why Did High Quality Mirrors Us Aluminum Coatings Instead of Silver? Physics StackExchange, 2 June 2014. Web. http://physics.stackexchange.com/questions/116452/why-did-high-quality-mirrors-use-aluminum-coatings-instead-of-silver

[99]Vacuum Equipment. UC Davis ChemWiki, n.d. Web. http://chemwiki.ucdavis.edu/Reference/Lab_Techniques/Vacuum_Equipment

[100]Davidson, Thomas A. and Emerson, David E. Direct Determination of The Helium-3 Content of Atmospheric Air by Mass Spectrometry. Journal of Geophysical Research: Atmospheres (19842012). Volume 95, Issue D4, pages 35653569, 20 March 1990

[101]What is Helium Leak Detection. HVS Leak Detection, 2014. Web. http://www.heliumleakdetection.net/Helium-Leak-Testing/what-is-helium-leak-detection.html

[102]Mckinney, J.L. and Taylor, W.L. Apparatus and Method for Separation of Helium Isotopes. 1989. US Patent 3,421,334

[103]Introduction to Liquid Helium. Goddard Spaceflight Center: Cryogenics and Fluids Branch. http://istd.gsfc.nasa.gov/cryo/introduction/liquid_helium.html

[104]St. Petersburg Old and New Mariinsky Theaters. Radio Free Europe, n.d. Web. http://www.rferl.mobi/a/24974775/i3.html

[105]Major Lunar Minerals. http://www.permanent.com/lunar-geology-minerals.html

[106]DOBBINS, M., DOMENICO, J., and DUNN, P. A discussion of magnetic separation techniques for concentrating ilmenite and chromite ores. The 6th International Heavy Minerals Conference Back to Basics, The Southern African Institute of Mining and Metallurgy, 2007.

[107]Ilmenite Treatment. http://www.outotec.com/en/About-us/Our-technologies/Direct-and-smelting-reduction/Ilmenite-treatment/

[108]Titanium Extraction by Molten Oxide Electrolysis. http://web.mit.edu/dsadoway/www/MOE_Ti.pdf

[109]Major Lunar Minerals. http://www.permanent.com/lunar-geology-minerals.html

[110]Brown, LeMay, and Bursten. Chemistry: The Central Science, AP Edition. New York: Pearson Education. Copyright 2006. ISBN 0-13-109686-9

[111]Lunar Carbon. http://www.asi.org/adb/m/08/08/lunar-carbon.html

[112]Properties of Aluminum. http://www.aluminiumdesign.net/why-aluminium/properties-of-aluminium/

[113]Anorthite Mineral Data. http://webmineral.com/data/Anorthite.shtml#.VI297mTF-cI

[114]Refining Process. http://bauxite.world-aluminium.org/refining/process.html

[115]Exploiting the FCC Cambridge Process. http://www.asminternational.org/documents/10192/1884362/amp16202p051.pdf/c40e8850-2fc7-456b-a0ec-b4b6e650e9bd

[116]Figure 1: Map of the Abundance of the Element Thorium on the Moon's Surface. http://www.nature.com/ngeo/journal/v4/n8/fig_tab/ngeo1225_F1.html

[117]Lunar Mining Possibilities. http://www.thelivingmoon.com/43ancients/02files/Moon_Mining.html

[118]Encyclopedia Britannica: Thorium Processing. http://www.britannica.com/EBchecked/topic/593298/thorium-processing

[119]Emily Lakdawalla, The Moon is a KREEPy Place. http://www.planetary.org/blogs/emily-lakdawalla/2011/3013.html

[120]David A. Noever et al. High Performance Materials Applications to Moon/Mars Missions and Bases. http://science1.nasa.gov/media/medialibrary/1998/05/11/msad28apr98_1a_resources/materials.pdf

[121]Roddy, Melissa. NASA Men on Moon Will Be Miners. http://guardianlv.com/2014/02/nasa-men-on-the-moon-will-be-miners/

[122]David, Leonard. Is Mining Rare Minerals on the Moon Vital to National Security? http://www.space.com/9250-mining-rare-minerals-moon-vital-national-security.html

[123]Soderman. Is Mining Rare Minerals on the Moon Vital to National Security? http://sservi.nasa.gov/articles/is-mining-rare-minerals-on-the-moon-vital-to-national-security/

[124]Atwell, Rojdev, Aghara, and Sriprisan. Mitigating the Effects of the Space Radiation Environment: A Novel Approach of Using Z-Graded Materials. AIAA SPACE 2013 CONFERENCE AND EXPOSITION

[125]How Are Rare Earths Used? http://www.namibiarareearths.com/rare-earths-industry.asp

[126]Ceramic Substrates and Components Ltd: About Ceramics. http://www.ceramic-substrates.co.uk/about-ceramics

[127]Uses for Advanced Ceramics. http://sciencelearn.org.nz/Contexts/Ceramics/Looking-Closer/Uses-for-advanced-ceramics

[128]Permanent: Major Lunar Minerals. http://www.permanent.com/lunar-geology-minerals.html

[129]Morgan Technical Ceramics: Silica Ceramics - Features and Applications of SiO2 Ceramics for Metal Casting. http://www.azom.com/article.aspx?ArticleID=4545

[130]Xiang et al. Structure and Properties of Sodium Aluminosilicate Glasses from Molecular Dynamics Simulations. J. Chem. Phys. 139, 044507 (2013); doi: 10.1063/1.4816378

[131]DigitalFire Ceramic Oxides Directory: CaO (Calcium Oxide, Calcia). http://digitalfire.com/4sight/oxide/cao.html

[132]Encyclopedia Britannica: Calcium (Ca). http://www.britannica.com/EBchecked/topic/88956/calcium-Ca/1018/Compounds#ref89814

[133]Encyclopedia Britannica: Cement (Raw Materials). http://www.britannica.com/EBchecked/topic/101833/ cement#ref609156

[134]Kobayashi and Kato. Low?Temperature Fabrication of Anorthite Ceramics, Journal of the American Ceramic Society (Impact Factor: 2.43). 03/2005; 77(3):833 - 834.

[135]Advanced Ceramic: Advanced Ceramic Powders. http://repository.uobabylon.edu.iq/2010_2011/4_8481_258.pdf

[136]H.C. Stark: Product Information (Nozzles). http://www.hcstarck.com/nozzle

[137]H.C. Stark: Product Information (Rotors). http://www.hcstarck.com/ceramic_rotors

[138]H.C. Stark: Advanced Ceramics. http://www.hcstarck.com/en/products/advanced_ceramics.html

[139]Building a New Kind of Graded-Z Shield. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20030032274.pdf

[140]Dashtpour, Energy Efficient Reverse Osmosis Desalination Process. International Journal of Environmental Science and Development, Vol. 3, No. 4, August 2012

[141]The Closed Loop Brayton Cycle at Sandia National Laboratory. http://energyfromthorium.com/2014/04/04/closed-loop-brayton-cycle-sandia-national-laboratory/

[142]SkyTerra. http://en.wikipedia.org/wiki/SkyTerra

[143]Lunar Laser Communication Demonstration. http://www.nasa.gov/sites/default/files/llcdfactsheet.final_.web_.pdf

[144]Laser Light Communications Frequently Asked Questions. http://www.laserlightcomms.com/faqs.php

[145] *The Fiber Optic Association - Tech Topics*. The Fiber Optic Association, 2005. Web. http://www.thefoa.org/tech/fo-or-cu.htm

[146] *Optical Communications Demonstrations*. NASA: Space Communications and Navigation, 6 May 2014. Web. http://www.nasa.gov/content/optical-communications-demonstrations/#.VK7DmWTF-cI

[147] Chu, Jennifer. *Shrink-Wrapping Spacesuits*. MIT News Office, 18 SEP 2014. Web. http://newsoffice.mit.edu/2014/second-skin-spacesuits-0918

[148] *Amsteel Blue Rope 8mm (13,700 lbf tensile)*. Sherrill Tree, 2015. Web. http://www.sherrilltree.com/Amsteel-Blue-87#.VLANVmTF-cI

[149] Pletka, B.J. Processing of Lunar Basalt Materials. Unknown.

[150] Small Nuclear Power Reactors. World Nuclear Organization, December 2014. Web. http://www.world-nuclear.org/info/nuclear-fuel-cycle/power-reactors/small-nuclear-power-reactors/

[151] Best Thin Film Solar Panels. http://energyinformative.org/best-thin-film-solar-panels-amorphous-cadmium-telluride-cigs/

[152] Solar Panel Efficiency. http://pureenergies.com/us/how-solar-works/solar-panel-efficiency/

[153] H-Series PEM Fuel Cell Systems. http://www.agofuelcells.com/files/H-Series.pdf

[154] Ambrose, William. *Water and Hydrogen Resources on the Moon, Mercury, and Mars*. Search and Discovery Article #70166 (2014). Web. http://www.searchanddiscovery.com/documents/2014/70166ambrose/ndx_ambrose

[155] Williams, David R. *Ice on the Moon*. NASA Goddard Space Flight Center, 2012. Web. http://nssdc.gsfc.nasa.gov/planetary/ice/ice_moon.html

[156] *Charge Your Model S*. Tesla Motors, 2015. Web. http://www.teslamotors.com/charging#/basics

[157] Latham, Thomas S. Studies of Nuclear Light Bulb Start-Up Conditions and Engine Dynamics. http://archive.org/stream/nasa_techdoc_19700002919/19700002919_djvu.txt

[158] Parsch, Andreas. *Vought SLAM (Pluto)*. Directory of U.S. Military Rockets and Missiles, 2003. Web. http://www.designation-systems.net/dusrm/app4/slam.html

[159] Lecture 9: Bi-elliptics and Out-of-Plane Maneuvers. http://mmae.iit.edu/ mpeet/Classes/MMAE441/Spacecraft/441Lecture21.pdf

[160] Hohmann transfer orbit. http://en.wikipedia.org/wiki/Hohmann_transfer_orbit

[161] International Space Station. NASA: 2014. http://www.nasa.gov/mission_pages/station/main/onthestation/facts_and_figures.html#.VJy5ssAAA

[162] Low-Cost Cold-Gas Reaction Control System. http://arc.aiaa.org/doi/abs/10.2514/1.5128?journalCode=jsr

[163] What's the Best Battery? http://batteryuniversity.com/learn/article/whats_the_best_battery

[164] New 'Space Glue' Developed. http://www.upi.com/Science_News/2011/03/23/New-space-glue-developed/UPI-94291300917785/

[165] *Variable Specific Impulse Magnetoplasma Rocket*. http://en.wikipedia.org/wiki/Variable_Specific_Impulse_Magnetoplasma_Rocket

[166] Space Launch System. http://www.nasa.gov/exploration/systems/sls/#.VHpUwye9KK0

[167] NASA's Space Launch System. http://www.spacelaunchreport.com/sls0.html

[168] Comparison of Orbital Launch Systems. http://www.en.m.wikipedia.org/wiki/Comparison_of_orbital_launch_systems

[169] Falcon Heavy. http://www.spacex.com/falcon-heavy

[170] Chinese Super-Heavy Launcher. http://aviationweek.com/awin/chinese-super-heavy-launcher-designs-exceed-saturn-v

[171] NASA's Space Launch System. http://www.spacelaunchreport.com/sls0.html

[172] NASA's Space Launch System. http://www.spacelaunchreport.com/sls0.html

[173] Saturn V/4-260. http://www.astronautix.com/lvs/satv4260.htm

[174] Orbital, 2015. Web. https://www.orbital.com/

[175] SpaceX, 2015. Web. http://www.spacex.com/

[176] *Skylab*. Rocket and Space Technology, 2015. Web. http://www.braeunig.us/space/index.htm

[177] Lien, Ryan. *Advanced Resistive Exercise Device (ARED)*. NASA, 29 SEP 2014. Web. http://www.nasa.gov/mission_pages/station/research/experiments/1001.html

[178] *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies*. United Nations Office for Disarmament Affairs, 2015. Web. http://disarmament.un.org/treaties/t/moon/text

[179] The L4 and L5 Lagrangian Points. http://www.phy6.org/stargaze/Slagrng3.htm

[180] Mr. Ried.org: Lagrange Points. http://wordpress.mrreid.org/tag/gravity/

[181] Vis-Viva Equation: Wolfram Mathworld. http://scienceworld.wolfram.com/physics/Vis-VivaEquation.html

[182] AstroShield (http://www.insul.net/prod_astroshield.php)

[183] Technical Guide (http://www2.dupont.com/Kevlar/en-US/assets/downloads/KEVLAR-Technical-Guide.pdf)

[184] K-29 Kevlar Ballistic Fabric (http://www.bulletproof-it.com/#!product/prd12/1904990955/k-29-kevlar-ballistic-fabric)

[185] Fibre Glast (http://blog.fibreglast.com/kevlar-2/kevlar-composites-grade-vs-ballistics-grade/)

[186] K-29 Kevlar Ballistic Fabric (http://www.bulletproof-it.com/#!product/prd12/1904990955/k-29-kevlar-ballistic-fabric)

[187] Neoprene Sponge Sheet (http://www.rhnuttall.co.uk/sheeting/neoprene-sponge-sheet/)

[188] DuPont Vertak Sealants (http://www.dupont.com/content/dam/assets/products-and-services/display-lighting-materials/assets/DEC-SealantsDatasheet.pdf)

[189] DOW: Foam Insulation. Web. http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_090e/0901b8038090efd3.pdf?filepath=styrofoam/pdfs/noreg/179-04478.pdf&fromPage=GetDoc

[190] BASF: SPF Home. Web. http://www.spf.basf.com/faq.php

[191] UC Berkeley: Concrete Containing Polymers. Web. http://www.ce.berkeley.edu/ paulmont/241/Polymer_concrete.pdf

[192] MNRubber: Elastomers and Thermoplastics. Web. http://www.mnrubber.com/Design_Guide/3-8.html

Thank you for reading about *The Freyr Project*. It is my hope that you have enjoyed exploring my settlement design and that it inspires further work in the field of space settlement. I have very much enjoyed the journey I took while writing this report, and I've learned quite a bit along the way. If you were interested by the design or any other part of this report, I have done my job - spread awareness about and interest in space settlement.

-Alex Reeves