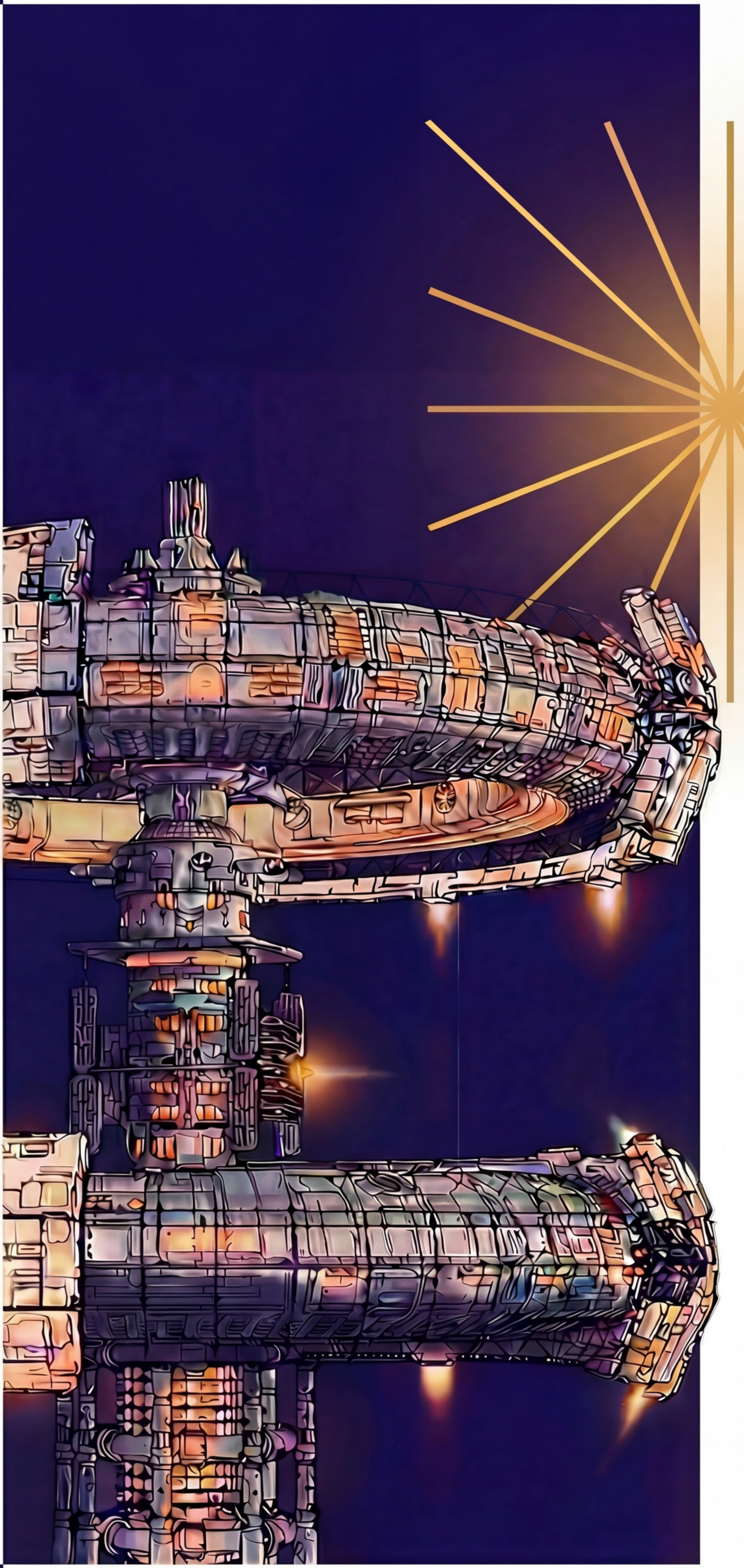
SAOIRSE

OUR FREEDOM
AMONG THE STARS.



PROJECT SAOIRSE

Contents

Meet the Team

The people behind Project Saoirse

Mahimn Patel

PPE & Design

Siddhant Vyas

Infrastructure & Communication

Aromal Mihraj

Radiation, PPE & Building Process

Rhythm Bhullar

Health & Agriculture

Neel Pathak

Infrastructure & Security

Deep Patel

Gravity & Energy

Lance Li

Radiation, Materials, Building Process & Structure

Ved Joshi

Health, Agriculture, Quality of Life & Design

Rehan Jafar

Materials & Energy

Thanosan Prathifkumar

Infrastructure, Security, Building Process & Communication

Aarsh Patel

Health & Agriculture

Faculty Advisor

Ms. Simona Matei

Teacher & Advisor

Executive Summary

> *"Any sufficiently advanced technology is indistinguishable from magic."*
> – Arthur C. Clarke

Project Saoirse (pronounced sur-sha, Irish for "freedom") is a permanent settlement in orbit for 10,000 people, orbiting the Mars-Sun L2 Lagrange point. Over the course of twelve years, the settlement is built in phases: first, the central spine is placed in low Earth orbit by the initial four spacecraft; second, the transition to the L2 point via a Hohmann transfer orbit, where nanoswarm and mining-bot-gathered asteroid belt resources are used to build the torus; and third, the people move in, 5,000 people per year. There are two toroidal living areas spinning at 4 revolutions per minute on a 100-meter extensible spine using YBCO superconducting magnetic bearings to simulate the gravity of Earth at a radius of 56 meters and sustain the gravity level indefinitely after a 34-day spin-up period using only passive V-groove radiator arrays to keep the bearings in a cryogenic state. Radiation shielding is provided by a 6-kilometer-radius Helmholtz coil in a three-axis configuration and electrostatically inflated gossamer and stuffed Whipple layers. 300 megawatts of constant power is provided by solar beaming via the CASSIOPeiA satellite constellation, SPARC magnetic confinement fusion, and subcritical fission.

Within the six levels of the stacked torus, the entire infrastructure of a successful city is accommodated: heavy industry is integrated into the hull, 14 million square meters of vertical hydroponic farming is provided in completely closed BioCircular nutrient cycles, and a public space is accommodated beneath a dynamically lit LED sky. As a primary focus of this report, the integration of original work has been a major priority, and the systems developed specifically for this design include the Directed Self-Automated Materials Manufacturing process, completely simulated for the 80-year settlement lifecycle and manufacturing structural composites on-site at a rate of greater than 3,000 kg/day, CRISPR-optimized crops biofortified to address the specific nutritional deficits of long-duration spaceflight, an AI-based early detection system for neurodegenerative diseases developed from work previously done by a member of the team, and a neutrino-based communication system that serves as a civilization-level survival beacon. We have also sought to extensively address other topics that settlement designs often treat as secondary considerations, including neurodiversity-friendly architecture and menstrual equity within closed-loop waste management systems, predictive systems-based security, the Biocircadian Meal System, and other original considerations of daily life such as RingBall, a sport designed specifically to utilize the curved arena of a rotating habitat.

The form of governance will be a hybrid of elected, expert, and sortition-based systems, within an economic system that uses a currency unit denominated in terms of the actual cost of the resources being used, or exergy, so that the economic decisions made by all citizens on a daily basis align with the survival of the habitat they share.

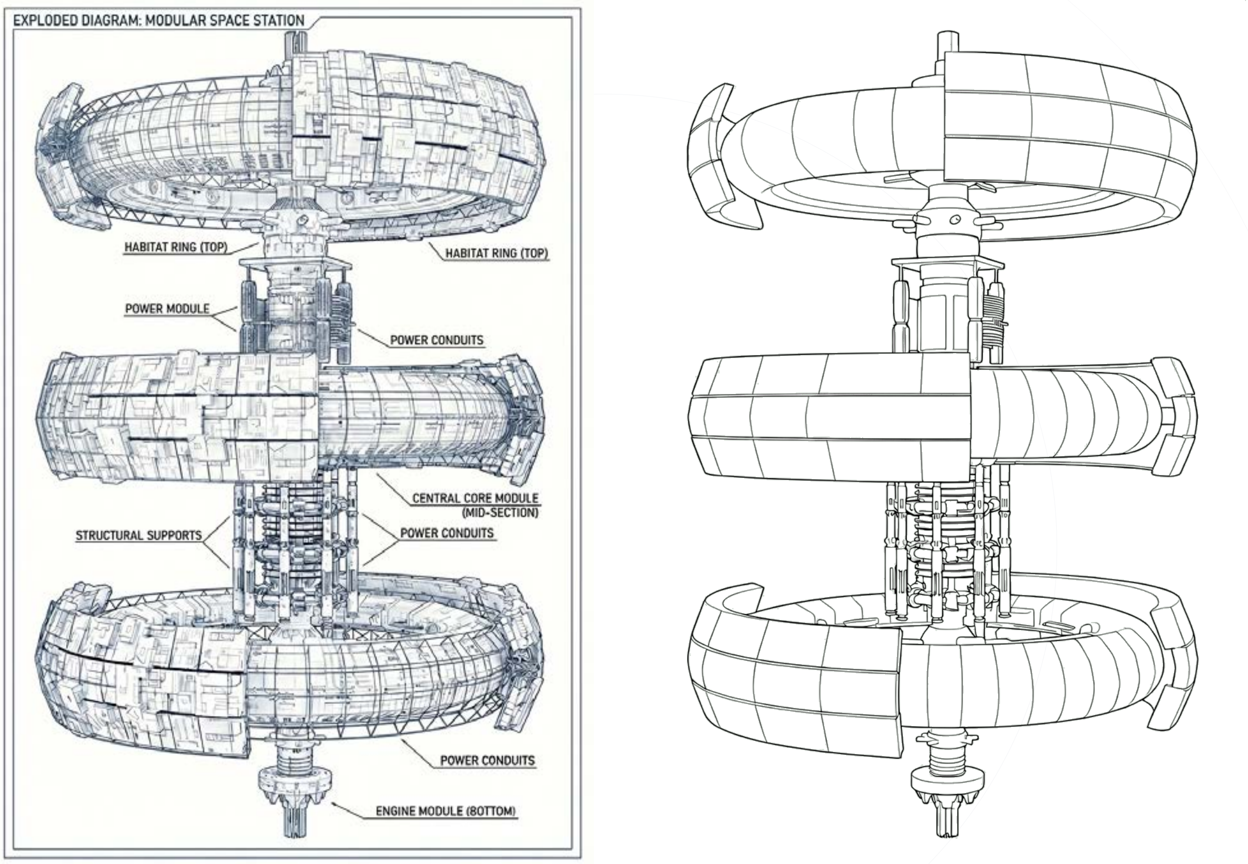
This report is the culmination of the efforts of eleven students who dared to dream of the impossible, beyond the limits set before us. We have an immeasurable debt of gratitude to our teacher and advisor, Ms. Simona Matei, who believed in us and provided the foundation on which we built the impossible. We would also like to express our gratitude to our families and friends who have witnessed our obsession with this project and have listened to our tales of spinning worlds, calculated orbits, closed loops, and stars beyond our reach.

The stars feel a little closer because none of us reached for them alone.

The Project Saoirse Team, 2026

Structure

The settlement is centered around a cylindrical spine from which all other future systems extend. This spine serves simultaneously as the primary structural backbone, the axis of rotation for artificial gravity, and the hub for power, data, and thermal management systems. Additionally, the toroidal habitation rings, the magnetic bearing assemblies, and the radiation shielding are centered around the central hub.



(a) Detailed exploded diagram.

(b) Structural outline.

Figure 2.1: Exploded diagram of the modular space station, showing habitat rings, central core module, power conduits, and engine module.

2.1 The Central Spine

The spine is an 8.5-meter-diameter cylinder, initially 100 meters long and designed for extension up to 1 kilometer. The cylindrical geometry achieves 94.4% volumetric efficiency within launch vehicle fairing constraints, compared to the 60–70% typical of rectangular modules:

$$\begin{aligned} \text{Internal Volume} &= \pi(4.25\,\text{m})^2(25\,\text{m}) = 1{,}419.43\,\text{m}^3 \\ \text{Envelope Volume} &= 1{,}504.69\,\text{m}^3 \\ \text{Efficiency} &= \frac{1{,}419.43}{1{,}504.69} = 94.4\% \end{aligned} \tag{2.1}$$

Beyond space utilization, the cylindrical form produces uniform radial stress distribution, meaning the spine can be extended in any direction without introducing asymmetric load concentrations.

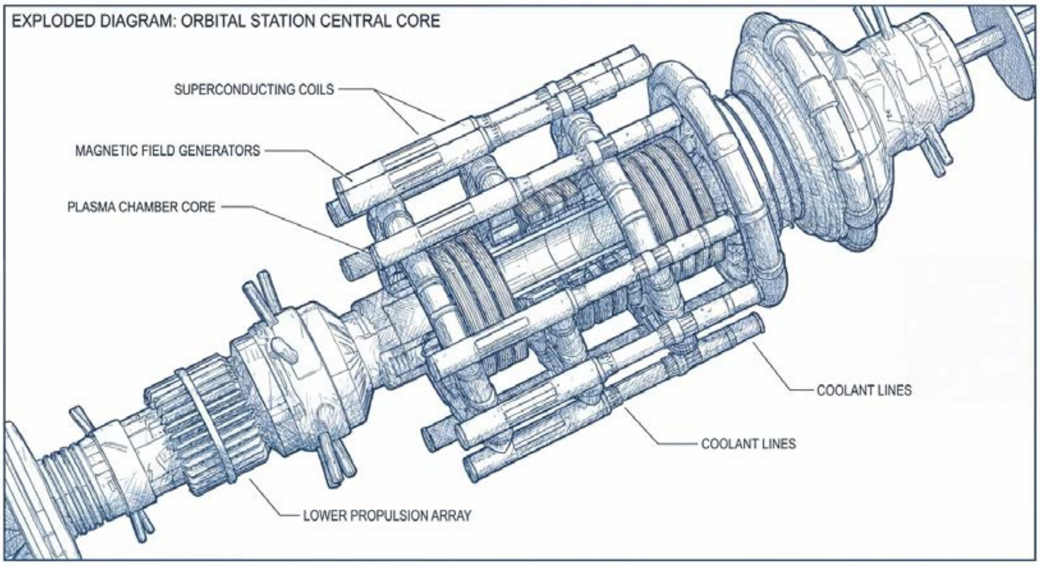


Figure 2.2: Exploded diagram of the orbital station central core, showing superconducting coils, magnetic field generators, plasma chamber core, coolant lines, and lower thruster array.

◇ 2.1.1 Material Architecture

Carbon fiber composites form the primary load-bearing layer. With a specific strength of 490.6 kN·m/kg, quasi-isotropic fiber orientation allows for the structure to distribute load along optimized directions.

Al 7075-T6 aluminum serves as the thermal management layer, with a thermal diffusivity of 5.71×10^{-5} m^2/s. This allows rapid heat dissipation before damaging thermal gradients can form. The aluminum is integrated as helical thermal channels woven directly into the spine's structure.

Lastly, Ti-6Al-4V titanium alloy is used at the interface rings installed every 10 meters which serve as docking ports, and the major sections at 50-meter intervals that serve as torus attachment points.

◇ 2.1.2 Primary Constructor Units (PCU)

The construction system is composed of Primary Constructor Units (PCU), each of which is a six-axis robotic system with an operational range of 15 meters. The PCUs work in pairs and are located on opposite sides of the spine to counterbalance the torque effect. The pairs of PCUs located on opposite sides of the spine have a 23% overlap between their spherical workspace volumes, ensuring that the entire construction volume is covered and that the construction process is uninterrupted between pairs of PCUs.

◇ 2.1.3 Helper Units (HU)

Helper Units (HUs) are inspection systems that travel along with the PCUs during construction. The Helper Units have a total of three measurement systems each: laser interferometry with a precision of ± 0.01 mm, optical photogrammetry with a precision of 0.05 mm, and contact metrology probes with a precision of ± 0.02 mm. The combined precision of the measurements obtained through these systems is 0.0082 mm, which is sufficient to detect the effects of thermal deformation at the interface of materials.

◇ 2.1.4 The Build Sequence

The spine is built in segments of 25 meters from the inside out. The construction phase will make use of PCU pairs. The first one will construct the first layer of carbon-fiber while operating at 180°C to create the initial structure. The node sections, which appear as sections along the spine, are built using rings made of titanium alloy, which are placed every 10 meters along the spine. These will act as docking ports and reinforcement locations for the torus attachments. The larger sections, spaced 50 meters apart, are reinforced with reinforcement struts, since these sections will also serve as attachment locations for the torus and will need to support the loads from the habitat rings. The second PCU pair simultaneously starts work on integrating the thermal conduits, such as the aluminum dissipation channels visible along the spine's surface. The outer layers receive their grid pattern of radiation shielding panels, mounted on standardized attachment points. Throughout this procedure, HUs are continually analyzing each segment of the spine, focusing on the thermal sections between the carbon-fiber core and the titanium alloy node sections, where thermal expansion could pose a threat to the structure. As a result, the HUs ensure that the structure still retains its desired 94.4% volumetric efficiency. To achieve faster assembly for large structures, multiple PCU-HU pairs can cluster together before separating again when more detailed work is required.

2.1.5 Superconducting Magnetic Bearings

Each toroidal ring connects with the central spine through superconducting magnetic bearings. The bearings employ magnetic forces to maintain a stable gap between the rotating torus and the stationary spine. This method eliminates any mechanical issues between the rotating and stationary structures.

The magnetic bearings employ Yttrium Barium Copper Oxide (YBCO), which are high-temperature superconductors. The rings are placed at 10-centimeter intervals along the spine where each torus connects. The choice of YBCO is due to its higher critical temperature compared to other superconducting materials. This minimizes the cryogenic requirements for the system.

The engineering requirements are based on the rotation parameters. To achieve Earth-equivalent gravity ($9.81\,\mathrm{m/s^2}$) within the habitation radius (R), the rotation speed (ω) is given by the equation:

$$\omega = \sqrt{\frac{9.81}{R}} \tag{2.2}$$

This results in a rotation period of approximately 2.4 minutes. This is slow enough that disorienting Coriolis effects are negligible while providing the centripetal acceleration necessary to create artificial gravity. The centrifugal forces that the bearings must counteract are on the order of 10^9 Newtons. This is spread across 100 individual bearings located along the circumference of each spine-torus interface. This means that each bearing must achieve a flux density of approximately 5 Tesla, which is possible using current technology involving YBCO.

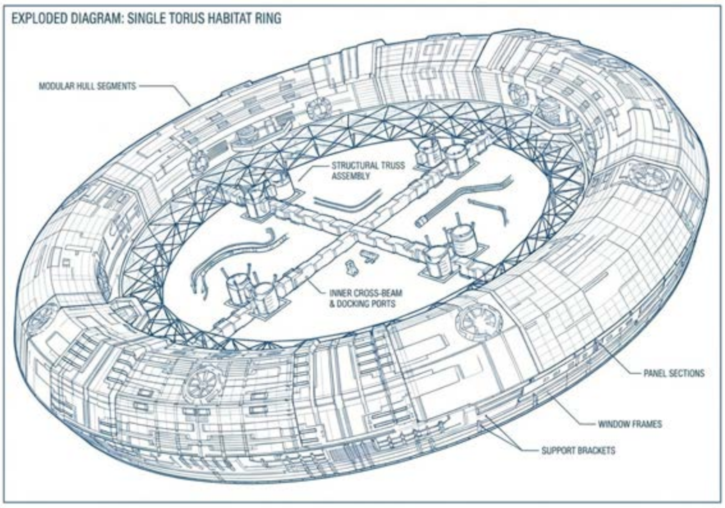


Figure 2.3: Exploded diagram of a single torus habitat ring, showing modular hull segments, structural truss assembly, inner cross-beam and docking ports, panel sections, window frames, and support brackets.

2.1.6 V-Groove Radiators

The superconducting state is temperature-dependent, and when the YBCO bearings experience a rise in temperature beyond a critical threshold, the magnetic field is lost, and the bearings fail. The cryogenic environment at the Mars-Sun L2 point, where the Mars settlement is located, is a requirement that must be addressed through a specialized cooling system architecture.

The V-groove system meets these needs through a simple geometric principle. A series of reflective surfaces, forming a 'V' pattern on the sun-facing side of the Mars settlement, creates a cascading effect. As each successive groove reflects the sun's radiation away from the structure, it simultaneously radiates any remaining heat into deep space. The result is a zone on the underside of the structure's shielding that is at an effective temperature equivalent to deep space, necessary to maintain the superconducting state of the YBCO at a fraction of the critical threshold without the need for active refrigeration systems to be the primary method of cooling.

The active systems, such as compressors and coolant systems, have a corresponding probability of mechanical failure and energy costs that increase over time. The V-groove system is a static geometric structure with no moving parts and no energy input, serving as a baseline environment. The active systems serve to augment and complement the V-groove system, addressing transient conditions such as construction activities and unusual solar exposure conditions.

(a) Single V-groove radiator unit.

(b) Complete V-groove radiator array distributed along the torus ring.

Figure 2.4: V-groove radiator system for passive cryogenic thermal management of YBCO superconducting bearings.

2.2 Artificial Gravity and Rotation

The centripetal acceleration required for artificial gravity is given by:

$$a = \omega^2 r \tag{2.3}$$

Using $\omega = 0.0443\,\mathrm{rad/s}$ and $a = 9.81\,\mathrm{m/s^2}$, this results in $r = 5{,}000\,\mathrm{m}$. This rate of rotation is well within the comfort limits described for long-term residency. Initial studies proposed very conservative values of below 0.1 rpm to prevent any Coriolis forces from being felt, necessitating habitat radii of more than 90,000 meters. But later studies by Young et al. [72] have shown that rates of up to 23 rpm can be easily adapted to in centrifuges, with the initial discomfort settling in a few hours to days. More recent recommendations from the compilation of data from a variety of studies [51] propose a comfort zone where the rate of rotation is below 6 rpm and the radius is above 12 meters. At 0.42 rpm and a 5 km radius, the settlement operates far within these comfort bounds.

The centripetal acceleration introduces a gradient over passenger height. For example, in a 2 m-tall individual, acceleration for the head is $9.806\,\mathrm{m/s^2}$, whereas that for the feet is $9.81\,\mathrm{m/s^2}$. This is an acceleration gradient of only $0.04\%/\mathrm{meter}$, effectively imperceptible under all conditions. Coriolis acceleration in walking dynamics (1–2 m/s), when calculated, gives values of about $0.13\,\mathrm{m/s^2}$, which is similarly negligible at this radius.

2.3 Spin-Up and Operations

The torque (τ) produced by thrusters providing force (F) at the rim is:

$$\tau = F \times r \tag{2.4}$$

The spin-up time is then determined by the change in angular momentum (ΔL):

$$t = \frac{\Delta L}{\tau} \tag{2.5}$$

With thruster clusters providing $F = 2{,}000$ N at a radius of $r = 5{,}000$ m, the resulting torque is given by $\tau = 1.0 \times 10^7$ N·m. Substituting the given value of $\Delta L = 1.1 \times 10^{14}$ N·m·s into the spin-up time t formula, the spin-up time t is approximately 127 days with a single thruster cluster. With eight clusters, the spin-up time t reduces to approximately 16 days, requiring a propellant mass of approximately 7.5×10^5 kg at a specific impulse of 3,000 s.

The Superconducting Magnetic Bearing (SMB) system will rotate indefinitely once spun up and does not require power to continue the rotation. This is the main advantage because the system does not consume power and therefore does not experience the wear and tear associated with bearings.

The slip rings at the rotating interface provide the power and are rated at 182 kW system power and 270 V DC (674 A) [38]. The resulting power transmission is approximately 4.5 kW, which is equivalent to a 2.5% transmission loss due to a contact resistance of $0.01\,\Omega$.

This modular nature of the system makes sure that even if one of the twelve bearing modules fails, the capacity loss would only be 8%, which would be compensated for by the other modules. The main things that need to be maintained are the thermal system (the V-groove shields are shielded from micrometeorite impact by redundant layers), the HTS material (the temperature margin is between 12–15 K to allow degradation), and the slip rings, which need to be inspected and cleaned every few years. The fact that the position is always being monitored with micrometer accuracy makes it possible to perform preemptive maintenance before any problems occur.

2.4 Conclusion

This shows that superconducting magnetic bearing systems make artificial gravity possible for a Mars-Sun L2 orbital habitat using today's technology. YBCO materials offer the necessary force strength (over 10^6 A/cm^2 current density) and a temperature working margin of 12–15 K above operating conditions, and V-groove radiators offer sub-80 K cooling in the Mars shadow via geometric cooling techniques. The 5-kilometer, 0.42 rpm system is capable of providing a gravity of $1g$ within human comfort constraints and keeping stresses below 1.5 MPa, which is well within material strength limits.

After 16-day spin-up with 7.5×10^5 kg propellant, operation with negligible friction will go on forever with little upkeep, as compared to the constant power and degradation of traditional mechanical bearings. Modularity (8 to 16 bearing modules) allows failure tolerance and graceful degradation. The major risks lie in the long-term effects of radiation on High-Temperature Superconductor (HTS) performance in multi-decade exposure and in the difficulties of assembly at L2, rather than in any fundamental physics. Incremental verification of performance in larger and larger models will be possible before full-scale development. This technology will eliminate the crucial barrier of artificial gravity, currently requiring power-intensive and consumable solutions, to permanent human residence in deep space.

Building Processes

3.1 Location

3.1.1 L2 Lagrange Point

The settlement will be located on the Mars-Sun L2 Lagrange point as a point of gravitational balance. While L2 is not considered stable, L4 and L5 are not tidally locked meaning that similar amounts of energy would be needed to maintain stability. The major benefit of inhabiting L2 is that the settlement is not at structural risk due to Trojan asteroids. Furthermore, occupying L2 would allow the settlement to use Mars' radiation shield in addition to its own.

3.2 Building Process

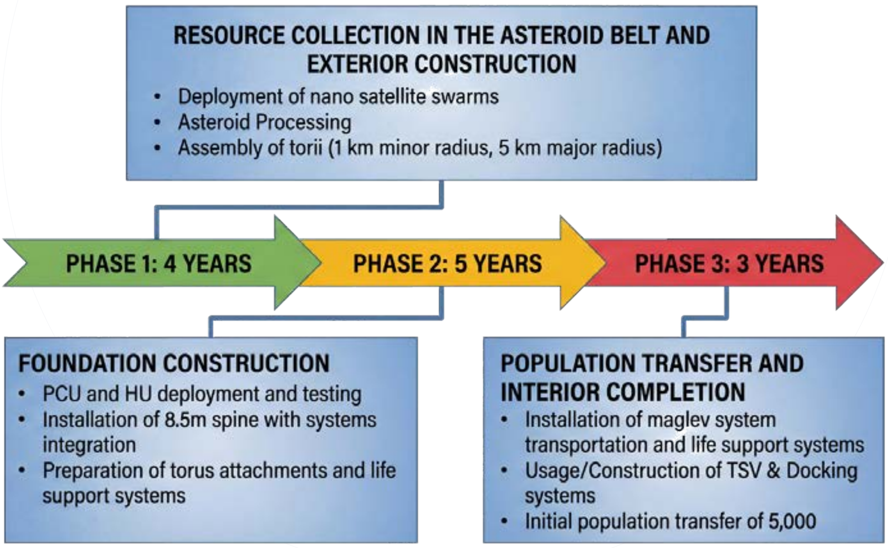


Figure 3.1: Overview of the three-phase construction timeline.

3.2.1 Phase 1: Central Rod Deployment in LEO

In the first phase of construction, 4 spacecrafts will be launched from Earth into LEO (Low Earth Orbit) to begin construction of a central rod that will ensure future missions in close proximity are possible. This central rod is the beginning of the settlement and will act as a control hub that enables the construction of Phase 2 and 3. To ensure that the rod makes it into LEO, propulsion systems will be put in place that reflect NASA spacecrafts such as Discovery.

3.2.2 Phase 2: Begin Trip to Mars L2 Lagrange Point

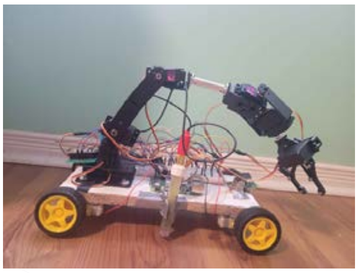


Figure 3.2: Prototype inspection robot.

The second phase will include the construction of the 3 toroidal rings that will inhabit 10000 people. Once the rod is at the L2 Lagrange point, materials from Earth will be transported to the settlement using spaceships comparable to the ones that were initially sent into LEO. These spaceships will unload at designated docking spaces in the central rod to begin sorting. When the central rod has established the initial life support systems and completes the construction of additional protection, then Project Saoirse will begin population transfer from Earth. Additionally, mining robots will be sent out into the asteroid belt to collect essential materials. Nanosatellite swarms will have near-IR sensors, LiDAR systems, and muon tomography will survey asteroids to identify ideal targets rich in nickel, iron, titanium, silicon, carbon and other volatiles. Mining robots will then use optical mining (using 1.69m diameter mirrors), radio frequency separation to sublime volatiles like zinc, and selective dissolution to separate metals from silicates. Laser ablation, particularly for larger asteroids, will be used to despin asteroids before mining operations start. Following LEO assembly completion, the central rod executes a Hohmann transfer to Mars L2. Trajectory optimization uses gravitational assists where available to minimize propellant requirements. Upon arrival at L2, the structure uses ion thrusters for fine positioning and long-term station-keeping. Xenon ion engines provide 90 mN thrust with specific impulse exceeding 3,000 seconds, ideal for the minimal but continuous corrections required at L2.

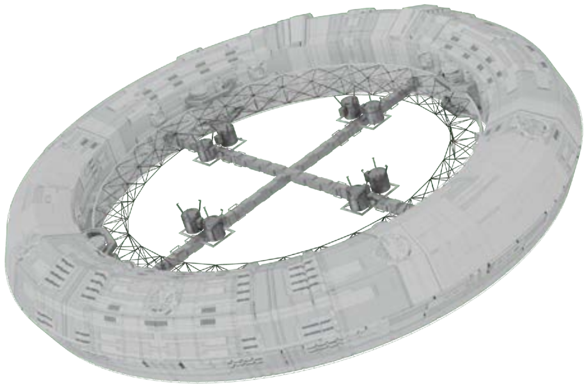


Figure 3.3: Inner shell with drum modules.

3.2.3 Phase 3: Population Transfer

Full-scale population transfer begins in Year 10 and proceeds at 5,000 persons per year, completing in Year 12. The transfer prioritizes specific skill sets required for settlement operations: 2,000 engineers and technicians, 1,500 agricultural and life support specialists, 1,000 medical and psychological support staff, 500 educators, and 5,000 general population including families. Psychological screening and training programs prepare residents for permanent relocation. Each settler undergoes 18 months of training including technical skills, emergency procedures, conflict resolution, and adaptation to closed-loop living. Family units are prioritized to establish stable social structures and ensure long-term viability. Furthermore, Zenithis X, the settlement's maglev train system, will be constructed for transportation across the settlement. Inspection swarms, consisting of varying robots that perform varying tasks, will be deployed to maintain the cleanliness and security of the settlement, completing the infrastructure of the settlement. Intrusion detection systems will also be deployed to ensure security of the settlement. The construction of life support systems will be completed, and all additional docking ports will be constructed. At this stage, the settlement is complete.

Materials

4.1 Exterior Materials

Aluminum and its subtypes have been utilized in many space stations since the beginning of space travel, and due to its lightweight composition while maintaining excellent strength and stability, the use of aluminum (especially Al 6061-T6 and Al 7075) has become the standard. For Project Saoirse, a combination of aluminum and the addition of titanium alloy Ti-6Al-4V will make up the basic interior and exterior parts of the structure. Each tori will have a mix of all three to achieve maximum stability to meet the requirements of different parts of Project Saoirse. However, there are notable problems that must be solved such as: "heat zones" and "cold zones." Fortunately, the crust of Mars is composed of 8.1% aluminum and since Mars has not yet been mined, there is a sufficient amount to build the main settlement. On the other hand, titanium is not as abundant on both Earth and Mars and thus Project Saoirse will occasionally use the iron available on Mars to make stainless steel (SS 316) to substitute for Ti-6Al-4V. Its ability to block out gamma radiation and X-ray radiation due to its higher density allows for it to be a great substitute for Ti-6Al-4V. As stated before, there are heat zones in Project Saoirse. Half of Project Saoirse is in "cold zones" which face away from the Sun, and half of Project Saoirse is in "heat zones" which face the Sun. To account for this issue, "cold zones" will consist of Al-7075 due to its lower thermal conductivity which will ultimately result in a higher thermal insulation in order to sustain the temperature above the brittle transition temperature of both SS 316 and Ti-6Al-4V at -196 °C. In the same sense, Al 6061-T6 is used in the "heat zones" since its melting point is higher than Al-7075 and can thus resist higher temperatures.

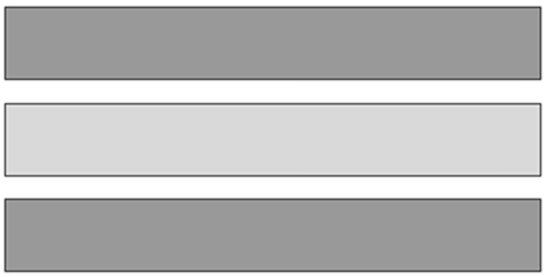


Figure 4.1: Exterior hull layering: Al 7075 outer shell, Ti-6Al-4V structural core, and Al 7075 inner shell.

Table 4.1: Structural and thermal properties of exterior materials.

Properties	Al-7075	Al 6061-T6	Ti-6Al-4V	SS 316
Density	2.81 g/cm^3	2.7 g/cm^3	4.43 g/cm^3	8.00 g/cm^3
Ultimate Tensile Strength	572 MPa	310 MPa	950 MPa	550 MPa
Tensile Yield Strength	503 MPa	276 MPa	880 MPa	240 MPa
Melting Point	477–635 °C	582–652 °C	1604–1660 °C	1370–1400 °C
Thermal Conductivity	130 W/m·K	167 W/m·K	6.7 W/m·K	16.3 W/m·K

4.2 Passive Shielding

A serious concern in space, aside from MMODs, are debris that travel at hypervelocity (~3000 m/s) which is a threat to any material. Our proposed solution to this problem is to use a stuffed whipple shield which consists of two layers of aluminum (both Al 7075 and Al 6061-T6) and one layer of both Mullite polymers and Kevlar polymers. The reason for this decision is to use a prolonged tensile effect that allows for debris to break down into smaller parts through the polymers. Now, Aluminum and Silicon can be obtained easily from Mars, considering that both are very abundant and second only to Oxygen. Mullite will be formed via polymerization, which heats Aluminum Oxide ($3Al_2O_3$) and Silicon Oxide ($2SiO_2$) to form Mullite ($3Al_2O_3 \cdot 2SiO_2$). On the other hand, Kevlar can also be formed easily through obtaining Benzene and creating different compounds through esterification, chlorination, and hydration.

Figure 4.2: Stuffed whipple shield layering: Al 7075 bumper, Mullite polymer, Kevlar polymer, and Al 6061-T6 rear wall.

Table 4.2: Properties of passive shielding polymers.

Properties	Kevlar	Mullite ($3Al_2O_3 \cdot 2SiO_2$)
Density	$1.44\,g/cm^3$	$2.8\,g/cm^3$
Ultimate Tensile Strength	3 GPa	132 MPa
Melting Point	590 °C	2165 °C
Thermal Conductivity	0.04 W/m·K	6 W/m·K

4.3 Directed Self-Automated Materials Manufacturing (DSAMM)

For a settlement to be self-reliant, it must be able to manufacture its own materials from recycled inputs using as little energy as possible. The Directed Self-Automated Materials Manufacturing (DSAMM) addresses this processing concern by taking in a recyclable solid-liquid particles mix, using an electric field to align the particles in special configurations, and then allowing them to harden the structure and particles so that it produces genuine usable product. A simulation is necessary for exploring a variety of energy-consumption bounds and usages given varying environmental conditions that may be difficult to foresee otherwise. The three dimensional interaction surfaces shown in Figure 4.3 show that DSAMM performance is controlled by two primary variables: electric field strength and solids-volume ratio (i.e. the ratio of solid material to liquid in suspension).

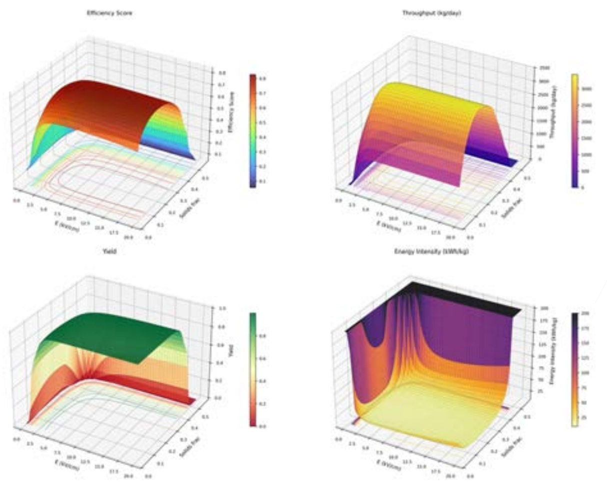


Figure 4.3: DSAMM performance surfaces showing throughput, yield, and energy intensity as functions of electric field strength and solids volume fraction.

The viscosity of the solid-liquid mix is modeled using the Krieger-Dougherty relation, which indicates a sharp change in behavior as the solids-volume ratio reaches maximum packing (i.e. when the particles are close enough that minimal liquid is present) aligning with experimentally tested values [28], [40]. This is significant as the solid-liquid mix (suspension) is the input within DSAMM which the electric field acts on, thus allowing the particles to harden in specific directions. When the solid content exceeds about 35%, the mixture becomes too thick to flow properly, causing air bubbles, material defects, and a dramatic drop in production quality. This viscosity cutoff is shown in the throughput (i.e. production rate in kg/day) and yield surfaces (i.e. percentage of usable product shown) in Figure 4.3, where the production declines from over 3000 kg/day to less than 500 kg/day. On the other hand, the particle alignment follows a saturating Hill-type response to the electric field strength as shown in

Figure 4.3. Furthermore, as the electric field strength increases beyond a certain point, DSAMM becomes more counterproductive. These fail-safe boundaries are important for self-regulation when environmental changes cause random variations in the input conditions.

Moreover, the energy intensity as depicted in Figure 4.3 shows two failures. At low throughput, the fixed overhead energy costs of running DSAMM bring the energy intensity to above 100 kWh/kg as the cost must be supported by only a few kilograms. At excessively high field strengths, there is marginally no benefit compared to lower fields. Thus, the optimal operating range depicted in Figure 4.3 achieves rough throughputs of 3,400 kg/day per production line with nigh perfect efficiencies and relatively low energy costs. The strong numerical gradients in Figure 4.3 indicate that the viability of DSAMM is determined by the input quality and not the tunable characteristics.

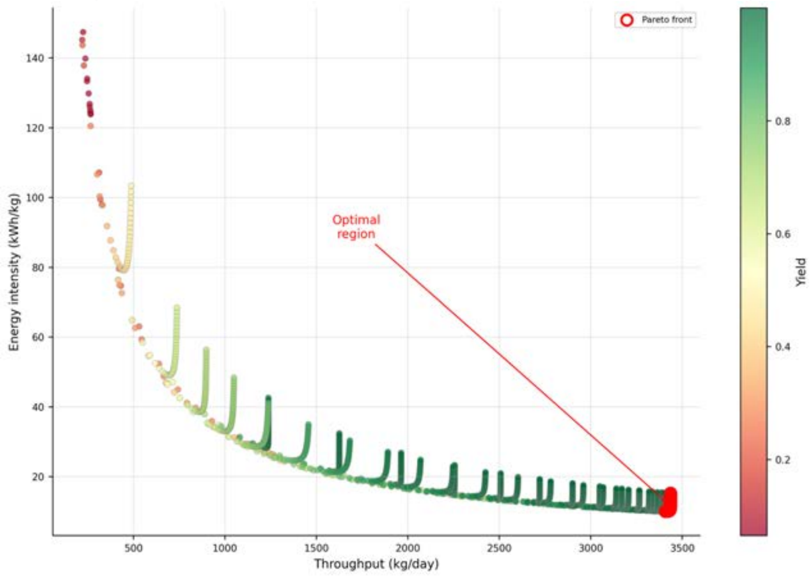


Figure 4.4: Energy–throughput Pareto front showing the non-dominated trade space and optimal knee region.

Figure 4.4 combines all of the previously discussed DSAMM parameters into a multiobjective trade space defined by energy intensity and throughput. The Pareto-front gives detailed information about the throughput and energy intensity especially in situations where prioritising one leads to the degradation of the other [18]. The curve in Figure 4.4 demonstrates a distinct knee at ∼2500–3000 kg/day and 12–15 kWh/kg. To the left of this knee, minor throughput gains come at significant energy costs due to the low-yielding; to the right of the knee, throughput gains practically do not exist. Moreover, the high-throughput region along the Pareto front is characterized by high yield, whereas the high-energy-intensity region is characterised primarily from quality degradation rather than the field power consumption alone. Thus, Figure 4.4 helps Saoirse find strong balances between energy intensity and throughput. For example, during periods of rapid expansion especially in early settlement progress, the settlement can operate slightly to the right of the knee in terms of throughput (labeled "Optimal region"); during maintenance-dominated periods, the settlement can operate to the left of the knee with respect to energy intensity, while still maintaining high yield.

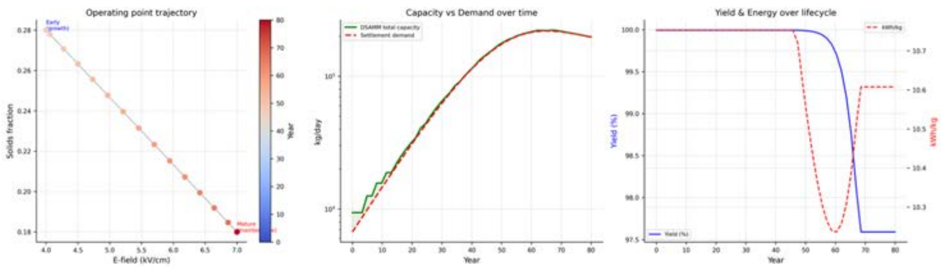


Figure 4.5: DSAMM adaptive operating trajectory over an 80-year settlement lifecycle, showing parameter evolution and scaling requirements.

Figure 4.5 illustrates how the DSAMM process can be adjusted as a function of settlement size throughout its lifetime. The population in the settlements is modeled to grow for 80 years, which includes an adjustable "growth phase" parameter based on the amount of demand created by the structure (structural demand). During the early years of the development of the settlement, the operational parameters are such that the

DSAMM system is typically operated close to electric field strengths of 4 kV/cm and solids-volume ratio values close to 0.28, which is optimal for producing high quantities of product at a reasonable quality level. As the settlement develops further, the operational parameters shift toward higher electric field strengths of approximately 7 kV/cm and lower solids-volume ratio fraction values of approximately 0.18. This results in a tighter quality control threshold, thereby reducing the possibility of defects.

The entire path along this trajectory is associated with the total DSAMM system having sufficient capacity to meet the settlement demand. Therefore, the scaling approach is primarily through increasing the number of parallel lines rather than increasing the operating voltage of each line. The yield from the DSAMM system remains about perfect during mature operation in the full operational period of the settlement and the energy consumption required to produce one kilogram of product (energy intensity) will stabilize at approximately 10.6 kWh/kg. Based upon these calculations:

Table 4.3: DSAMM scaling requirements by settlement population.

Population	Production Lines	Electric Power Consumption	Available Power %	Total Power
10,000	15	21 MW	7%	300 MW
100,000	500	1.4 MW	15%	700 MW

Thus, settlement expansion is very feasible. Ultimately, DSAMM is a viable process of producing in-house goods for settlement use to minimize destructive environmental factors.

4.4 Water Mining

4.4.1 Geo Pooling

To collect water in space, the robot will capture water moisture from space. The robot leverages the idea of geopooling. This is when a celestial body forms water from solar moisture. Magnesium chloride ($MgCl_2$) will collect solar moisture and form water on the surface. The water content of the asteroid will increase until hydrostasis.

$$\mathrm{MgCl_2} + 6\mathrm{H_2O} \rightarrow \mathrm{MgCl_2} \cdot 6\mathrm{H_2O} \tag{4.1}$$

4.4.2 Cold Trap

Using a cold trap, water can be extracted via thermal decomposition. The goal is to condense water vapour into liquid.

Given the energy required to condense water is:

$$Q = mL \tag{4.2}$$

where L is the latent heat of vaporization (2.25×10^6 J/kg) and m is the mass of water to be condensed. This means, to condense 100 kg of water vapour:

$$Q = 100 \times 2.25 \times 10^6\ \mathrm{J/kg} = 2.25 \times 10^8\ \mathrm{J/day} \tag{4.3}$$

Assuming the system works at 85 W/m^2, to condense 100 kg of water per day, the area required is:

$$A = \frac{2.25 \times 10^8\ \mathrm{J/day}}{86{,}400\ \mathrm{s/day} \times 85\ \mathrm{W/m^2}} = 30.6\ \mathrm{m^2} \tag{4.4}$$

This means the area of the cold trap system will need to be at least 30.6 m^2 for each robot to collect 100 kg of water vapour per day.

Infrastructure

Before we go into the individual sections of the settlement, it is important to think of the settlement as a physical world that is the place and work environment for 10,000 people. From the beginning, every design including zone, ceiling heights, materiality, sightlines must be made with the curved shape in mind. The overall goal is to accommodate the psychological and practical requirements of living inside a closed space.

5.1 Overall Form

The internal zoning of the settlement is not based on gravitational variation—since the gravitational force is constant at $1g$ everywhere; but rather on the separation of incompatible functions, grouping compatible functions together, in accordance with the same laws that govern good urban planning back on Earth.

5.1.1 Internal Organization: The Five Levels

The torus is divided into five levels, with each torus being 25–30 meters in height. This allows for multi-story structures within each level, as well as corridors for power, water, atmosphere, etc. The levels are numbered from Level 1 to Level 5, going from outside to inside. The torus is zoned so that the industrial operations and buildings go on the very outside of the torus, and operations which require more human activity go on the inside.

Level 1 – Heavy Industry and Core Infrastructure

The outermost level accommodates heavy industry, primary recycling systems, main power distribution, bulk storage, and water processing. Placing the heaviest equipment and densest materials against the hull maximizes the efficiency of the structure's shell. The vibration and noise of the heavy industry are also damped by the inter-level structural deck above the heavy industry level. This level also accommodates the primary utility systems for the settlement: the main distribution trunks for the atmospheric distribution systems, water distribution systems, and the main electrical distribution systems that serve the higher levels of the settlement.

Level 2 – Agriculture and Light Manufacturing

The second level is dedicated to the settlement's food production and light manufacturing activities.

Level 3 – Primary Residential

Main residential level. The housing clusters are organized around a courtyard type that is more efficient than a corridor type in reducing the perception of density. In addition, it ensures that all housing units have a primary outlook onto a green space and not onto the wall of another housing unit. The typical family housing unit is 900 square feet with three bedrooms and two bathrooms. However, compact units for single persons or groups of persons are also provided. The housing clusters reduce the perception of density and provide a sense of neighborhood identity for the inhabitants of the housing levels. Each housing cluster is a unique neighborhood within the larger neighborhood of the housing levels.

Level 4 – Residential and Recreation

This level adds more residential space, but also includes the major parks and recreational facilities of the settlement. The large park zones are the settlement's major psychological relief zones. They are large, open, non-urban spaces intended to offset the psychological effects of confinement within a tube. Trees, water features, and varied terrain provide the complexity that sealed environments lack. Walkways through these large park zones are designed to curve, branch, and make use of natural topographic features such as small hills and sunken gardens to create the illusion of a larger space than the square footage of the settlement would normally provide. Recreational facilities, sports, swimming, and open-air performances are included throughout the large park zones.

Level 5 – Public Space and The Sky

The innermost level of the torus is the most unique space in the settlement. The ceiling of this level, which is the surface of the torus closest to the center, acts as the artificial sky in the settlement. LED lights, which can change color and adapt to recreate a natural day to night cycle, cover the entire surface of this level. During the day, they display a blue sky, and as the day progresses, they change through varying shades of sunset, and at night, they will display a star field. Additionally, the color temperature, brightness, and cloud patterns change gradually to mimic the natural circadian rhythm necessary for human biological health.

5.2 The Spine Interior

The central spine is the vertical transit area of the settlement and also acts as the connection between the two residential rings. Inside the 8.5-meter-diameter cylinder, the interior of the central spine has three functions:

Transit. Elevators along the inside of the spine connect the two habitation rings and allow access to the docking ports. As people move from the rotating torus to the spine, they pass through a rotating airlock, which slowly decelerates them to the stationary part of the spine.

Docking access. Ships dock at the settlement dock along the spine, where the handling of cargo is facilitated by the direct route to the radial freight elevators that service the rings. Since this part is positioned at the center of the settlement, the route to any point in either ring is the same distance.

Specialized facilities. In the spine hub, there are research facilities, manufacturing processes such as crystal growth and alloy casting, and a medical facility that can be used for procedures due to the stable environment at the core of the settlement.

5.3 Environmental Design

The biggest problem of the settlement regarding agriculture is due to the difference in the environment in space and on Earth. As a species that lives in a world where the landscape constantly changes, it is difficult to adapt to a world where none of that exists. To combat this, we have a ceiling instead of a sky, and the same temperature everywhere. Every subtle detail we would normally use to determine where we are on Earth has to be artificially created, and made well enough to be registered by the psyche of our citizens' mind.

More specifically, there is an adaptive LED sky on Level 6, which provides circadian light that protrudes down to the lower levels through strategically placed atrium shafts to allow simulated daylight to reach Levels 4 and 5. Additionally, there is a system of atmospheric change: variable ventilation that simulates a light breeze, and there are natural sounds of running water, rustling leaves, and other natural sounds provided by speakers in the floor to simulate low-frequency hums.

Aesthetically, the institutional look that most engineered environments have is avoided. We have used wood-textured panels, exposed aggregate, and ceramic tile and textiles on residential levels, which aim to have a natural look.

A study showed that contact with plants has measurable effects on stress reduction and cognitive function [8], [69], and in a fully enclosed environment with no external source of stimulation, these effects are maximized. The plants are fully integrated throughout the facility: balcony planters on residential units, living walls in corridors, community greenhouses, and the extensive parks on Level 5.

5.4 Transportation Systems

5.4.1 Primary Transit: Zenithis X Maglev

The main form of transit that the settlement uses is a magnetic levitation train named the "Zenithis X", which runs along the inside of the toroidal rings. The reason why a maglev train was chosen over a more conventional train with wheels and a rail was because it does not create any debris, which would is a problem in a closed environment, nor does it create any friction, which is a problem in a rotating frame of reference, as it creates drag forces that a conventional train would not have been able to compensate for.

To be specific, the train has 16 cars, is 354 meters in length, and has a load capacity of 470 tons. The train makes use of superconducting magnets that are cooled to 4.5 K by liquid helium in order to suspend the train and interact with conductive coils that are installed along the track bed. As the train runs along the track, the magnetic field that it generates causes a current to be induced in the coils, which then allows for a constant 10 cm gap between the train and the track at all times. Additionally, the system uses 2,800 turns per unit, being each capable of lifting between 11,760 and 16,170 N, and can automatically adjust the current to each coil to accommodate different loads without the need to change the system mechanically. The body of the train consists of an aluminum alloy shell and a carbon fiber frame to ensure that the overall mass remains at a level that would allow the superconducting magnets to operate within their load limits.

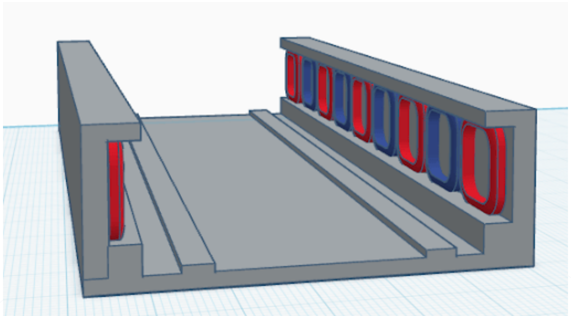


Figure 5.1: Zenithis X maglev train guideway cross-section.

5.4.2 Secondary Transit: Pod Network

The maglev technology will be used for high-capacity fixed route travel on each ring. For point-to-point travel, such as within a ring to a different deck, between rings along the spine, or to low-traffic destinations, a three-dimensional pod system will be used in this settlement.

The pods are spherical and are designed to carry between 2 to 6 people or equivalent cargo. The pods travel in a pressurized tube system at speeds of up to 250 km/h, and quantum flux pinning is used for the suspension mechanism. The YBCO parts of the pods lock onto the magnetic field geometry of the tube system. The pods are stably levitated without touching the tubes, regardless of orientation. This is important because the geometry is complex and three-dimensional.

There are thousands of pods in operation at the same time. The AI system routes the pods through a central system. It does this by taking into account the current demand, the position of the pods, and the level of congestion. As such, it treats the tube system like a graph and re-optimizes the routing constantly.

5.4.3 Wayfinding

There are three types of movement in the settlement. The local type consists of the paths on each floor that connect the residential clusters to the commercial areas, the parks, and the transit areas. These paths are curved and branched using differences in floor materials, lighting, and the use of plants to create "neighborhoods" that help guide the inhabitants without the need for directions. Without these, the inhabitants will be confused about where they are, a problem which is well-known for causing low-level stress in space station crews.

The ring scale comprises the Zenithis X maglev system for fixed route transit around the circumference of each torus, which completes a circuit in minutes. The inter-ring and vertical scale comprises the pods for movement between levels within a ring, between two rings, and to the spine hub. The radial elevators provide connectivity from every level of every ring to the spine, with freight-rated elevators on the industrial level and passenger-rated elevators on the residential and commercial levels. The design of movement ensures that no location is more than 15 minutes travel time away from any other location, and no residence is more than a 5-minute walk to a transit stop.

5.4.4 Pedestrian Infrastructure

The pedestrian paths on the habitation rings have a double function as they not only function as walkways, but they also function as energy generators. The tiles have piezoelectric materials that generate power through the movement of people on the surface. The tiles generate power equivalent to 15–20% of the energy needed in the pedestrian areas. This is not meant to generate power, but rather to reduce the load on the power distribution network in the pedestrian areas. The substrate of the road surface has calcium carbonate precipitating bacteria. The bacteria have the function of repairing micro-fractures in the surface material. The bacteria precipitate calcium carbonate to bridge the fractured surface. The photosynthetic organisms have the function of providing bioluminescent signage. The bioluminescent signage reduces the load on the power distribution network to almost zero. The bacteria reduce the cost of maintaining the road surface by about 80%.

5.5 Docking

The settlement has a distributed node architecture consisting of 48 docking nodes, each of a different function:

- **Heavy Cargo Ports (4 nodes)** handle bulk freighters of 500 to 2,000 tons carrying raw materials and supply goods. These nodes are located along the spine near the ring junctions to allow structural loads to be directly applied to the titanium bulkheads of the spine, rather than the ring structure.
- **Personnel Transfer Stations (12 nodes)** handle crew rotation, visitors, and diplomats. This function is located on the ring structure at accessible points, with a pressurized corridor leading directly into the habitation areas.
- **Emergency Docking Rings (8 nodes)** are always kept clear and available for emergencies and unscheduled arrivals. No infrastructure is present to handle cargo or personnel.
- **Small Craft Bays (24 nodes)** handle inspection vessels, maintenance craft, and short-range shuttles. This function is distributed around the exterior of both the inner and outer rings.

All the nodes utilize a Variable Geometry Docking Interface (VGDI), which is a set of concentric rings of articulated capture nodes that can be adjusted to accommodate vessels of different sizes and hull shapes. The process of docking is done in three phases. In the approach phase, the LIDAR array of the port creates a 3D model of the vessel's hull in real-time and determines the velocity vector, mass distribution, and rotation of the vessel. It determines the optimal contact points on the hull of the vessel using the 3D model it created, not predetermined contact points on the vessel. This is why the settlement is able to accommodate vessels it has never encountered before. In the next phase, the VGDI stretches out the concentric rings of the interface to distribute the contact pressure across multiple points on the hull of the vessel. Magnetic grapples are then used to make the initial soft capture of the vessel before the latches engage for the hard docking. In the third phase, the VGDI aligns the nodes to seal the atmospheric transfer corridor. Each of the VGDI nodes is provided with an emergency release mechanism that can be used to rapidly release the vessel in the event it becomes a hazard.

5.6 Maintenance

A system of this magnitude cannot rely on human inspection teams or maintenance schedules. Instead, the settlement utilizes an autonomous maintenance swarm, a set of robotic systems that monitor, diagnose, and maintain the infrastructure without human input.

The system operates on a predictive model, not a reactive one. Sensors throughout the settlement monitor vibration signatures, temperature profiles, pressure differentials, and other performance metrics. Using machine learning algorithms applied to these sensors, failure probabilities are calculated for each system, and the maintenance swarm operates accordingly, with life support systems always being addressed before convenience systems, even if their failure probability is low.

The robotic team is divided by environment and ability. "Drones" travel along habitation corridors and open spaces, using multi-spectral sensors to detect leaks in the atmosphere, unusual vibrations, corrosion, contamination, and biofilm buildup on surfaces. "Crawler" and "snake" robots function inside spaces inaccessible to the drones. Rail-based robots travel along service rails installed along the spine and ring structure, carrying spare parts, tools, and other items to where they are needed. Manipulation robots have the ability to carry articulated robotic arms to change faulty parts, tighten fasteners, and perform the physical repair work detected by the inspection robots.

5.7 Housing

Designing for residential space is a consideration that is not necessary for terrestrial housing, as the inhabitants of the space will be confined permanently to the structure and will not have a horizon or weather to look out on, nor the ability to leave the space. Every decision made in the design of the space is a consideration for the long-term sustainability of the inhabitants' mental health.

Three levels of housing units are provided for different household sizes and life stages: compact units for individuals, shared units for small groups, and family units. A uniform housing stock in which all residents have the same housing type—in other words, all the same apartment type—has a negative effect on the mental health of the inhabitants due to the homogeneity of the environment. Heterogeneous housing units help the inhabitants feel a sense of progression and a sense of individual space, both of which have been shown to mitigate the effects of long-term confinement [8].

The standard family unit is about 900 square feet (see Figures 5.2), with three bedrooms and two bathrooms. The residential cluster on Level 4 and Level 5 is organized around a courtyard and interior green space, following a courtyard-block typology as discussed above. The courtyard design allows no primary line of sight from any residential unit directly into another, and all units have immediate access to green space on balconies, along living corridors, and within the courtyard spaces that provide the organizing framework for each residential cluster.

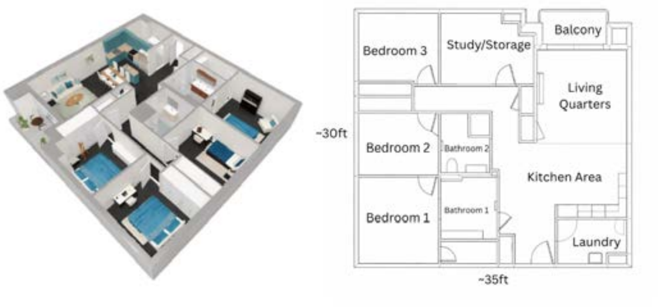


Figure 5.2: Standard family housing unit: 3D render and floor plan.

Radiation

▷ **Problem Statement**

In present space settlements, one major concern around the effectiveness of a singular active radiation shielding technique becomes apparent: electrostatic shields are unable to defend against certain radiation while magnetic fields pose threats to human life at higher levels. As such, Project Saoirse proposes a hybrid radiation shield, which combines both electrostatics and magnetism to create a more effective active radiation shield.

While electrostatic shielding systems have the potential of shielding against the positively charged ions from a solar flare event, it does not protect against negatively-charged ions. The problem that reveals itself in this case is that negatively-charged ions would neutralize the gossamer structure, reducing the effectiveness against solar events. Presently, electrostatic shielding systems still transmit over 80% of Galactic Cosmic Rays (GCR) ions that have voltages of 1–4 GeV/nucleon [53].

While both electrostatic shielding and magnetic shielding both present themselves as strong contenders for radiation protection, they have their many faults. In addition to the electrostatic system being unable to defend against negatively-charged ions, it is still unclear whether it can defend against the GCR spectra [60]. Additionally, the typical human can only withstand a magnetic field strength of 0.4T due to the iron that makes up blood, and a stronger magnetic field potentially leads to damaged currents within blood vessels.

6.1 Approach

Presently, the energy requirements of a standalone magnetostatic shield and an electrostatic shield are far too high and pose extreme threats to humanity. For example, protecting against the GCR spectra with a magnetostatic configuration would require a field strength of over 10T [60]. To solve this issue, the implementation of a radiation shield that combines both magnetostatics and electrostatics in the former of a gossamer structure and a three-axis Helmholtz coil. The selection of a three-axis Helmholtz coil lies in the fact that the center of one holds a saddle point, where the magnetic force & field magnitudes remain constant and uniform.

Positioning outer spheres in the shape of a gossamer structure at a negative potential with inner spheres being held at a positive potential pose a stronger alternative to a preexisting electrostatic shield. Additionally, the addition of a three-axis Helmholtz coil at the center which surrounds the settlement will be set in place to defend against stronger solar winds. The electrostatic shield produced by gossamer structures on the outside layers of the settlement will be used as a means of repelling the free electrons that typically passed through traditionally electrostatic shields. As the Helmholtz coil at the center will carry a current, it acts as a second layer of defense against incoming solar radiation. The core idea is that the electrostatic field will repel weaker ions and reduce the kinetic energy of higher voltage ions, allowing the magnetic field to shield against GCRs. To validate this approach, the following calculations will identify the potential that the gossamer structures must be held at in order to effectively adopt our strategy.

For an energetic proton at ∼1 MeV, the gossamer structure must have the ability to repel it electrostatically. The work energy theorem gives:

$$qV \geq KE \implies V \geq \frac{KE}{q} = \frac{1 \times 10^6\,\text{eV} \times 1.6 \times 10^{-19}\,\text{J/eV}}{1.6 \times 10^{-19}\,\text{C}} = 1\,\text{MV} \tag{6.1}$$

This shows that the outer sphere must be held at ≥1 MV to repel typical GCR protons. Additionally, using our model with an outer radius of 6 km and an inner radius of 5 km, the electric field at the inner surface is:

$$E = \frac{V}{r_1} \cdot \frac{r_2}{r_2 - r_1} = \frac{1 \times 10^6}{5000} \cdot \frac{6000}{1000} \approx 1.2\,\text{kV/m} \tag{6.2}$$

For a GCR proton at 1 GeV entering the electrostatic shield, the energy reduced after the proton transverses 1 MV potential is:

$$KE_{\text{remaining}} = 1000\,\text{MeV} - 1\,\text{MeV} = 999\,\text{MeV} \tag{6.3}$$

Thus, the magnetic rigidity (R) drops from:

$$R = \frac{\sqrt{KE^2 + 2 \cdot KE \cdot m_p c^2}}{qc} \tag{6.4}$$

$$R_{\text{before}} \approx 1.696\,\text{GV}, \qquad R_{\text{after}} \approx 1.695\,\text{GV} \tag{6.5}$$

While the absolute reduction seems to be rather small, this shows that the electrostatic shield has the ability to repel against weaker ions, with the Helmholtz coil having to deal with higher energy ions.

Due to the size of the settlement, varying the size of the magnetic coil would greatly decrease the amount of current and energy needed to maintain the magnetic field. The most efficient method to deploy the electrostatic shield is by using a lightweight gossamer structure. By providing an initial charge, this structure will expand to distribute charges and result in the desired surrounding structure.

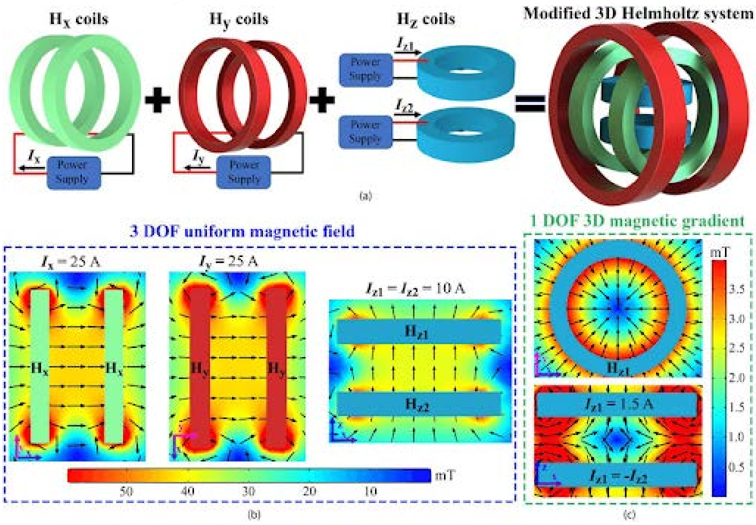


Figure 6.1: Depiction of a 3-Axis Helmholtz Coil [15].

Using three orthogonal Helmholtz rings (Figure 6.1) enhances isotropic coverage for the entire settlement. This further improves the weaknesses of magnetic field distribution with single coil designs. The volume within will enclose a uniform magnetic field by carrying equal current in the same direction on each opposing coil pair. This emanates a magnetic field with minimal weak points for shielding. This is best with materials like YBCO tape and high temperature superconductors to maintain cooling.

Since the settlement has a radius of 5 km, the coil will measure 6 km in radius. This would ensure the settlement stays within the uniform field and is not exposed to magnetic field gradients on the outer edges (Figure 6.2).

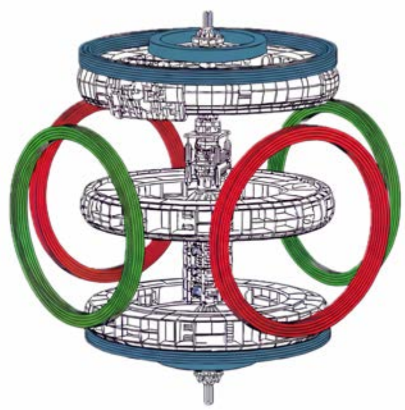


Figure 6.2: Three-axis Helmholtz coil configuration surrounding the settlement, showing orthogonal superconducting coil pairs enclosing the torus stack.

The magnetic field at the centre of a single Helmholtz coil pair is given by:

$$B_{\text{pair}} = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 N I}{R} \tag{6.6}$$

For a three-axis configuration, the total field magnitude is:

$$B_{\text{total}} = \sqrt{B_x^2 + B_y^2 + B_z^2} = \sqrt{3}\,B_{\text{pair}} \tag{6.7}$$

Solving for the required field per pair:

$$B_{\text{pair}} = \frac{B_{\text{total}}}{\sqrt{3}} = \frac{0.4\,\text{T}}{\sqrt{3}} \tag{6.8}$$

The required current is then:

$$I = \frac{B_{\text{pair}} \cdot R_c}{\left(\frac{4}{5}\right)^{3/2} \cdot \mu_0 \cdot N} \approx 1.545 \times 10^9\,\text{A} \tag{6.9}$$

Since the field strength is dependent on the current through the coils, proximity between coils does not affect shielding and that can be controlled by adjusting the current. According to this equation, to achieve a field of approximately 0.2 T, it would require a magnitude of 10^9 ampere-turns (as per Equation 6.9). Although this poses a challenge, it can be achieved by using multi-turn superconducting cables to distribute the load over many parallel loops. In the case of Project Saoirse, 155 turns of a 10 MA cable will be used. The large coil radius also allows for the field to protect against high-energy particles in space.

The major improvement with the use of such a structure to produce electromagnetic shielding is that it is scalable due to the large coil structure and the lack of reliance on field strength. This would allow for the settlement to grow within the Helmholtz structure and not affect humans' safety with high levels of magnetic fields (>0.4 T).

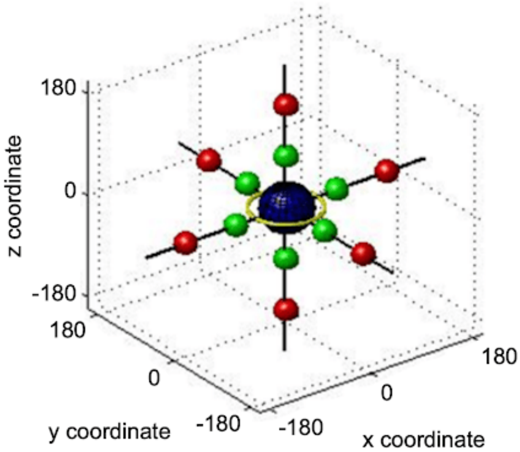


Figure 6.3: 3D coordinate representation of electrostatic gossamer structure positions [64].

It is necessary to consider the transportability of the electrostatic shield, which will serve as the first stage to set up the electromagnetic shield. Transportation is feasible given that gossamer structures are extremely light, allowing the transportation vehicle to move at higher speeds. Traditional rigid or solid electrostatic shielding concepts failed largely due to instability, excessive mass, and enormous power requirements. In contrast, gossamer structures, which are thin and lightweight membranes allow electric fields to be distributed over very large areas while keeping the amount of physical material minimal. This drastically reduces the interaction cross-section with incoming radiation, which in turn lowers secondary particle production and minimizes charge loss, making long-duration operation at high voltages more realistic [64].

A defining feature of gossamer structures in this study is their ability to use electrostatic forces not only for radiation deflection but also for structural inflation. Electrostatically Inflated Membrane Structures (EIMS) rely on Coulomb repulsion between charged membrane layers to create internal pressure, eliminating the need for pressurized gas systems. This makes the structures inherently resilient to micrometeoroid punctures and removes failure modes associated with leaks. Because inflation pressure is controlled electrically, the deployed shape and stiffness of the gossamer structure can be actively tuned by adjusting voltage, allowing the shielding geometry to adapt to mission requirements and environmental conditions.

Shapes such as toroidal rings, umbrella-like shells, and layered membranes produce stronger and more spatially efficient electric field gradients than older spherical configurations [64]. Toroidal gossamer structures, in particular, were shown to significantly reduce the transmission probability of high-energy galactic cosmic rays when compared to equivalent-energy spherical systems.

6.2 Materials

In order to ensure that both the magnetic and electrostatic shields are implemented properly, the materials that are used must be fit to accommodate the needs of both shields. As a result, high conductivity metals such as copper, aluminum, and gold are important due to their ability to distribute charge. In addition, dielectrics such as mylar, kapton, glass, polyethylene have extremely low conductivity with a moderate relative permittivity which makes them perfect for structural support. As the gossamer structure is thin in its nature, it is necessary for a layer of support to be installed to allow seamless transportation.

The requirements for our Helmholtz coil differs from the gossamer structure, as the presence of superconductors such as niobium and YBCO enable the high quantity of ampere-turns required for the settlement. Due to its high critical temperature, YBCO will be the primary material for the Helmholtz coil, with niobium acting as a supplement in case there is a shortage of YBCO. Additionally, copper and NdFeB will act as supports to maintain the magnetic field generated by the Helmholtz coil.

Table 6.1: Electrostatic shielding material properties.

Material	Type	Avg. Conductivity (S/m)	Avg. ε_r	Avg. ρ (g/cm^3)	Use in Shielding
Copper, Aluminum, Gold	Conductors	4.52×10^7	1	10.33	Lightweight and corrosion resistant
Mylar, Kapton, Glass, Polyethylene	Dielectrics	$< 1 \times 10^{-12}$	3.38–4.7	1.56	Support for charged layers, radiation blocking, strong insulator

Table 6.2: Magnetic shielding material properties.

Material	Critical Temp.	Elec. Conductivity	μ_r	Primary Use in Shield
Niobium (Nb)	9.2 K	∞ (SC)	≈ 1	Persistent current loops
YBCO	90 K	∞ (SC)	≈ 1	Space-viable coils, flux pinning
Copper (Cu)	—	5.9×10^7 S/m	≈ 1	Standard electromagnet coils
NdFeB	—	Low	≈ 1	Fixed magnetic field source

Energy

7.1 Space-Based Solar Power

▷ Problem Statement

A settlement of 10,000 people requires approximately 300 MW of continuous power with zero interruptions. Surface solar on Mars fails this requirement: dust storms block 80–95% of sunlight for weeks at a time, and every 24.6-hour day has hours of darkness. No surface-only solar system can guarantee uninterrupted baseload power.

7.1.1 Continuous Solar Collection and Efficiency Chain

At Mars' distance from the Sun (1.524 AU), sunlight is weaker than on Earth, delivering approximately 590 W / m^2 compared to Earth's 1,361 W / m^2. Fortunately, a solar platform at the Mars–Sun L2 point, which is approximately 1.5 million kilometers beyond Mars along the Sun–Mars line, sits in continuous sunlight with no day-night cycle and no dust interference.

One challenge for SBSP is that energy is lost during the conversion process. First, solar panels convert sunlight into electricity at 30% efficiency [24]. Then, that electricity is converted into a microwave beam at approximately 68% efficiency [11]. The beam travels across space with small propagation losses before reaching an antenna on the settlement, which converts the microwaves back into electricity at approximately 72% efficiency [56]. As a result, the efficiency is approximately 14%. Subsequently, in order to deliver 10 MW of energy, about 71 MW must be collected at the source. Although most of the collected energy is lost in the process as heat, the system is able to operate without interruption.

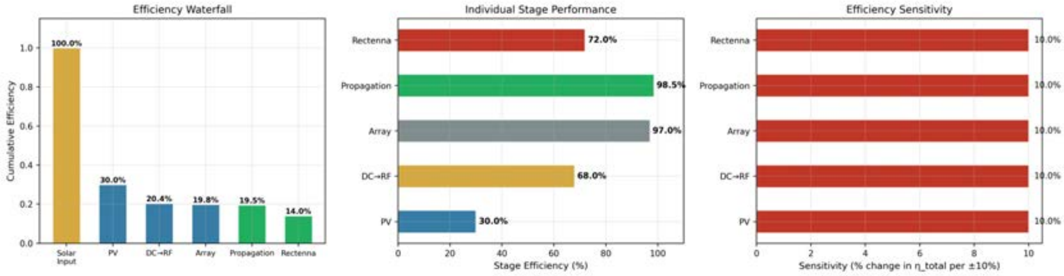


Figure 7.1: SBSP efficiency waterfall, individual stage performance, and sensitivity analysis.

7.1.2 Beam Divergence and Surface Integration

The energy beam is transmitted at 2.45 GHz ($\lambda \approx 0.122$ m). Over a distance of roughly one million kilometers, the beam spreads out due to diffraction. A 500-meter transmitter produces a beam spot approximately 600 km wide, while a 1,200-meter transmitter narrows this to approximately 250 km [11]. Despite this spread, the power density at the receiving end stays well below the safety limit of 250 W / m^2.

The rectenna works most efficiently between 20 and 200 W / m^2, where it converts approximately 70–75% of incoming microwave energy into electricity [33]. As a result, delivering 10 MW requires roughly 50,000 m^2 of rectenna area, 100 MW requires approximately 0.5 km^2, and 1 GW requires approximately 5 km^2. These areas are appropriate for the settlement's infrastructure, so while the beam's spread determines the size of the receiving array, there is no concern for safety.

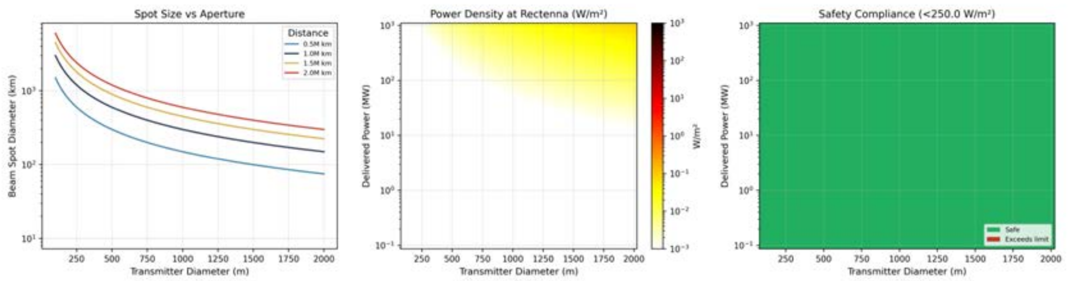


Figure 7.2: Beam divergence analysis: spot size vs. aperture, power density at rectenna, and safety compliance.

7.1.3 Heat Dissipation

The biggest engineering challenge for SBSP is managing heat dissipation. For example, every 10 MW delivered to the settlement comes with 61 MW of heat that must be radiated away from the satellite into space.

At a radiator temperature of 290 K, this requires 160,000–170,000 m^2 of radiator panels, which is roughly the same area as the solar panels themselves (190,000 m^2). As a result, the total satellite mass reaches approximately 800,000 kg.

Two factors play a large role in reducing this issue: By increasing the radiator temperature by 30 K, the required radiator area is reduced by 30–40%, and improving solar panel efficiency by 20% reduces total satellite mass by 15–20%.

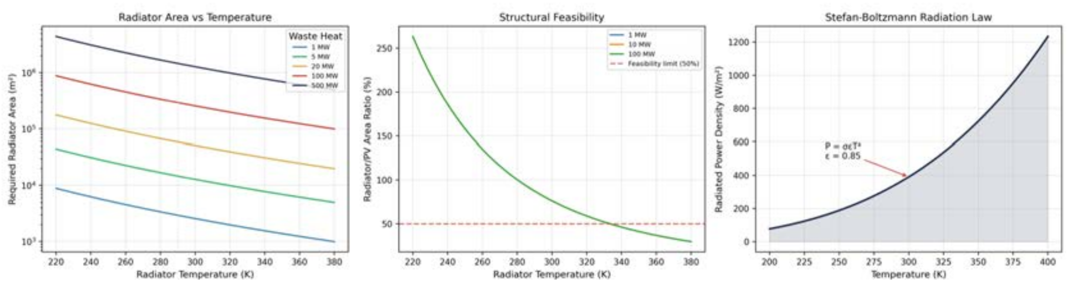


Figure 7.3: Thermal rejection analysis: radiator area vs. temperature, structural feasibility, and Stefan–Boltzmann radiation law.

7.1.4 Settlement Coupling and Modular Scaling

It follows that a settlement of 10,000 people requires approximately 300 MW of continuous power. Hypothetically, if SBSP supplies 60% of this load (180 MW), the settlement needs 18 modular 10 MW satellites at Mars–Sun L2, with a total mass of approximately 15,000,000 kg.

The modular design allows satellites to be added one at a time as the settlement's population grows. However, the ability to manufacture the panels at a large scale becomes the main bottleneck.

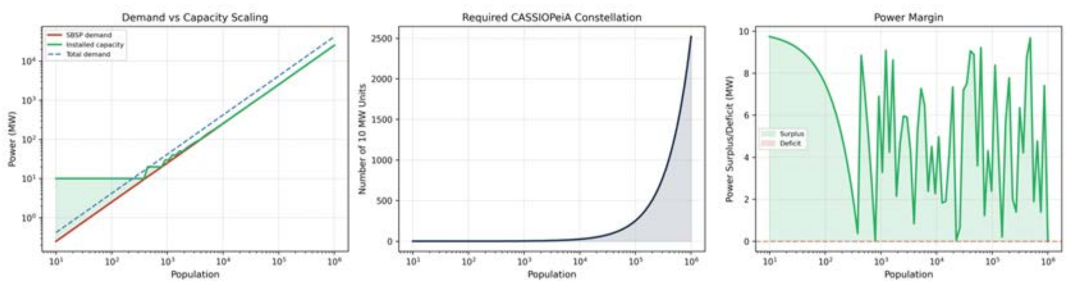


Figure 7.4: Settlement scaling: demand vs. capacity, required CASSIOPeiA constellation size, and power margin analysis.

7.1.5 Reliability and Lifecycle

Solar panels degrade at roughly 0.5–1% per year due to radiation exposure and component aging [24]. Modular replacement strategies can extend system lifespan by swapping degraded components. A Monte Carlo analysis indicates that total system efficiency remains within approximately 14% $\pm$ 1% of planned output, which provides predictable margins for long-term planning.

7.1.6 Integrated Assessment

Mars–Sun L2 SBSP is physically achievable but requires significant mass in orbit. Beamed power transmission is safe and scalable across large distances, and the primary constraint is radiator mass and thermal management. Despite its inefficiency, SBSP provides reliable, continuous power with minimal maintenance, which makes it well-suited for Project Saoirse.

SBSP works best as part of a hybrid energy system. On the settlement itself, magnetic-confinement fusion reactors will provide high-density power for industrial areas, while fission reactors will provide backup power and the ability to restart the grid after potential outages.

7.2 Nuclear Energy System

7.2.1 Design Basis and System Coupling

Each fusion power plant is designed to produce 100 MW of electricity, with the ability to handle peak loads of 150–200 MW. As a result, each nuclear system must meet three requirements:

1. Provide $N + 1$ redundancy, which means that if one plant fails, the other nuclear power plants can cover its load
2. Handle sudden spikes in power demand without affecting life support systems
3. Manage all waste heat within the settlement's thermal infrastructure.

7.2.2 Magnetic-Confinement Fusion Baseload

The settlement's primary power source is deuterium-tritium (D-T) fusion. In this process, two hydrogen isotopes are heated to extreme temperatures until they fuse together, releasing 17.6 MeV of energy per reaction [71]. About 80% of this energy is carried by fast-moving neutrons, which heat a surrounding blanket material. That heat then dissipates into turbines, generating electricity. The remaining 20% is carried by alpha particles, which help keep the fuel hot enough to sustain the reaction.

The reactor design is based on MIT's SPARC compact tokamak, which uses a powerful 12.2 Tesla magnetic field to confine superheated plasma inside torus. Each reactor produces 140 MW of fusion power. The ITER project has demonstrated the physics basis for this approach, achieving a net-positive fusion gain, producing 500 MW from 50 MW of heating input, verifying that fusion can produce far more energy than it requires.

Using a Brayton cycle to convert heat into electricity at 35–40% net efficiency, each reactor generates 49–56 MW of electric power, with the remaining 84–91 MW released as waste heat. Two reactors operating together provide 100–112 MW of total electric power for the settlement.

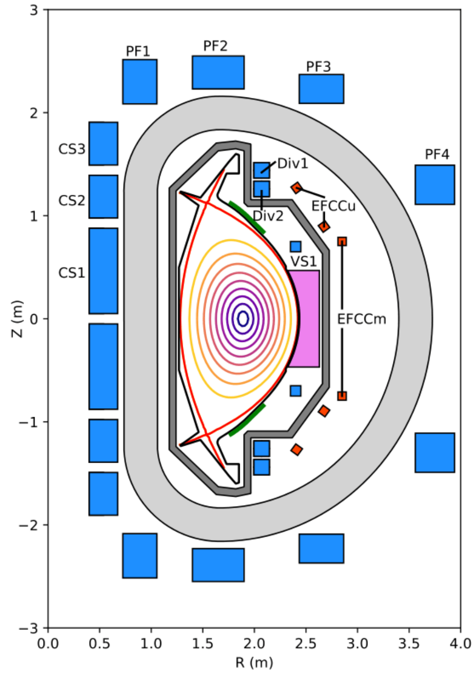


Figure 7.5: SPARC-class compact tokamak cross-section.

7.2.3 Advanced Fission Redundancy

While fusion provides the settlement's main power, modular fission reactors serve as a backup in case fusion fails. When fusion reactors need maintenance these smaller reactors run at partial load during normal operation and take over critical functions such as life support and thermal controls. They also respond quickly to sudden changes in power demand and are used to restart the entire electrical grid in the case of a complete shutdown.

For safety, the fission reactors use a subcritical design ($k_{\text{eff}} \approx 0.95$ to 0.989), meaning they cannot sustain a chain reaction on their own. These reactors thus require an external neutron beam from a particle accelerator to operate. If the beam is shut off for any reason, fission stops immediately.

7.2.4 Radiative Output and System Size Requirements

As with SBSP, managing waste heat is a major design factor. The Brayton cycle turbines convert heat into electricity, but the remaining thermal energy must be radiated into space through large panels. At a radiator temperature of approximately 575 K, each fusion plant requires 18,000–20,000 m^2 of radiator area to reject approximately 90 MW of waste heat. At a panel density of 6–12 kg / m^2, this means 120,000–240,000 kg of radiator mass per plant. Improving conversion efficiency directly reduces waste heat and therefore radiator size. If a reactor produces more heat than its radiators can reject, the result is a thermal bottleneck that limits power output. The nuclear system must therefore be designed as an integrated thermal and structural system, where reactor output, conversion efficiency, and radiator capacity are balanced together.

```
# CASSIOPeiA SBSP Simulation -- Core Models (Pseudocode)

def solar_flux(orbit_phase):
    r = MARS_AU * (1 - ECCENTRICITY * cos(orbit_phase))       # eccentric orbit
    return SOLAR_CONSTANT / r^2                                 # inverse-square law

def beam_spot_diameter(D_tx, R, wavelength):
    return 2.44 * wavelength * R / D_tx                         # Airy diffraction
def power_density(P_beam, D_tx, R):
    d_spot = beam_spot_diameter(D_tx, R, WAVELENGTH)            # spot diameter
    return P_beam / (pi * (d_spot/2)^2)                         # W/m^2

def efficiency_chain(eta_pv, eta_rf, eta_array, eta_prop, eta_rect):
    return eta_pv * eta_rf * eta_array * eta_prop * eta_rect   # end-to-end ~14%

def satellite_sizing(P_delivered, eta, F_solar, packing):
    P_solar = P_delivered / eta_total                           # gross collection
    A_sat   = P_solar / (F_solar * packing)                     # PV array area m^2
    P_beam  = P_solar * eta_pv * eta_rf * eta_array             # radiated power
    P_waste = P_solar - P_beam                                  # on-board waste heat
    return A_sat, P_waste, P_beam                               # full power balance

def radiator_area(P_waste, T_rad, emissivity):
    return P_waste / (SIGMA_SB * emissivity * T_rad^4)          # Stefan-Boltzmann

def lifecycle_degradation(year):
    pv_factor  = (1 - 0.005)^year                               # 0.5%/yr PV aging
    rf_factor  = (1 - 0.003)^year                               # 0.3%/yr RF aging
    return pv_factor * rf_factor                                # combined factor

def settlement_demand(population, growth_phase):
    base_kW = 30.0 * population                                 # 30 kW/capita
    return max(182, base_kW * (1 + 0.8*growth_phase)) * 0.60   # 60% from SBSP
```

Figure 7.6: Pseudocode summary of the CASSIOPeiA SBSP simulation: solar flux, beam optics, efficiency chain, satellite sizing, thermal rejection, mass budgets, rectenna performance, lifecycle degradation, and settlement demand coupling.

Communication

▷ Problem Statement

Extreme distances, variable delays and intermittent connectivity are all problems in space. Traditional internet protocols, such as TCP/IP, involve low-latency, always-connected networks. As such, no single communication technology is able to satisfy all of these needs. This motivates the usage of a layered communication system.

8.1 System Architecture

The system consists of three layers: (1) an application layer that contains scientific data, telemetry, commands, medical data and other general communications, (2) a Delay-Tolerant Networking (DTN) layer that creates, routes, stores and prioritizes data bundles, and (3) a physical communication layer that uses Radio Frequency (RF) and optical links.

8.2 Network Topology

The settlement network uses a hub-and-spoke architecture. Local settlement networks, such as those needed in mining stations, use full-mesh topologies. Each hub maintains high-gain antennas pointed at neighboring hubs. They can store-and-forward bundles across numerous hops.

8.3 Delay Tolerant Networking

The communication system is built upon Delay Tolerant Networking (DTN). DTN is designed for environments that experience intermittent connectivity [12], [42]. DTN follows a store-carry-forward model. They work by packaging data into bundles that can then be carried and forward by intermediate nodes when links become available. In terms of the data protocol, the DTN Bundle Protocol will be implemented.

In order to route bundles throughout this layer, we use the Contact Graph Routing (CGR) algorithm. This uses orbital mechanics to compute optimal paths of communication. Pre-planned schedules will be used to build a contact graph. Then, algorithms will run to find optimal data paths that improve efficiency. For more unpredictable nodes, probabilistic routing protocols will be used. PRoPHET will be integrated to complement CGR [21]. PRoPHET maintains probabilities for each pair of nodes whenever they encounter each other. It estimates the likelihood of future encounters with other nodes.

The DTN layer implements custody-based reliability to ensure that data bundles reach their destination despite any link failures. If acknowledgements do not arrive within an expected time window, which is calculated from the contact graph, automatic retransmission starts.

8.4 Protocol

Not all data is equally urgent, so the system sorts messages into three tiers: life-support readings and emergency alerts are sent first, scientific data second, and routine logs last. Because signals take minutes to travel between nodes, clocks cannot be synchronized in real time; instead, each node keeps its own high-precision clock and receives periodic corrections through DTN bundles.

All messages follow the Consultative Committee for Space Data Systems (CCSDS) Space Packet format [48], a standard structure that labels every chunk of data with an identifier and sequence number. Every transmitter and receiver stores a record of these packets, so if any chunk is lost in transit it can be specifically requested and resent.

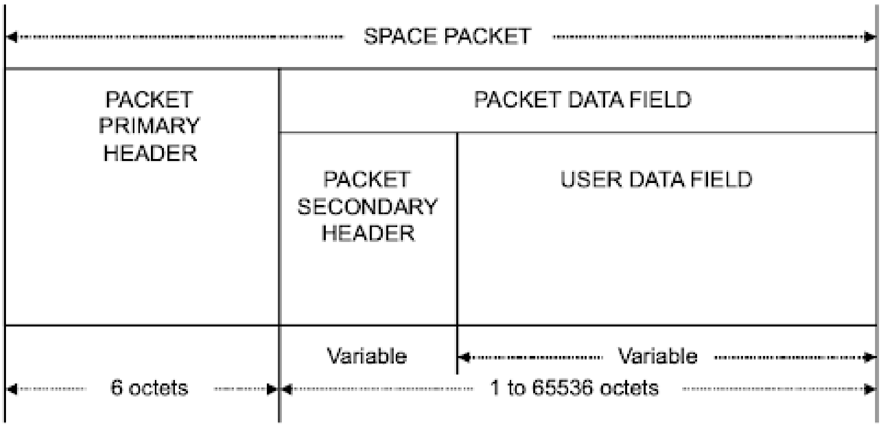


Figure 8.1: Structure of CCSDS Space Packet [48].

8.5 Radio Frequency

RF communication is an extremely reliable method to physically transmit data. For settlement to Earth communication, which will be crucial during the building process, we will use the X-band (7.1–8.5 GHz). Communication from the Earth to the settlement will be 7.145–7.190 GHz, while communication from the settlement to the Earth will be 8.40 GHz – 8.450 GHz. The Ka-band (31.8–34.7 GHz) will serve as a secondary option, used for bulk data transfer due to its reliability. For mining spacecraft, the Ultra High Frequency (UHF) band (400–450 MHz) will be used for simple, reliable communication. Each spacecraft will be equipped with a quarter-wave monopole antenna at 437 MHz in order to minimize power consumption and maximize data transfer speed. For all of these methods, we use phase-shift keying (PSK) to encode data.

With radio frequency, there are lots of issues in terms of data loss. Channel loss is primarily due to free space path loss, caused by the loss required to send the signal over a long distance, and pointing loss, due to the imperfect alignment between receiver and transmitter. The effective transmitter power is referred to as Effective Isotropic Radiative Power (EIRP). In order to increase effective EIRP, all transmitters will be equipped with travelling wave tube amplifiers and solid state amplifiers. One problem that arises with RF communication is noise and bit errors. Trying to send data faster means that each bit occupies less time, making receiving hard. Our goal is to maintain a bit-error target less than 10^{-5}. This means we have one error per 100k bits. To achieve this, we target a minimum energy per bit to noise power spectral density ratio (E_b/N_0) 9.6 dB. This means that the energy in each bit must be 9.6 times stronger than the noise. In order to do this, we use forward error correction [44]. This allows receivers to be able to detect and correct bit errors. Furthermore, we separate transmit and receive ports. This is to prevent the increasing noise figure (N_0).

8.6 Optical Communication

For long distance communication, optical communication is extremely powerful. These optical links can provide high amounts of bandwidth and narrower beam divergence than RF systems, making the system much more efficient.

Atmospheric turbulence is a challenge for optical links involving the surfaces of planets. So, to mitigate this, discrete-time analog transmission will be used. Instead of transmitting data as binary, data can be transmitted as distributions. Data will be encoded and decoded into these distributions via a joint source-channel coding and modulation (JSCCM) network [74]. JSCCM networks are able to map source data to waveforms, improving data integrity.

Multiple data streams can be encoded into a single beam by using different orbital angular momentum (OAM) modes. The general idea is to take a Gaussian laser beam and pass it through a spatial light modulator (SLM) to impose a helical phase front. SLMs apply a desired phase hologram onto an incident beam. On the other hand, for receivers, mode-sorting detectors are necessary.

8.7 Data Freighters

Oftentimes, we want to transmit large, bulky, non time-sensitive data. Real time datalinks will be used for urgent data, but data freighters will be used for large datasets. These datasets consist of scientific data, sensor data, industrial data, medical data and administrative data that need regular backup. This mirrors how Earth uses aircraft for people and time critical goods, but relies on container ships for global trade. Delay Tolerant Networking already treats space communication as custody based and intermittent, so extending it from packets to petabytes is natural evolution.

We would implement data freighters by embedding them directly into the settlement's communications stack as a third layer alongside RF, lasers, and neutrinos. Orbital data vaults would package bulk datasets into encrypted storage cartridges that are loaded onto uncrewed data ships on fixed schedules. DTN would manage the digital side of this process by tracking manifests, custody, and delivery acknowledgements, while the freighters move the actual petabytes through space.

Data freighters will be small autonomous spacecraft with a propulsion bus, navigation, and docking systems, carrying a pressurized or shielded vault module filled with standardized data cartridges. Cartridges would hold 10–100 petabytes of data using 5D optical data storage and MRAM/ReRAM technology. Each of these spacecraft will use radiation-hardened flight computers.

8.8 Neutrino Communication

Neutrino communication would serve as the deepest, most resilient layer of the space settlement's communications stack, operating beneath RF, laser, and data freighter systems [6], [13], [57], [62]. Because neutrinos pass through rock, ice, dust, and entire planetary bodies, with almost no loss, they enable communication where nothing else can, such as between the lunar farside and nearside, with underground habitats on Mars, or during extreme space weather that disables satellites and optical links. The signal is inherently secure and nearly impossible to intercept, since detection requires enormous, precisely aligned detectors. However, the physics that make neutrinos unstoppable, also make them inefficient, limiting data rates to bits per second and requiring enormous energy and infrastructure. This means neutrino links will never carry normal traffic; they exist purely as a civilization scale survival channel for emergency authentication, continuity of government messages, and "we are still here" beacons.

We would implement neutrino communication by embedding it as a dormant but always available Tier 5 system across major settlements, with each colony hosting a compact neutrino system and a massive ice or water based detector built using in-situ materials. These systems would normally remain idle, consuming no operational bandwidth, but would activate automatically or by high authority command if all conventional communication fails. Messages would be short, cryptographically signed, and pre-defined in structure, a few detected neutrino events to confirm identity, status, and survival. In practice, this would function like a planetary-scale distress beacon and secure backchannel, ensuring that even if satellites, relays, and surface networks are destroyed, space settlements can still confirm their existence and maintain continuity across decades or centuries.

Agriculture

9.1 Introduction

The process of feeding a population requires care and consistency, and the importance of such a process is perhaps most evident in space. Keeping that in mind, the agricultural component of our colony is centered on the process of providing a healthy and renewable food source.

The settlement follows a plant-based diet, known for its benefits to the ecosystem and health. These diets require significantly less water and energy to produce and generate fewer byproducts than non-vegetarian diets.

9.2 Growing Method

Using hydroponics as an approach to minimize resources and maximize the amount of produce, the plants will be grown in the agricultural corridors using the artificial gravity flow, which simulates how fluids move on Earth. Since little to no mechanical fluid pumping is necessary to reach the roots of the plants, there will be less chance of clogging, damage to equipment, and greater reliability.

Hydroponics uses a recirculating channel with a continuous, flowing 5.5–7 pH water-based solution, providing the necessary nutrients to support plant growth. Crops are grown with their roots submerged in the solution (at a depth of about 1/8 inch). The roots are held in place by a bar or mesh screen and can absorb the dissolved minerals directly into the roots.

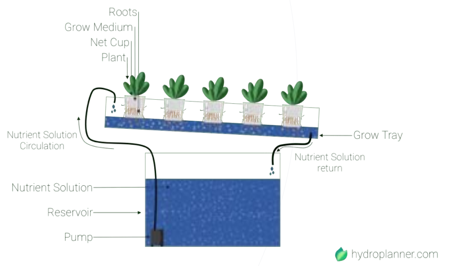


Figure 9.1: Hydroponic nutrient film technique system [1].

The nutrient solution contains all of the necessary ingredients for plant growth and includes macronutrients and micronutrients. The macronutrient levels are typically set as follows: nitrogen levels (for leaf growth and protein synthesis) are 170–200 parts per million (ppm); phosphorus levels (important for transferring energy and developing roots) are 40–50 ppm; and potassium levels (helps regulate water balance and enzymatic functions in plant cells) are 200–230 ppm.

Secondary nutrients are also added to the solution to help support the development of the plant. The secondary nutrients include calcium (for supporting cell wall structure) at 140 ppm, magnesium (for forming chlorophyll) at 45–55 ppm, and sulfur (for producing amino acids) at 60 ppm. Trace nutrients, including iron, manganese, zinc, copper, boron, and molybdenum, are also included in the solution in a chelated form to ensure they remain available to the plants throughout the growing cycle.

Once the plants have absorbed the nutrients from the solution, it is filtered again to remove debris and microbes that may have accumulated in the solution during the growing process. This allows the same volume of water to support multiple growth cycles. The average daily water consumption of this type of hydroponic system is approximately 2–3 liters per square meter of growing space, much less than traditional soil-based agriculture. Crops that exhibit sensitivity to nutrient concentration or require additional root support are grown in substrate-assisted modules adjacent to the main channels. These modules use coconut coir as the growth medium due to its high porosity, strong water retention, and resistance to structural breakdown over time. Coconut coir allows root systems to anchor securely while still permitting efficient diffusion of nutrients from the circulating solution.

9.3 Capacity and Yield

Level 2 provides approximately 1.3 million m^2 of net agricultural floor area after infrastructure allocations. With vertical cultivation, this expands into more than 14 million m^2 of effective growing area, depending on crop height and tier spacing. Controlled-environment agriculture typically produces 2,000–8,000 kcal per m^2 per day depending on crop type, lighting intensity, and growth cycle. Even at conservative mid-range yields, this production capacity generates well over the settlement's annual requirement of ∼11.5 billion kcal, ensuring that only a fraction of total growing space must operate at full intensity at any time.

This surplus allows agricultural zones to rotate offline for sanitation, replanting, or repair while still maintaining stable food supply. In effect, food production is engineered for continuity.

9.4 Waste Management and Nutrient Recovery

Waste is processed through a BioCircular Waste System. This system transforms food and human scraps into fertilizer, fuel, and reusable water. The process begins with Black Soldier Fly larvae, which feed quickly on soft organic waste. They break waste down into protein-rich biomass and frass, which works as a fertilizer [30]. Plant matter, which is more difficult to digest, in turn, travels down into the mycelium chamber. Cellulose is broken down by the fungal networks and part of the partially processed waste is transferred to an anaerobic digester. This is where a nutrient-enriched fluid and biogas that can be used for heating and cooking are generated. This fluid is then filtered and pumped back into hydroponic systems in order to help with food growth.

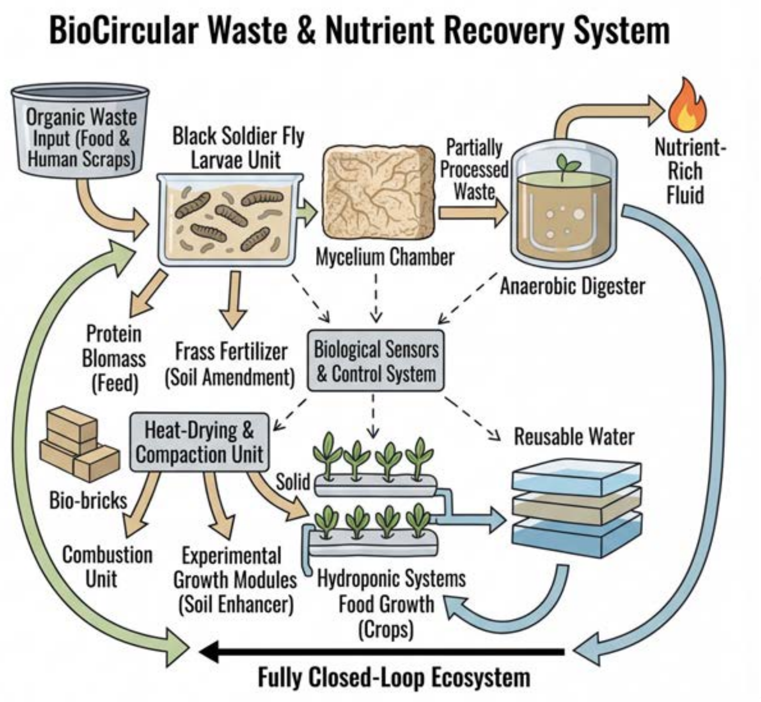


Figure 9.2: BioCircular Waste & Nutrient Recovery System.

Once nutrient rich fluids have been returned to the hydroponics, excess water is captured and filtered using bio-filtration.

Solid residue from anaerobic digestion is heat-dried and then compacted into stabilized bio-bricks. Bio-bricks can be processed further to create a carbon-rich material that can be used in experimental growth modules to enhance soils.

Biological sensors monitor the BioCircular Waste System in real-time to determine nutrient concentrations and overall system performance. If there are any disruptions to balance in the system, the system immediately responds by adjusting feed rates, temperature or microbial population to optimize its performance.

The nutrient enriched fluid produced is filtered to an acceptable standard for agricultural use and fed back into the recirculation loops of the hydroponic channel systems. This creates an opportunity for the settlement to reduce its reliance on off-site fertilizer storage and maintain full control of the amount of each nutrient provided to specific types of crops based upon their needs.

Additionally, an integrated nitrogen fixation component is used. Nitrogen can be lost during anaerobic digestion through denitrification and biomass sequestration in Black Soldier Fly larvae. Therefore cyanobacteria-based bioreactors convert atmospheric nitrogen into bioavailable ammonia through natural biological fixation processes. This fixed nitrogen is then stabilized and reintroduced into the hydroponic nutrient reservoir to maintain optimal nitrogen concentrations required for sustained crop production. In addition, harvested Black Soldier Fly larvae are mineralized to recover their stored nitrogen back into the nutrient stream.

9.5 Water

Greywater, which comes from daily use such as showering and bathing, is filtered and cleaned using a variety of disinfection processes. This greywater is then fed into hydroponic systems used to grow various types of crops. Blackwater, which is considered to have the highest level of contaminants from toilet waste, undergoes an anaerobic process to break down the contaminants with the help of microorganisms. The by-products of the anaerobic reactor are biogas, which can be used to fuel the settlement's energy needs, and clean water, which can be used to safely water crops. Since the reclaimed water will be consumed by humans, it continues to support crop growth, conserve the limited amount of available fresh water resources and supports a sustainable farming system that will provide for future generations [30], [41].

9.6 Lighting

The settlement uses energy-efficient, full-spectrum red and blue LEDs proven to help plant growth. Blue light (450 nm) supports root development and dense foliage, while red light (660 nm) encourages flowering and fruit production [23], [36]. White light (400–700 nm) maximizes algae yields [29]. Adjustable LED panels allow for tuning of intensity and spectrum, which with automated systems, can create individualized lighting for each producer along with lighting for different phases of the plant life cycle [39]. LED lighting will not be run 24/7, as this can stunt the growth of the plants. The lighting cycles will follow the circadian rhythms of the plants using AI-monitored systems.

UV light is used to help plant health and boost growth. Different LED combinations can have different effects on different crops. For example, in kale, white-LED lights improve carotenoid production, and blue-LED lights are efficient in increasing the accumulation of phenolics and their biological activities [52]. In terms of UV light, UV-A and UV-B wavelengths stimulate the production of secondary metabolites such as flavonoids and terpenes, improving the nutritional and sensory qualities of crops [25]. UV-C light, with its germicidal properties, is used to sterilize water and crops to limit the contamination of harmful microbes [47]. Additionally, in Chinese baby kale, UV-A light presented a positive effect on the growth of the plant, main stem length, leaf area, and petiole length [31].

Although these lights aim to be energy-efficient, they still produce waste heat. In the settlement, this heat is captured through cooling systems and fed into the central thermal loop to help warm greenhouses and support water processing, with any excess released through external radiators.

9.7 Crop Selection

The crops are chosen according to their nutrient density, ability to thrive, and ability to perform when there are more ions, as would be expected with a closed-loop system [49], [61]. Leafy greens and fruiting crops, such as spinach, kale, tomatoes, peppers, cabbage, and broccoli, are grown through channels because they have dense yield even when electrical conductivity levels are increased to as high as 4 dS/m [55], [61]. Root crops and legumes with moderate tolerance are selected when their root depth matches the channel depth [49]. These are all considered when meal planning to ensure nutritional completeness while keeping the system steady. The meal plan includes application of these crops in nutrient-dense meals.

9.8 Biofortification

9.8.1 Nutritional Biofortification

A complete dietary framework includes sixteen essential nutrients: protein, calcium, iron, vitamin A, vitamin C, thiamine, riboflavin, vitamin B12, folate, vitamin D, vitamin E, magnesium, potassium, zinc, fiber, and pantothenic acid [68]. A baseline macronutrient distribution of approximately 15% protein, 30% fats, and 55% carbohydrates is recommended to maintain metabolic balance and physiological function [41].

Given the increased caloric needs of residents in space, biofortification through transgenic genetic modification is implemented [5]. Crops are enhanced to increase nutrient density and deliver protective compounds directly through the daily diet.

Long-duration habitation in confined environments is associated with elevated oxidative stress and inflammatory load, both of which are linked to cognitive decline over time. Diet-derived antioxidants, particularly anthocyanins, support neuronal function and reduce oxidative damage. To increase anthocyanin concentration in blueberries, genes responsible for flavonoid biosynthesis are introduced and stably integrated into the plant genome. Successfully modified plants are propagated and crossbred to increase yield and maintain trait stability.

Residents also experience environmental stressors such as vibration, noise, and circadian rhythm disruption [63]. NASA studies have identified metabolic alterations linked to energy regulation and bone density loss [59]. To counteract this, additional biofortification strategies are applied. For example, genes that enhance calcium transport and accumulation are introduced into crops such as carrots to increase calcium bioavailability. Modified plants are subsequently crossbred to expand production.

Other nutritional enhancements include increasing vitamin K to assist with calcium utilization and bone development, and designing crops with elevated omega-3 fatty acids to support heart and brain health. With genetic optimization, food production becomes a protective mechanism against the physical stresses of life in space, not just a means of obtaining calories.

9.8.2 CRISPR Optimization

Using delivery methods such as biolistic gene transfer and CRISPR-based epigenetic editing, CRISPR enables the development of crops that require less water, grow more efficiently, tolerate environmental stressors, and exhibit better nutritional profiles [75]. Recent studies demonstrate that plant architecture itself can be treated as a modular trait; targeted editing of genes controlling determinacy and growth habit allows crops to be made more compact [50]. For example, CRISPR-Cas9 targeting of soybean phytoene desaturase genes (GmPDS1 and GmPDS2) has demonstrated high mutation specificity, allowing the production of distinct soybean lines optimized for different functional requirements [32]. As such, crop varieties can be precisely tailored to meet the spatial and nutritional demands of the settlement.

CRISPR is also used with algae, bacteria, and cyanobacteria to improve yields [66]. In specific, cyanobacterium *Synechococcus elongatus* UTEX 2973 has been used for various photosynthesis studies, with an easily modifiable base [73]. One problem is that cyanobacteria, including *S. elongatus*, have uneven light distribution; this can be avoided by using cell cultures with smaller antenna sizes packed in high-density cell culture [37]. CRISPR can be used to delete 4 kb of the phycocyanin gene cluster, removing three rod-rod linker proteins (cpcC1, cpcC2, cpcD) and one phycocyanin gene copy (cpcB2A2), leaving a truncated antenna [27]. This mutant has exhibited up to 36% improved growth under highlight and ambient CO_2 conditions [27].

9.9 Melatonin

Salt stress and oxidative damage are the two main types of abiotic stress that affect crop growth in closed-loop systems. Research has shown that the application of melatonin to plants exposed to salt stress results in reduced oxidative damage and increased antioxidant activity that protects photosynthesis [26]. In addition, melatonin has beneficial effects on plant growth and physiology when plants are exposed to salt stress.

The delivery of melatonin to crops is done through seed priming. The application of melatonin to seeds is a practical method to enhance crop emergence and promote the development of stress-resistant traits in crops growing in salinity and combined stress conditions [20]. The application of melatonin to leaves of crops experiencing salt stress has shown to alleviate salt stress and maintain physiological homeostasis in tomatoes grown in controlled environments, which makes it suitable for high-value fruiting crops [35]. In both cases, the application of melatonin acts as a biochemical stabilizer that enhances crop yield consistency and promotes consistent yield timing and reduces the risk of performance losses during stress fluctuations.

9.10 Agriculture in Society

Agriculture is integrated into daily life. Research in environmental psychology and urban studies supports this, showing that access to green spaces improves mood, reduces stress, and enhances cognitive function [8], [69]. As a result, food production areas are located among residential areas and community spaces. Walkways lined with crops, groups of greenhouses, and trees in community courtyards are designed as shared spaces that community members pass through.

Research on community gardens has demonstrated that participation in food systems promotes social cohesion and a feeling of belonging [2]. Plants, for example, reduce stress hormones like cortisol and boost mental resilience [69].

9.11 Using Mycelium to Enhance Growth

Mycelium is a new construction material that will have several benefits when it is used for construction of our settlement. One of the biggest benefits to using mycelium for construction is that its low launch mass will allow astronauts to transport a minimal amount of feedstock and the dormant fungal culture to the site and build much of the habitat at the site, reducing the cost of transporting large amounts of heavy materials from earth. Also, mycelium's bio-fabrication process will greatly reduce the need for tools and parts to launch. A damaged area of the habitat will be able to repair itself and potentially support growth of the settlement by reactivating the original colony to produce additional habitat material. Thermal insulation can also be achieved with the high porosity of the mycelium-based structure.

Mycelium is also advantageous to use as a building material for a space settlement with respect to the long term development and stability of the settlement. For example, mycelium can be grown to create molds or inflatable shapes, allowing habitats to be constructed as modular units that can be expanded over time as the crew population increases and/or mission requirements dictate a larger infrastructure. The high hydrogen content in the organic structure of mycelium combined with the potential presence of melanin in mycelium-based composite materials will provide excellent radiation protection for these types of materials. Radiation protection is one of the major concerns related to limiting the exposure to the crew during solar flares and long duration surface stays. From a sustainability aspect, mycelium can be incorporated into a closed loop process where organic waste streams (i.e., plant biomass from agriculture) can be utilized as a feedstock, converting what would have been waste into structural resources and minimizing the generation of waste and the reliance on launch supplies. Finally, the porous nature of the micro-structure of mycelium-based composites will provide the opportunity for multiple functions within a single wall (i.e., providing thermal insulation and containing channels for electrical wiring, air flow or moisture management to maintain interior environmental conditions).

Health

▷ Problem Statement

Health in space is defined by the absence of external assistance. There is no evacuation and there will be no room for decline. Residents need to maintain physical capacity, mental stability and social functionality across multiple generations. The ability to provide health services defines the success of a settlement.

Along with clear healthcare needs, long term stabilization of the settlement's health system will be the primary objective of the health system. Crisis response will be replaced by early detection. In addition to being able to restore physical function when needed, the physical and mental health of the settlers (and their psychological well-being) will be considered to be part of the overall infrastructure of the settlement. Along with this, the system must scale with the growth of the settlement.

10.1 Neurodiversity and Inclusive Design in the Settlement

Long-term space travel can accommodate the spectrum of human diversity through the inclusion of neurodiverse individuals and their specific requirements. These include but are not limited to; individuals diagnosed with Autism Spectrum Disorder (ASD), Attention Deficit Hyperactivity Disorder (ADHD), Sensory processing disorders, anxiety disorders, and/or other neurological conditions. If we fail to meet the needs of neurodiverse residents in a confined, high technology environment, we risk decreased productivity and poor long term mental health outcomes. Therefore, our habitat has been specifically designed from the ground up to incorporate adaptive support systems to ensure all residents have an opportunity to contribute to their community without undue burden [70].

A development area is included in the settlement to house a learning center that utilizes sensory friendly architectural design to avoid overwhelming while providing both functionality and efficiency. Quiet corridors lined with sound absorbing wall materials reduce echo and ambient noise associated with enclosed habitats. The lighting in the learning center has dimmable, indirect light that allows the brightness level to be altered according to the needs of each resident. Additionally, the light temperatures can be changed to help regulate the residents' circadian rhythms as many neurodiverse individuals struggle to maintain normal sleep patterns due to difficulty regulating their internal body clock [3].

Color coding is used instead of written signs to provide direction to residents who require less reliance on written language and have difficulty with spatial orientation or become overwhelmed by the complexity of their surroundings. The use of consistent colors and easily identifiable visual cues increases predictability and therefore decreases anxiety for many neurodiverse individuals [70].

Each resident also has developed a personal, sensory profile tied to their individualized digital health card which is a comprehensive medical and wellness document that follows the resident throughout the settlement. The use of the sensory profile with resident consent enables automatic adjustments to the shared spaces of the settlement including the classrooms, workspaces, and recreational facilities. This adaptable environment serves to reduce the need for the neurodiverse residents to advocate for themselves continuously to meet their needs. Rather, the environment responds to their needs to decrease their cognitive load, thereby increasing their ability to engage in learning [3].

Furthermore, this design philosophy views neurological differences as a normal component of human diversity and enables residents who are autistic, residents who have ADHD, and residents who experience difficulties with sensory processing to be full participants in the life of the settlement [70].

10.2 Food Processing and Preservation

Nutrient retention and minimal waste during food processing are primary goals. The farm-to-table model is being utilized to preserve the freshness of products while crops are moving through the supply chain. Only necessary processing steps are taken to ensure food safety. Fermentation facilities are producing probiotic foods and yogurt alternatives. These alternatives have a longer shelf life than traditional yogurts, and do not require additional chemical preservatives.

Products such as fresh fruits/vegetables and reserve meals are dehydrated and decrease spoilage while being consumed daily along with fresh food.

A plant-based diet, high in fiber is used to control metabolic instability within the settlement. Foods such as nuts, seeds, complex carbohydrates, vegetables, and omega-3 fatty acid sources are emphasized. Calcium and vitamin D-enriched materials are used to prevent bone demineralization [45], [59]. Probiotic foods, produced through fermentation bioreactors maintain the balance of the microbiome. In addition to calcium and vitamin D, B12 and omega-3 fatty acids, produced through algae bioreactors, are used to support the long-term nutritional needs of the settlers [22].

The community's meal planning process uses a centralized monitoring system that provides tracking of crop yields and population demand. Using this data to adjust the diets of the various populations based on their age and health level minimizes food waste. Additionally, the promotion of healthy eating practices is supported by the education and training provided to community members in nutrition. This ensures that they understand how their diet impacts their ability to sustain their physical health over a long period of time.

10.3 Nutritional Guidelines and Diet Design

The Biocircadian Meal System is our team's original method for nutrition as meals adapt to the individual's body type, as well as environmental limitations including age. Instead of selecting a menu based on demographic information, the Biocircadian Meal System has one basic meal option that has variable portion sizes and nutrient combinations. All meals are scheduled according to the biological cycles of humans to support regular metabolic functions.

The majority of the meals consist of vegetables, fruits, and grains that are grown within a controlled environment. These foods contain high amounts of fiber, essential minerals, antioxidants and plant-based proteins. The meal plan table describes each meal, its basic componentry, and an estimate of the meal's nutritional content.

As a result, the Biocircadian Meal System provides for the needs of residents from birth through old age, while also minimizing the pressure on agricultural modules. Younger children and teenagers have their diets supplemented with calcium, iron, and Vitamin D [45]. Adult diets include consistent levels of B12, while diets for older adults are supplemented with extra protein and Vitamin D to help maintain bone strength and brain function [22]. Throughout the day, the meal system maintains balance in the metabolism and minimizes spikes in blood glucose levels.

10.3.1 One-Day Multi-Age Biocircadian Meal Plan

Meal	Dish (Adult Base)	Nutritional Facts (Adult Base)
Breakfast	Oat Bowl • ½ cup oats + ½ cup millet • ½ soy yogurt • ½ cup fruit • 1 tbsp chia/flax • ½ tsp algae powder	Calories: 400 kcal Protein: 15 g Carbs: 58 g Fat: 10 g Fibre: 9 g Calcium: 220 mg Omega-3: 2 g

Meal	Dish (Adult Base)	Nutritional Facts (Adult Base)
Morning Snack	Veggie Sticks and Hummus • 1 cup mixed vegetables • 2 tbsp hummus	Calories: 120 kcal Protein: 3 g Carbs: 12 g Fat: 4 g Fibre: 3 g
Lunch	Grain Plate • ¾ cup quinoa-lentil blend • ½ cup sweet potato/red beetroot/eggplant • ½ cup greens • 1 tbsp seeds	Calories: 680 kcal Protein: 22 g Carbs: 80 g Fat: 9 g Fibre: 13 g Iron: 4 mg
Afternoon Snack	Fruit and Roasted Chickpeas/Soy Nuts • 1 piece of any chosen fruit • ½ cup chickpeas or soy nuts	Calories: 410 kcal Protein: 9 g Carbs: 29 g Fat: 6 g Fibre: 5 g
Dinner	Stew • 1 cup lentil/bean stew • ½ cup whole grain • ½ cup greens • 1 tsp oil	Calories: 690 kcal Protein: 21 g Carbs: 66 g Fat: 8 g Fibre: 14 g
Evening Snack	Soy Milk and Whole Grain/Pumpkin Seeds • ½ cup soy milk • small whole-grain piece • 1 tbsp pumpkin seeds	Calories: 250 kcal Protein: 6 g Carbs: 16 g Fat: 7 g Magnesium: 80 mg

10.3.2 Lunch Grain Plate

Figure 10.1: Preparation steps for the Lunch Grain Plate.

10.4 Psychological Support Systems

Maintaining a circadian rhythm in an environment with no natural sun rise or sunset is essential to the quality of life in the community we plan to develop. Our model has created a single clock within the community by using a series of coordinated behavioral cues that help support agricultural interactions and cultural activities throughout the day. This creates a common experience of time for all residents, regardless of their age, ability or senses, and provides a constant rhythm to the day.

Automated lights slowly grow brighter throughout the day to introduce a "start-of-the-day" timing effect to all components of the settlement. While the inhabitants are initiating their individual morning routines, the plant systems have initiated photosynthesis. The timing for eating remains constant, as do the meal schedules that serve to regulate the metabolic function. The food schedule serves to reinforce the daily structure through the daily routine of agricultural functions that include the harvesting of fresh produce toward the end of the day. Women specifically benefit from routines that align with different phases of their menstrual cycle. This ensures that high-energy tasks match peak alertness and restorative activities are mixed with more sensitive periods. At the end of the day, the automated light is made to appear dimmer as well as warmer, which stimulates sleep and increases melatonin secretion [17]. A particularly important feature of this system is for individuals who may be neurodivergent, as well as children, whose reliance upon a sensory environment can provide feelings of safety.

A vital part of the community aspect of the settlement is community-based cueing throughout each day. Cueing can take the form of a soundscape or an informal gathering near green spaces that have natural sensory input provided by plants. Exposure to green spaces and consistent routines can be effective for reducing stress and promoting emotional regulation [7], [8]. This also helps assist with regulating emotions, particularly for individuals experiencing difficulty understanding time awareness.

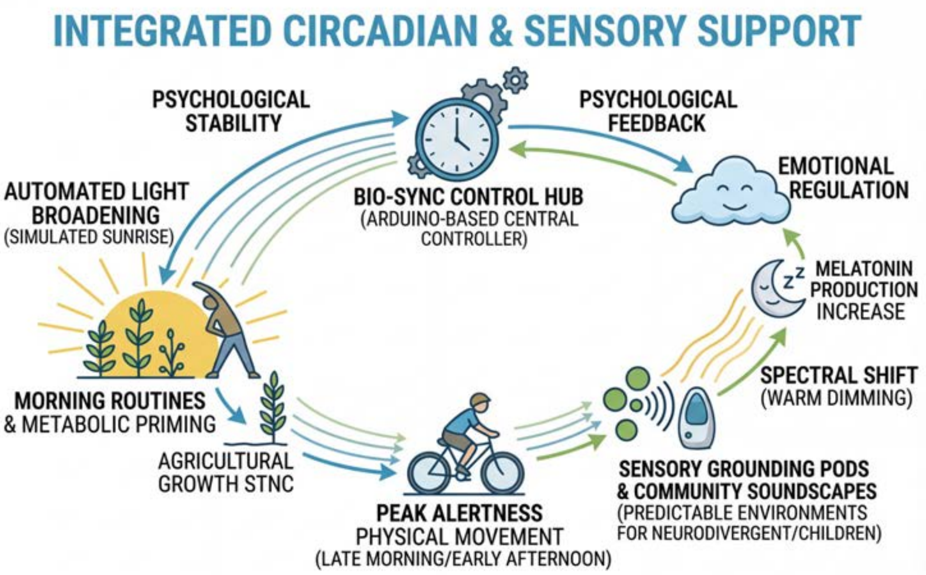


Figure 10.2: Integrated Circadian & Sensory Support system.

Activity-based time anchoring serves as another way for the community to establish a steady circadian rhythm. The settlement includes physical movement during the peak alertness times of day. For example, exercise areas and active transportation routes are placed and designed to encourage residents to be physically active during these times of day (late morning/early afternoon). Additionally, the evening hours include lower stimulation opportunities for relaxation, such as quiet recreational spaces, reading spaces, and reflection on culture, which signal that it's time to get ready for bed [43].

10.5 Women's Health

10.5.1 Integrated Menstrual Equity

Women's health is integrated into daily living in our space colony and not treated as secondary. Plastic waste generated through menstruation is a large source of landfill waste on Earth. Since every gram of material is expensive to transport in space, we are utilizing the Aruna Revolution [10] to reinvent menstrual care using plant based technologies.

Menstruation is a closed-loop, sustainable regeneration process in this context. Menstrual pads, for instance, are made from vertically farmed crop fibers (hemp and flax) that the textile industry would have otherwise disregarded. This method transforms waste products into usable ones and produces hypoallergenic products that prevent skin irritation in microgravity. They are also absorbency products that work across all gravity levels and are fully compostable to ensure that no waste is generated. Once the product is used, it does not go to the landfill as waste. It is instead put right into our solid waste bioreactors, where it breaks down into a nutrient-rich fertilizer within a couple of weeks. That fertilizer is then fed into our hydroponic bays, and the crops grow using that fertilizer. In other words, a pad used in March can fertilize the tomatoes eaten by the settlers in May.

◇ 10.5.2 Cycle-Aware Health and Daily Routines

Women's health in a microgravity environment must consider both physiological and psychological factors. Women experience greater loss of bone density and fluid shift in a microgravity environment than most males [43], [59]. Loss of bone density can cause disruptions in menstrual cycles, lead to decreased levels of energy and sleep disturbances. We have a "cycle aware" work schedule to plan for the time when an individual has the most energy (follicular) and less energy (luteal) to perform high energy tasks. There will be times to engage in restorative activities like meditation and yoga.

Meals will be nutritionally tailored to provide individuals with sufficient amounts of vitamins to support their hormone systems. Additionally, individuals have the option to track cycles, moods, sleep quality and body changes in a journal. This allows them to start to identify patterns and maintain control over their health, also providing valuable insight into how women adapt to the microgravity environment.

◇ 10.5.3 Pregnancy and Maternal Nutrition in Space

Pregnancy is supported through vitamin-rich nutrition and careful environmental design. The body's needs are increased in microgravity due to fluid movements, radiation exposure, and overall bone density loss. In response, our system produces a nutrient-dense diet that protects the development of the fetus as well as the health of the mother.

Increased folate, choline, iron, and vitamin B12 levels in the early stages of pregnancy promote proper oxygen transport and brain development. Calcium and vitamin D intake rises as the fetus develops to assist skeletal formation and preserve the mother's bone density. Omega-3 fatty acids, particularly docosahexaenoic acid (DHA) from algae bioreactors, support the development of the brain and eyes. Throughout pregnancy, magnesium and iodine improve the regulation of energy levels and muscle function. Protein intake is carefully regulated through high-quality plant sources and electrolytes are balanced to counteract fluid redistribution in microgravity.

10.6 Supplementation

Previous space missions have demonstrated consistent physiological changes in astronauts over time, particularly when missions last for approximately four to six months (128–195 days). The data indicate that there are significant reductions (from 5–10%) in body mass and changes in how the body utilizes nutrients [59]. If these trends continue over years in a permanent space settlement without intervention, they could create serious problems for the health of the settlement's residents.

Therefore, the primary objective of the nutritional supplementation program is to provide a stable body composition for the metabolic functions of the residents. Supplements are used to support the balance between bone density and the regulation of calcium metabolism. This includes; 2,000–4,000 IU of vitamin D per day, along with 90–180 micrograms of vitamin K2 [4], [45]. The magnesium supplement levels are intended to support both neuromuscular function and energy metabolism, with the recommended daily intake being 300–400 mg. Additionally, residents consume omega-3 fatty acids (EPA + DHA = 1–2 grams / day) to help preserve muscle tissue and enhance cognitive performance. Increased oxidative stress during space flight has also resulted in the inclusion of antioxidant support in the form of vitamin C (250–500 mg / day) and coenzyme Q10 (100–200 mg / day) in the supplement program [16].

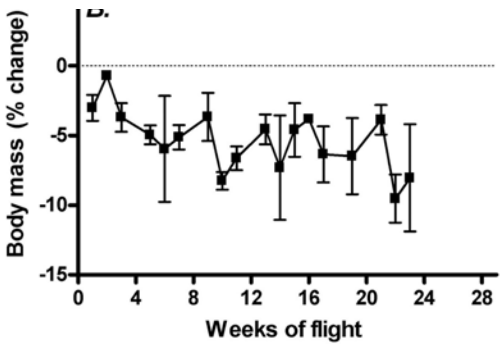


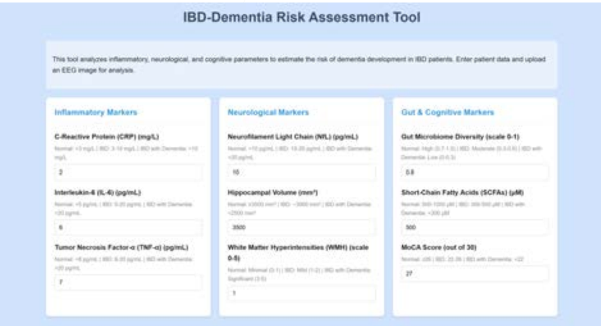
Figure 10.3: Body mass changes during spaceflight [58].

Supplement use is directed by the regular health monitoring of the residents, which enables the intake levels to be adjusted based on factors such as age, activity level and physiological response.

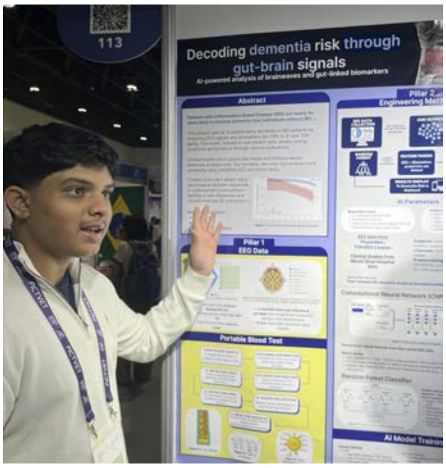
10.7 Predicting Alzheimer's Using Artificial Intelligence

The long-term effects of isolation can negatively impact the brain's ability to function properly. As such, we have recognized that early detection and automated tracking of risk are crucial for providing timely interventions. Therefore, one member of our team previously developed an artificial intelligence (AI)-based system for early detection of neurodegenerative diseases, specifically related to cognitive decline due to Alzheimer's disease, which we propose to adapt for use in the settlement environment. When deployed to the settlement, this AI Platform acts as a longitudinal monitoring tool for neurodegenerative diseases and cognitive decline, focusing on the earliest possible identification of risk.

The AI-Platform utilizes two input designs, with no low infrastructural requirements. First, a low-cost three electrode EEG was developed to measure the brain regions in which functional activity changes occur early (Alzheimer's-related decline), specifically the temporal and frontal lobe at position TP9, FP1, and FP2. Second, a Portable Blood Testing System was also developed to operate without the use of centrifuges or heavy bench equipment.



(a) AI-powered IBD-Dementia Risk Assessment Tool interface.



(b) Team member presenting the research at a science fair.

Figure 10.4: IBD-Dementia Risk Assessment: tool interface and research presentation.

Additionally, the system enables the selective screening of high-risk groups of people, such as those with inflammatory conditions like IBD (inflammatory bowel disease) who have shown a greater likelihood of developing dementia and experiencing an earlier onset.

The AI produces a risk score and trajectory report based on EEG, blood biomarker panel and short cognitive tasks data. All residents who are flagged will receive tighter follow-up and targeted counter-measures (circadian stabilization, stress modulation, exercise prescription, and medical review) when their risk increases. This system saves 32 clinician hours per patient and $4200 per patient, significant when considering the environment.

Security

Problem Statement

Fundamentally, security in a permanent space settlement is unlike security on the Earth. On Earth, security is very reactive. Crimes tend to occur and institutions respond through investigation. However, in a permanent space settlement, any failure can cause catastrophic problems within the space settlement. Security must be predictive and system-driven. All threats can be categorized as one of the following: (1) control, (2) decision making, (3) containment and life support, and (4) external threats. By organizing security architecture, resources can be allocated proportional to risk.

11.1 Control

11.1.1 Cybersecurity

In a space settlement, software mediates critical operations, such as life support, navigation and power distribution. All critical systems will operate on formally verified code. This will minimize any undefined behaviour that could lead to any failures. No user or process is trusted by default. Permissions are task-specific and time-limited, in order to prevent any system failure. Intrusion detection systems continuously monitor traffic to detect any anomalous patterns that may indicate attack.

11.2 Decision-Making

11.2.1 Crime

Because of limited space, the shortage of workers, and the psychological effects of seclusion, the system of exclusionary justice proves ineffective in the closed system of security. Threats of security are more probable in situations of negligence, decrease in intelligence, or in procedural infractions than in intentional actions.

11.2.2 Law as Infrastructure Protection

Critical infrastructures like air, water, power, data, and life support services are considered legal stakeholders rather than mere property. Codes of law that regulate infrastructure are critical.

11.2.3 Systems-Based Legal Enforcement (SBLE)

The Systems-Based Legal Enforcement (SBLE) also transforms the concept of policing through access, where the regulation of the systems that the individual can utilize supplants the practice of incarceration and arrest. Because all major activities carried out in a space colony are software-mediated, enforcement takes place at an authorization level. The SBLE can be considered as a closed-control system, where data regarding interactions and behavior act as the input, while the determination of the systems' level of risk, as the controller, is carried out using algorithms related to the legality of the systems. Moreover, the output, which is the actuators, takes the form of dynamic permissions. The consequence of violating the laws of the systems takes the form of withholding permissions related to the use of systems, such as those related to high amounts of energy, as well as transit, while the freedom of the individual is maintained.

11.3 Containment and Life Support

11.3.1 Hull Integrity

The settlement will be divided into pressure zones. Any breached zones can be isolated within seconds. Pressure sensors will be used to detect any minor leaks.

11.3.2 Fire

Material selection prioritizes non-flammable materials. Electrical systems use arc-fault detection and thermal monitoring to prevent any ignition. Atmospheric composition will be controlled to reduce flammability.

11.3.3 Structural Fatigue

Long-horizon threats, such as microcracking and material fatigue will be monitored with acoustic sensors, strain gauges and ultrasonic inspection systems.

11.3.4 Emergency Response Protocols

A tiered emergency classification system enables rapid and coordinated responses. Level 1 emergencies involve immediate threats to life support or hull integrity requiring automated responses. Examples of these are pressure loss, fire detection and toxic gas release. Level 2 emergencies are serious but contained threats. Level 3 incidents are developing situations that may escalate.

11.4 External Threats

11.4.1 Space Debris and Micrometeroids

External physical threats will also be analyzed. Lidar, IR, radar tomography and spectroscopy will be used to characterize objects. Sensor fusion will be used to reconstruct internal structure and material composition. Pulsed lasers will be used to alter the orbits of debris through pulsed-lased ablation [9], [14]. They will deorbit threats before interception.

Early characterization of asteroids is the primary security mechanism. As before, lidar, infrared imaging, radar tomography and spectroscopy will be used to reconstruct asteroids. Specifically, size and mass, internal structure, material composition and rotation state will be extracted.

11.4.2 Cascading Failure Prevention

The biggest goal is to prevent any external problems to start cascades. An external event should not propagate inward through the system inwards and start affecting the population inside. Failure mode and effects analysis (FMEA) is used to systematically identify how individual component failures can actually propagate throughout the entire settlements. Every critical system, such as life support systems, undergoes an analysis that documents potential failure modes, severity ratings and mitigation strategies.

Circuit breaks and compartmentalization bulkheads contain failures within specific subsystems to prevent any propagation. Graceful degradation strategies are also used to maintain essential functions during system failures. If total capacity falls below 100%, non-essential functions automatically shut down to preserve communications and life support. Even with up to 60% system capacity loss, the settlement can survive long enough for repairs or evacuation.

Quality of Life

▷ Problem Statement

While a settlement may have all the technological elements necessary to sustain its population safely, and provide for basic needs such as food and medical care, it needs to be able to allow for the residents to be happy. A long-term closed system will often result in repetitive environments with limited ability to experience the natural cycles of Earth, resulting in a loss of energy and relationship building and a loss of overall sense of purpose over time.

Life requires beauty, private moments, celebrations, challenges, and times of rest. The design of the settlement must ensure the preservation of both physical and mental health, of cultures and traditions and of the individual's experiences on a daily basis; and in doing so provide the opportunity for the inhabitants to feel that their lives are worthwhile.

12.1 Work Structure

Regarding work structure, the settlement adopts a four-day workweek. This has been observed in pilot programs and large-scale trials in the UK, Europe, and other countries. Results from the largest trial of its kind conducted in the U.K. indicated that employees who moved to a four-day work week experienced lower stress and less sickness than those working a five-day work week and were just as productive at their jobs [34], [65]. Of those surveyed in the trial, 71% of respondents reported they experienced less burn out after adopting a four-day work week, while 39% of respondents reported experiencing less stress.

As part of this four-day work week structure, residents work four eight and one-half hour shifts per week, with a 30 minute break between each shift. That totals 34 hours of work per week. Cafeteria services are available to residents during all work hours within sectors; food service is decentralized: each sector includes its own dining hub so residents can access meals without long transit times, helping maintain consistent work schedules. Residents also have three sick days and five paid days for religious/cultural holidays, as well as a minimum of a two-week annual vacation.

The educational sector follows the same four-day work week structure, providing additional time for both contemplation and rest, as well as other personal interests outside the classroom. Results from research on the four-day work week indicate that reducing workplace pressures results in better work-life balance while potentially increasing or maintaining productivity [46], [67].

12.2 RingBall & Games

RingBall is the settlement's main sport, built around controlled gravity shifts and spatial strategy. There are three scoring rings suspended at different heights along the inner curve of a curved arena. Two teams of five compete over four 10-minute quarters (40 minutes total). The goal of the game is to move a weighted Core through the opponent's ring to earn a point. The Core contains an adjustable mass core that can shift its center of gravity when activated by contact panels built into the arena floor. When a team is in possession, they can trigger these panels to alter how the Core moves. The arena is a circular rectangular shape: the arena curves upward, players can sprint along angled surfaces to gain vertical advantage.

Along with RingBall, common earth sports from years are present; including sports known to promote physical activity, such as basketball, cross country, soccer, rowing, and racket sports.

12.3 Education and Schooling

The first step in a society that follows norms is the education provided to its youth. A child's mind is one that can be shaped and moulded to follow standards that will ensure a society with knowledge, peace, and collaboration. This is why a program, which will be active from grade 8 to the last year of post-secondary education, will be a way to transition the minds of interested youth to participate and aid in the space settlement. The program begins in Grade 8 because this is typically when students develop the cognitive maturity needed for abstract systems thinking, career exploration, and sustained interdisciplinary learning. The program works through the basics of space science to important skills for inter-settlement communication.

By the end of the training program, the number of graduates will exceed the capacity of the settlement. However, the skills taught in this program will be useful outside the settlement in roles such as ground crew to manage, communicate, and analyze research from the settlement. The skills taught in this program are to educate students in their specified field that can be transferable and can be used effectively for mission control and other jobs in a terrestrial economy.

The transition program includes grade-specific course content to transition into higher level topics that will focus on concentrations for different purposes required for the program. Important subjects learned in high school such as mainstream language arts, chemistry, geography, computer technology, etc. will be mandatory – with electives also available – for grade 9 to grade 12. Students will have a choice of their intended "major" in university, which will provide a path to certain careers in the space settlement project. Thesis projects, internships, technical training, and more will be focused on chosen pathways.

To be clear, the core subjects (math, language, science, and history) remain, but there is an added goal of space science, engineering, and systems thinking.

To succeed as a civilization, humans must know when they have failed in the past. As such, there is an emphasis on the knowledge and history of earth. Earth studies remain a priority to preserve the history of human-kind. Students study all of Earth: ecosystems, climate systems, biodiversity, political history, technological development, and past global crises.

12.4 Creativity, Art, and Expression

Creative expression is woven into daily life to prevent emotional stagnation in a closed environment. Residents have access to specialized studios designed for different forms of art, including ceramics labs that use recycled mineral dust, textile studios where residents weave fabrics from plant fibers grown in hydroponics, and soundproof music rooms equipped for both digital composition and acoustic performance. In addition to this, there is a "Memory Archive" program, enabling residents to express their memories about Earth, migration and settlement experiences through visual murals, digital film, and written works. Public corridors feature rotating light-based art installations that change color and intensity over time to simulate seasonal shifts, preventing the environment from feeling static. Along with these, there are annual festivals of creative expressions, providing opportunities for residents to share and celebrate their inventions, sculptures, short films and performances. The artistic representations of the residents continue to evolve as a representation of the evolving identity of the community.

12.5 Community & Social Bonding

Each unit of community life has its own system of small, familiar social structures to promote feelings of trust and reduce feelings of being isolated. Each residential sector shares a "shared table" evening that takes place once a week, with people cooking a meal together using fresh produce from local hydroponics. A "Skill Exchange" program pairs residents based on interests — for example, a retired engineer may teach repair skills while learning a musical instrument from another resident. Regular intergenerational mentorship circles take place so elder members can share their stories about past environments and personal experiences to help younger generations connect with human history. Residents have many opportunities to contribute to cooperative projects such as garden areas, habitat decoration teams, and volunteer festival planning committees. These repeat, low-stress events are an opportunity for residents to develop their roles in creating their community's environment and developing a sense of belonging in their community.

Politics, Philosophy & Economics

13.1 The Philosophy Behind Politics and Economy in Space

▷ Problem Statement

A sealed space settlement cannot externalize waste, deplete distant resources, or defer consequences to future generations. Every political and economic decision directly affects the finite life-support system that everyone shares. The settlement therefore needs governance that keeps resource use within physical limits while preserving democratic freedom, and an economy whose prices reflect real thermodynamic cost rather than arbitrary monetary units.

13.2 Solutions

13.2.1 Economics

Currency Solution

In this settlement, the unit of currency will be the exergy, which is the maximum work that can be obtained from a certain resource, according to the Extended Exergy Accounting method that Sciubba developed [54]. This means that the price of each and every good and service will reflect the actual physical work that the settlement puts into the provision of these resources, rather than the arbitrary monetary system that Earth uses. This is important because the simple energy solution does not always produce the correct results, such as a process that uses a lot of energy to produce difficult-to-recycle trash, which may cost the settlement more than a process that uses a small amount of energy to produce easy-to-recycle trash.

In this settlement, the price of each and every resource, including water and labor, will reflect the cost of generation, heat rejection, recycling, and life support.

As the settlement changes, the exergy of the resources will change, and new calculations will be necessary to determine the new prices, which will be done by sensors, thermodynamic calculations, and audits to ensure that efficiency is always profitable and that waste is always expensive.

The Conservation Market

On Earth, the electrical grid already gives people incentives to conserve electricity during peak times. This is a mandate of FERC Order No. 745 [19]. In the settlement, this is extended to all scarce resources. Every person receives a standard allowance, and if they consume less of a scarce resource, they create a saleable unit of “negaliters,” “negawatts,” or “negacubics” that can be sold to those who have a larger requirement.

The three problems with the previous system are addressed. The first is that the standard allowance is determined through algorithms and audits to prevent people from working the system. The second is that the equity adjustment addresses those with special medical needs, those with demanding jobs, and those with children to care for. The third problem is the verification problem that killed the carbon trading system on Earth. In the settlement, the use of each and every scarce resource is precisely measured to ensure the survival of the system.

This gives the settlement a feedback loop in which the prices accurately reflect the thermodynamic cost of the resources, creating a distributed control system for survival.

13.2.2 Politics

Political Structure

The Executive Council

While having executive authority resting in a single individual is likely to result in an increase in the potential for authoritarian drift, placing such authority solely in the hands of those elected is also problematic due to the likelihood of the same individuals being technically incompetent during crises. An alternative approach to structuring the Executive Council is a three-member council per constituency consisting of an elected representative (providing democratic legitimacy), an appointed expert (providing technical competence) and a citizen selected by sortition (providing social representation and a balance between insiders and outsiders).

> **Democracy:** A democracy is where political decisions are made by the citizens, usually through the means of freely elected representatives.
>
> **Technocracy:** A technocracy is where political decisions are made primarily by technical experts based on knowledge and skills rather than popular elections.
>
> **Sortition:** Sortition is used to randomly choose representatives from the citizen population to ensure broad social representation.

The political system for many first world countries (US, Canada, UK, Germany, etc.) is bicameral as the legislature which makes decisions is divided into two houses, one proportionally representing the population and the other representing the state's interests. This amalgamation of the people and the state is a viable alternative to avoid "the tyranny of the majority" while also ensuring competent decisions.

The sortition member is intended to be the disruptive force within the Executive Council. Sortition members were used in Ireland's Citizens' Assemblies to assist in addressing polarizing constitutional issues. The inclusion of sortition members increased public trust in the assemblies and required the technical experts to explain their decisions clearly and openly. The sortition member within a settlement's Executive Council serves to represent the interests of the non-elite population and to discourage consensus building among insiders.

The Citizen Assembly

Sortition bodies have a long history dating back to classical Athens, where random selection was widely used for the creation of juries and oversight bodies. The belief was that using random selection would help to prevent the elite from capturing power. Gąsiorowska's research on sortition based systems has shown that sortition bodies are representative of the general population, less susceptible to lobbyists, and are more likely to ask questions about the underlying assumptions of institutions than either elected or appointed bodies.

The Citizen Assembly has no authority over the operation of life support systems, safety infrastructure, and emergency operations. Its authority extends to education policy, cultural development, budget priorities, long-term expansion strategy, and the establishment of new constitutional rules. This separation of authority prevents the historically observed problem where citizen bodies attempted to operate critical systems without possessing the necessary expertise and, conversely, avoids the institutional capture that often occurs with permanent bureaucracies.

The Expert Directorate

Life-support, medical services, radiation shielding, agriculture, and energy production are non-negotiable technical systems. If the ability to influence these domains by popularity or ideology occurs, the outcome could be disastrous. Historical examples include the politicization of famine responses, delays in intervening during pandemics, and the explosion of the Challenger space shuttle.

Temporal Democracy

Temporal Democracy addresses inequitable policy consequences by weighting votes based on how long a decision will affect the voter. Decisions are classified as low-horizon (short-term) or high-horizon (long-term), and votes are weighted by years remaining in the voter's expected residence duration. This consequence-based weighting enables intergenerational justice.

References

[1] T. Adelmann, *What is the hydroponic nutrient-film-technique (NFT)*, Hydroplanner, Accessed: 2026-02-13, 2023. [Online]. Available: https://hydroplanner.com/blog/hydroponic-nutrient-film-technique-nft.

[2] K. Alaimo, T. M. Reischl, and J. O. Allen, "Community gardening, neighborhood meetings, and social capital," *Journal of Community Psychology*, vol. 38, no. 4, pp. 497–514, 2010. doi: 10.1002/jcop.20378. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/jcop.20379.

[3] American Psychiatric Association, *What is autism spectrum disorder?* American Psychiatric Association. [Online]. Available: https://www.psychiatry.org/patients-families/autism/what-is-autism-spectrum-disorder.

[4] S. L. Booth, "Vitamin K: Food composition and dietary intakes," *Food & Nutrition Research*, vol. 56, p. 5505, 2012. doi: 10.3402/fnr.v56i0.5505.

[5] H. E. Bouis and A. Saltzman, "Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016," *Global Food Security*, vol. 12, pp. 49–58, 2017. doi: 10.1016/j.gfs.2017.01.009.

[6] B. Brasson, *Neutrino communication: A future deep-space signaling method*, Medium, 2019. [Online]. Available: https://medium.com/@brandontbrasson/neutrino-e65bcafc9a69.

[7] G. N. Bratman et al., "Nature experience reduces rumination and subgenual prefrontal cortex activation," *Proceedings of the National Academy of Sciences*, vol. 112, no. 28, pp. 8567–8572, 2015. doi: 10.1073/pnas.1510459112.

[8] G. N. Bratman et al., "Nature and mental health: An ecosystem service perspective," *Science Advances*, vol. 5, no. 7, eaax0903, 2019. doi: 10.1126/sciadv.aax0903.

[9] J. Campbell et al., "The IMPACT IMPERATIVE: Laser ablation for deflecting asteroids, meteoroids, and comets from impacting the earth," NASA, Tech. Rep., 2002. [Online]. Available: https://ntrs.nasa.gov/api/citations/20020092012/downloads/20020092012.pdf.

[10] Canadian Intellectual Property Office, *The story of rashmi prakash and Aruna Revolution*, Innovation, Science and Economic Development Canada. [Online]. Available: https://ised-isde.canada.ca/site/canadian-intellectual-property-office/en/corporate-information/canadian-ip-voices-podcast-case-studies-and-blog/story-rashmi-prakash-and-aruna-revolution.

[11] W. Cash, "Space-based solar power: A technical review," University of Colorado Boulder, Tech. Rep., 2019, Review of SBSP beam transmission and DC-to-RF conversion efficiencies.

[12] V. Cerf et al., "Delay-tolerant networking architecture (RFC 4838)," Internet Engineering Task Force, Tech. Rep., 2007. [Online]. Available: https://www.rfc-editor.org/rfc/rfc4838.html.

[13] C. Q. Choi, *Message encoded in neutrino beam transmitted through solid rock*, Scientific American, 2012. [Online]. Available: https://www.scientificamerican.com/blog/observations/message-encoded-in-neutrino-beam-transmitted-through-solid-rock/.

[14] S. Choi and R. Pappa, "Assessment study of small space debris removal by laser satellites," NASA, Tech. Rep., 2012. [Online]. Available: https://ntrs.nasa.gov/api/citations/20120009369/downloads/20120009369.pdf.

[15] *Configuration of modified 3D helmholtz coil system comprising two pairs of coils*, ResearchGate. [Online]. Available: https://www.researchgate.net/figure/a-Configuration-of-modified-3D-Helmholtz-coil-system-comprising-two-pairs-of-coils_fig1_354668261.

[16] F. A. Cucinotta and M. Durante, "Cancer risk from exposure to galactic cosmic rays: Implications for space exploration by human beings," *The Lancet Oncology*, vol. 7, no. 5, pp. 431–435, 2006. doi: 10.1016/S1470-2045(06)70695-7.

[17] C. A. Czeisler et al., "Stability, precision, and near-24-hour period of the human circadian pacemaker," *Science*, vol. 284, no. 5423, pp. 2177–2181, 1999. doi: 10.1126/science.284.5423.2177.

[18] K. Deb, *Multi-Objective Optimization Using Evolutionary Algorithms*. John Wiley & Sons, 2001, isbn: 978-0-471-87339-6.

[19] Federal Energy Regulatory Commission, *Order no. 745: Demand response compensation in organized wholesale energy markets*, FERC Docket No. RM10-17-000, Issued March 15, 2011, 2011.

[20] J. Fu et al., "Seeds priming with melatonin improves root hydraulic conductance and plant growth under salt stress," 2024. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/38732273/.

[21] S. D. Han and Y. W. Chung, "An improved PRoPHET routing protocol in delay tolerant network," *The Scientific World Journal*, vol. 2015, pp. 1–7, 2015. doi: 10.1155/2015/623090.

[22] Harvard T.H. Chan School of Public Health, *Vitamin B12 – the nutrition source*, Harvard University. [Online]. Available: https://nutritionsource.hsph.harvard.edu/vitamin-b12/.

[23] S. W. Hogewoning et al., "Blue light dose–responses of leaf photosynthesis, morphology, and chemical composition of *Cucumis sativus* grown under different combinations of red and blue light," *Journal of Experimental Botany*, vol. 61, no. 11, pp. 3107–3117, 2010. doi: 10.1093/jxb/erq132.

[24] P. Jaffe and J. McSpadden, "Space solar power: An overview of challenges and opportunities," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 20–34, 2021. doi: 10.1109/JMW.2020.3030196.

[25] G. I. Jenkins, "Signal transduction in responses to UV-B radiation," *Annual Review of Plant Biology*, vol. 60, pp. 407–431, 2009. doi: 10.1146/annurev.arplant.59.032607.092953.

[26] M. S. S. Khan et al., "Phytomelatonin: A key regulator of redox and phytohormones signaling against biotic/abiotic stresses," *Redox Biology*, vol. 64, p. 102 805, 2023. doi: 10.1016/j.redox.2023.102805. [Online]. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC10363481/.

[27] H. Kirst, C. Formighieri, and A. Melis, "Maximizing photosynthetic efficiency and culture productivity in cyanobacteria upon minimizing the phycobilisome light-harvesting antenna size," *Biochimica et Biophysica Acta (BBA) – Bioenergetics*, vol. 1837, no. 10, pp. 1653–1664, 2014. doi: 10.1016/j.bbabio.2014.07.009.

[28] I. M. Krieger and T. J. Dougherty, "A mechanism for non-Newtonian flow in suspensions of rigid spheres," *Transactions of the Society of Rheology*, vol. 3, no. 1, pp. 137–152, 1959. doi: 10.1122/1.548848.

[29] H. K. Kwon et al., "Effects of light spectra on microalgae growth and lipid accumulation," *Bioresource Technology*, 2019.

[30] C. Lalander et al., "Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*)," *Journal of Cleaner Production*, vol. 208, pp. 211–219, 2019. doi: 10.1016/j.jclepro.2018.10.017.

[31] Y. Li et al., "Mixed red and blue light promotes tomato seedlings growth by influencing leaf anatomy, photosynthesis, CO_2 assimilation and endogenous hormones," *Scientia Horticulturae*, vol. 290, p. 110 500, 2021, Study on UV-A effects on Chinese baby kale growth parameters. doi: 10.1016/j.scienta.2021.110500.

[32] Z. Li et al., "Cas9-guide RNA directed genome editing in soybean," *Plant Physiology*, vol. 169, no. 2, pp. 960–970, 2015. doi: 10.1104/pp.15.00783.

[33] X. Liu, H. Zhu, and M. Zhang, "High-efficiency rectenna design for wireless power transmission: A comprehensive review," *Electronics*, vol. 13, no. 3, p. 456, 2024. doi: 10.3390/electronics13030456.

[34] G. Lockwood, J. Gifford, and K. Lewis, "The world's largest four-day working week trial: Findings from the UK pilot," University of Cambridge, Tech. Rep., 2023. [Online]. Available: https://www.cam.ac.uk/stories/four-day-work-week.

[35] H. Masoumi et al., "Effects of foliar spraying with melatonin on physiological and biochemical traits of plants under salinity stress," 2024. [Online]. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC11476536/.

[36] G. D. Massa et al., "Plant productivity in response to LED lighting," *HortScience*, vol. 43, no. 7, pp. 1951–1956, 2008. doi: 10.21273/HORTSCI.43.7.1951.

[37] A. Melis, "Solar energy conversion efficiencies in photosynthesis: Minimizing the chlorophyll antennae to maximize efficiency," *Plant Science*, vol. 177, no. 4, pp. 272–280, 2009. doi: 10.1016/j.plantsci.2009.06.005.

[38] Moog Inc., *Slip rings for space applications: Technical specifications*, Moog Components Group, Accessed: 2026-02-13, 2023. [Online]. Available: https://www.moog.com/products/slip-rings.html.

[39] R. C. Morrow, "LED lighting in controlled environments," *HortScience*, vol. 43, no. 7, pp. 1947–1950, 2008. doi: 10.21273/HORTSCI.43.7.1947.

[40] S. Mueller, E. W. Llewellin, and H. M. Mader, "The rheology of suspensions of solid particles," *Proceedings of the Royal Society A*, vol. 466, no. 2116, pp. 1201–1228, 2010. doi: 10.1098/rspa.2009.0445.

[41] NASA, "Human integration design handbook (HIDH)," National Aeronautics and Space Administration, Tech. Rep. NASA/SP-2010-3407 Rev 1, 2014. [Online]. Available: https://www.nasa.gov.

[42] NASA, *Delay/disruption tolerant networking (DTN)*, National Aeronautics and Space Administration. [Online]. Available: https://www.nasa.gov/communicating-with-missions/delay-disruption-tolerant-networking/.

[43] NASA, *Fundamentals of human health*, National Aeronautics and Space Administration. [Online]. Available: https://www.nasa.gov/reference/fundamentals-of-human-health/.

[44] "NASA reference publication 1367," National Aeronautics and Space Administration, Tech. Rep., 1996. [Online]. Available: https://ntrs.nasa.gov/api/citations/19970009858/downloads/19970009858.pdf.

[45] National Institutes of Health, *Vitamin D – consumer fact sheet*, Office of Dietary Supplements, NIH. [Online]. Available: https://ods.od.nih.gov/factsheets/VitaminD-Consumer/.

[46] I. Rae, *Four-day work week: Global evidence and outcomes*, The Conversation, 2024. [Online]. Available: https://theconversation.com/four-day-work-week.

[47] R. P. Rastogi et al., "Molecular mechanisms of ultraviolet radiation-induced DNA damage and repair," *Journal of Nucleic Acids*, vol. 2010, p. 592 980, 2010. doi: 10.4061/2010/592980.

[48] "Recommendation for space data system standards: Space packet protocol recommended standard CCSDS 133.0-B-2," Consultative Committee for Space Data Systems, Tech. Rep., 2020. [Online]. Available: https://ccsds.org/Pubs/133x0b2e2.pdf.

[49] H. M. Resh, *Hydroponic Food Production*, 7th. CRC Press, 2013, isbn: 978-1439878675.

[50] D. Rodríguez-Leal et al., "Engineering quantitative trait variation for crop improvement by genome editing," *Cell*, vol. 171, no. 2, 470–480.e8, 2017. doi: 10.1016/j.cell.2017.08.030.

[51] *Rotation rate comfort boundaries for space habitat design*, ScienceDirect, Compilation of rotation comfort data from multiple studies. [Online]. Available: https://www.sciencedirect.com/topics/engineering/artificial-gravity.

[52] G. Samuolienė et al., "LED lighting and seasonality effects antioxidant properties of baby leaf lettuce," *Food Chemistry*, vol. 134, no. 3, pp. 1494–1499, 2012. doi: 10.1016/j.foodchem.2012.03.072.

[53] W. Schimmerling and F. A. Cucinotta, *Radiation shielding studies*, As cited in Tripathi (2011), 2006.

[54] E. Sciubba, "Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems," *Exergy, An International Journal*, vol. 1, no. 2, pp. 68–84, 2001. doi: 10.1016/S1164-0235(01)00012-7.

[55] M. C. Shannon and C. M. Grieve, "Tolerance of vegetable crops to salinity," *Scientia Horticulturae*, vol. 78, no. 1–4, pp. 5–38, 1999. doi: 10.1016/S0304-4238(98)00189-7.

[56] N. Shinohara, "Beam control technologies with a high-efficiency phased array for microwave power transmission in Japan," *Proceedings of the IEEE*, vol. 101, no. 6, pp. 1448–1463, 2013, Rectenna RF-to-DC conversion efficiency analysis. doi: 10.1109/JPROC.2013.2253062.

[57] J. Smith and D. A. Vakoch, "Neutrino communication and messaging for extreme environments," *Progress in Aerospace Sciences*, vol. 135, p. 100 868, 2022. [Online]. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC9649493/.

[58] S. M. Smith et al., "The nutritional status of astronauts is altered after long-term space flight aboard the International Space Station," *The Journal of Nutrition*, vol. 135, no. 3, pp. 437–443, 2005. doi: 10.1093/jn/135.3.437.

[59] S. M. Smith et al., "Benefits for bone from resistance exercise and nutrition in long-duration spaceflight: Evidence from biochemistry and densitometry," *Journal of Bone and Mineral Research*, vol. 27, no. 9, pp. 1896–1906, 2012. doi: 10.1002/jbmr.1647.

[60] J. Song et al., "Evaluation of current coil positioning for an enhanced hybrid active space radiation BioShielding concept," *Astrology & Outreach*, vol. 1, p. 103, 2013. doi: 10.4172/2332-2519.1000103.

[61] C. Sonneveld and W. Voogt, *Plant Nutrition of Greenhouse Crops*. Springer, 2009. doi: 10.1007/978-90-481-2532-6.

[62] D. D. Stancil et al., "Demonstration of communication using neutrinos," *Modern Physics Letters A*, vol. 27, no. 12, p. 1 250 077, 2012. doi: 10.1142/S0217732312500770.

[63] J. Stuster, "Behavioral issues associated with long-duration space expeditions: Review and analysis of astronaut journals," *Aviation, Space, and Environmental Medicine*, vol. 81, no. 6, pp. 593–597, 2010.

[64] R. Tripathi, "Meeting the grand challenge of protecting astronaut's health: Electrostatic active space radiation shielding for deep space missions," NASA, Tech. Rep., 2011. [Online]. Available: https://www.nasa.gov/wp-content/uploads/2017/07/niac_2011_phasei_tripathi_electrostaticactivespace_tagged.pdf.

[65] UK Research and Innovation, "The results are in: The UK's four-day week pilot," Autonomy Research, Tech. Rep., 2024. [Online]. Available: https://www.4dayweek.co.uk/research.

[66] K. E. Wendt et al., "CRISPR/Cas9 mediated targeted mutagenesis of the fast growing cyanobacterium *Synechococcus elongatus* UTEX 2973," *Microbial Cell Factories*, vol. 15, p. 115, 2016. doi: 10.1186/s12934-016-0517-6.

[67] World Economic Forum, *4-day work week: Results from the world's largest trial*, World Economic Forum, 2023. [Online]. Available: https://www.weforum.org/stories/2023/01/4-day-work-week-work-life-balance-productivity/.

[68] World Health Organization, *Vitamin and Mineral Requirements in Human Nutrition*, 2nd. World Health Organization, 2004. [Online]. Available: https://www.who.int.

[69] World Health Organization, "Urban green spaces and health: A review of evidence," WHO Regional Office for Europe, Tech. Rep., 2016. [Online]. Available: https://www.euro.who.int/en/publications/abstracts/urban-green-spaces-and-health-2016.

[70] World Health Organization, *Autism spectrum disorders: Fact sheet*, World Health Organization, 2023. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/autism-spectrum-disorders.

[71] World Nuclear Association, *Nuclear fusion power*, World Nuclear Association, Accessed: 2026-02-13. [Online]. Available: https://world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.

[72] L. R. Young et al., "Spatial orientation in weightlessness and readaptation to earth's gravity," *Science*, vol. 225, no. 4658, pp. 205–208, 1984, Extended rotation adaptation studies by Young et al. reported through 2001. doi: 10.1126/science.6610215.

[73] J. Yu et al., "*Synechococcus elongatus* UTEX 2973, a fast growing cyanobacterial chassis for biosynthesis using light and CO_2," *Scientific Reports*, vol. 5, p. 8132, 2015. doi: 10.1038/srep08132.

[74] W. Zhang et al., "Robust end-to-end FSO transmission with joint coding modulation and BiLSTM-based channel modeling under atmospheric turbulence," *ArXiv.org*, 2025. [Online]. Available: https://arxiv.org/abs/2509.03835.

[75] Y. Zhang et al., "The emerging and uncultivated potential of CRISPR technology in plant science," *Nature Plants*, vol. 5, pp. 778–794, 2019. doi: 10.1038/s41477-019-0461-5.