PROJECT GAIA

Created by
Barış İnandıoğlu
Ahmed Metin Karaköse
Ayşesu Özdoğan
Arda Deniz Altınok
Emre Ekici
Ekin Dirican
Alp Dinçkoç

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Original artwork by Barış İnandıoğlu

Dedicated to those who envision humanity's future in space…

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Story

It was the year 2025 when a breakthrough in tissue engineering came. It all started as an aspiration of a young scientist by the name of Gaia. After years of staying up for restless nights in cold laboratories, one of her experiments could finally yield a result. That night, her eyes filled with a child's wonder as she curiously strolled toward the biosafety cabinet. After witnessing that the power switch had been turned off, those very eyes filled with panic and frustration. Hoping that the experiment would be fine if she could just turn the switch back on, Gaia rushed towards the fuse box. The switch clicked. The machine hummed. And the lights turned back on. She swiftly flattened her forehead to the glass, in a desperate attempt to see what was inside. The petri dish was covered in a complex web of red, tubular, palpitating structures working in harmony. These were the first capillary tissues to be synthesized artificially by vasculogenesis.

Organs are fundamentally tissue layers with different sizes, functions, and cell types. Yet, the capillary tissues that feed and connect those layers are often overlooked. All healthy organs develop capillaries in the embryonic stages of development. These capillaries then grow and spread by vasculogenesis. Artificial organs without capillaries can only survive for a couple of hours before dying due to a lack of oxygen and a buildup of waste. The process of vasculogenesis remains to be a mystery, thus hindering all attempts to synthesize viable organs in vitro. A discovery that shines light on the process of vasculogenesis may allow scientists to 3D-print artificial organs with ease. Hence, revolutionizing healthcare and space travel.

Gaia's discovery encompassed the international scientific community within days. Scientists, engineers, and ethics professors across the globe came to visit and accompany Gaia in a new age of discoveries. Hopefully, one that would eradicate disease, suffering, and death. Another scientist soon followed in the footsteps of Gaia, by managing to promote capillary growth in a 3D-printed human heart. An avalanche of breakthroughs followed. Within a few years, artificial organs were widely available on the market, and the average life expectancy doubled. However, no one was prepared for the disasters that followed.

Humanity is already facing major challenges like the climate crisis, world hunger, and increasingly frequent droughts. As Earth's natural resources become increasingly scarce and the human population continues to rise due to increasing life expectancies, these problems will only be exacerbated.

As the population boomed, Earth's resources *and land soon became insufficient. Shortages were followed by famines, and even seemingly minor conflicts led to wars. The disasters took a considerable toll, yet the population continued to grow uncontrollably. Nevertheless, humanity still had one hope: leaving Earth to settle the universe. In an unprecedented century of unity, people and governments worked together to prioritize space research. These efforts quickly paid off, as new telescopes, satellites, and space stations were installed around Earth's orbit. Men and women set foot on Earth's moon, Mars, and numerous asteroids for temporary research missions. These pioneers set the stage and gathered the data for the next major leap: colonization.*

Human expansion into space can be simplified into three stages: exploration, colonization and terraforming. These stages can take place at different times and varying locations across the Solar System; hence, different projects can take place in several stages at once. In our case, Project Gaia focuses on colonization.

To take the next major leap, governments across the World agreed to take part in Project Gaia, consisting of three main phases. The first phase aimed to establish a mining camp on Mars, extracting the planet's natural resources for later use. The second phase was to build a space settlement (Polaris) located at a Lagrange point near the Main Asteroid Belt. And the final phase was to commence asteroid mining activities and send resources back to Earth. In a matter of decades, phases one and two were completed. Project Gaia began searching for volunteers to live in Polaris, and Gaia was the first settler to board a space shuttle with her two kids. For the past century, I have been living in Polaris with my family. My mother, father, little sister and my dear grandmother, Gaia.

Figure 1 Project GAIA cover pages, each corresponding to a primary aspect of the project

Meet The Team

Alp Dinçkoç

- Administration
- Communications
- Zero-G Virtual Reality
- Dual Structure of the Tori

Ekin Dirican

- Water Management
- Aquaponics
- Waste Management
- Bioprinting

Barış İnandıoğlu

- 3D Modelling & CAD
- Arduino/C++
- Circuitry Schematics
- Document Layout

Ayşesu Özdoğan

- Hand-Drawn Graphics
- Internal Structure and Design
- Artificial Gravity

Arda Deniz Altınok

- Editing & Proofreading
- Bacteria Farming and CRISPR
- Astronomical Research
- External Structure

Ahmed Metin Karaköse

- Magnetic Confinement Fusion Reactors
- Mars Mining Camp
- Citations

Emre Ekici

- Shielding
- Resource Acquisition
- Main Asteroid Belt

Executive Summary

This paper describes all aspects of Project Gaia in detail, beginning with its origin story of a miraculous escape from the famines, nosediving prosperity levels, and battles over trivial conflicts on Earth. Project Gaia is named after the mythological goddess Gaia, who is the mother of all life in Greek and Roman Mythology. Project Gaia aspires to be the hub facilitating humanity's expansion to the Solar System, following in the footsteps of Gerard K. O'Neill. The realistic perspective toward the near future and scientific accuracy of the background story are some of the most alluring aspects of Project Gaia.

Project Gaia begins with the colonization of Earth's moon and is followed by the establishment of a supply base on Mars. The main settlement is located in the Main Asteroid Belt, due to the accessibility of resources and the belt's relative proximity to Mars. Meanwhile, asteroid and planetary mining technologies are utilized to supply the settlement with a sustainable source of raw materials and fuel.

Polaris is the name of the main settlement in Project Gaia and shelters more than five thousand individuals. The settlement is named after the North Star, in hopes that it will influence human expansion into space just like the North Star has provided a sense of direction to navigators on Earth for centuries. Moreover, Polaris has an astonishing design consisting of two tori connected by an end-capped cylinder. The interior of the settlement is vividly depicted with the help of numerous renderings of key sections. And, the exterior design of Polaris is displayed through realistic 3D models.

Furthermore, shielding also plays a vital role in the design of Polaris. Due to a lack of a strong magnetic field in the Main Asteroid Belt, ionizing radiation is of immediate danger to the settlers. Other factors like rapid temperature changes and meteor impacts also pose a credible threat to the structural integrity of the settlement. Thus, the multitude of measures taken and our original choice & positioning of materials to shield Polaris from outside threats are detailed with tables and evaluation matrices in this section.

Apart from its creative structure and shielding, Polaris successfully achieves the most vital step of building a settlement: creating a self-sustaining system. Bacteria, whose microscopic size contradicts their tremendous potential, are utilized in an innovative & original design of production pathways for bacteria farms. These production facilities have a massive role in meeting the energy, food, and medicinal requirements of Polaris's inhabitants, and a CRISPR experiment is also performed to mimic these "bacteria farms". In addition, Arduino/C++ code, circuitry schematics and an Arduino circuit are also included to add detail to our aquaponics system.

Last, the population dynamics of Polaris have been carefully mapped out to ensure full cooperation in Polaris. The meticulous planning to create a positive synergy between two separate sections of the settlement and the political status & system of Polaris are featured in this section. Perhaps most importantly, major tourist attractions and commercial opportunities in Polaris like the zero gravity virtual reality rooms and the Solar Festival are detailed in this section.

Overall, Polaris is designed to be a new and permanent home for pioneers facilitating humanity's expansion into space. Our team has worked very hard in the past year to ensure that Project Gaia covers all fundamental aspects of human survival and space colonization. All of the visuals, tables and graphs in this document were designed by our team. We also integrated various original features to Polaris, which were all inspired from our own areas of interest. Project Gaia is dedicated to pioneers like Gerard K. O'Neill and those who envision humanity's future in space.

Location

Polaris will be orbiting the Sun from the resource-rich Main Asteroid Belt. While such a location has major benefits like the potential for asteroid mining and close proximity to Mars, it also has significant drawbacks such as less efficiency in harvesting solar energy, extreme physical conditions and inability to receive any immediate aid from Earth. Therefore, Project Gaia is designed to make the most of the resources available near the Main Asteroid Belt, with the Mars Mining Camp and asteroid mining.

Mars Mining Camp

Mars has a variety of ores that are profitable to sell and practical to use in a space colony. As part of Project Gaia, the Mars Mining Camp is tasked with extracting and transporting these materials to Polaris for either further transportation to Earth or use in the settlement. Moreover, the camp itself is located underground to protect workers from ionizing radiation, sandstorms, martian dust and other perils on Mars's surface.

Table 1 List of Raw Materials Available in the Mars Mining Camp

Name of Ore	Symbol	Primary Uses
Niobium	Nb	Production of superconductors
Europium	Eu	Technological appliances (television monitors, energy efficient light bulbs…)
Deuterium	2H	Used as fuel in fusion reactor
Aluminum	Al	Structure of the settlement
Silicon	Si	Used for 3D-printed plastics
Oxygen	O	Climate control and fuel ignitor
Titanium	Ti	Space shuttle engines

Magnesium	Mg	Muscle and nerve function, ATP production
Calcium	Ca	Nerve function and bone growth
Potassium	K	Fertilizer, nerve function

The resources listed above, and many other raw materials are extracted from Mars and sent to Polaris via shuttles for processing, use and sale.

The Main Asteroid Belt

The Main Asteroid Belt is located between Jupiter and Mars and has a torus-like circular shape. The belt contains numerous irregular solid shapes which vary in size and composition. Even though the estimated total mass of the belt is very high due to the large number of asteroids, the belt itself is mostly empty space, as, contrary to popular belief, asteroids are separated from each other over long distances.

Asteroids are equipped with a rich diversity of minerals and metals that are vital for the perpetuity of the space settlement. There are three distinct categories of asteroids: C - type (carbonaceous) asteroids, S - type (silicate) asteroids, M - type (metallic) asteroids.

- C - type asteroids are carbon rich and compose 75% of the visible asteroids.
- S - type asteroids are silicate rich and are mostly located toward the internal region of the belt. According to the spectra of their surfaces, these asteroids include some metal and silicates; however, they don't have materials composed of carbon. These asteroids compose 17% of the visible asteroids.
- M - type asteroids are metal rich and compose 10% of the asteroid population. According to their spectra, they have an iron - nickel like structure.

Structure

External Structure of Polaris

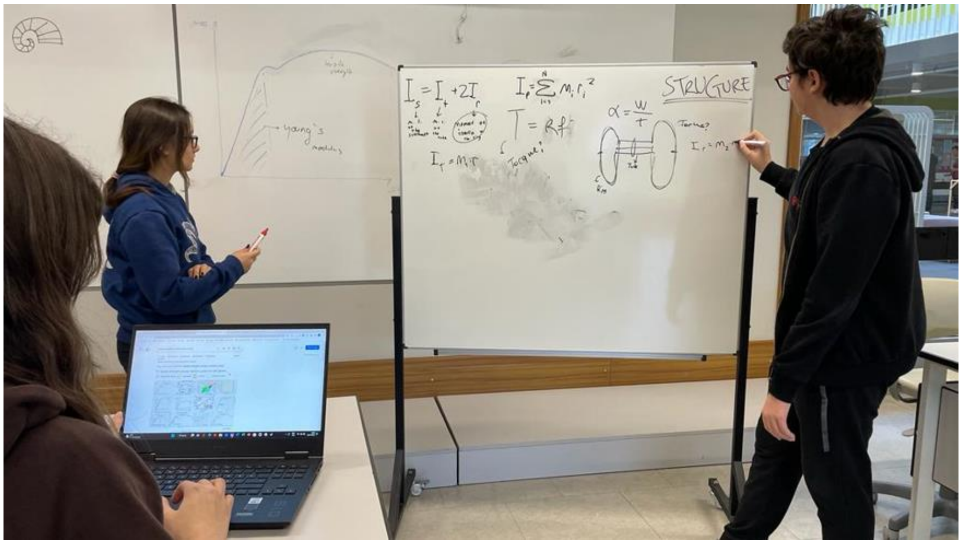

Figure 2 Team Members Discussing Alternative Structures for Polaris

When deciding upon the shape of the settlement, our choices are limited by the criteria for generating an artificial gravity effect. These choices included the cylinder, torus, dumbbell, and sphere. Yet, out of these options, the torus was chosen due to its reliability as a stable form for a rotating body, lack of edges and symmetry around at least two axes. Additionally, utilizing a torus also expanded the habitable area, while keeping the structural mass to a minimum.

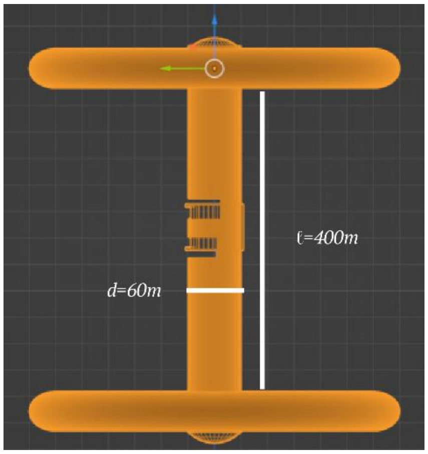

Figure 3 Side view of Polaris

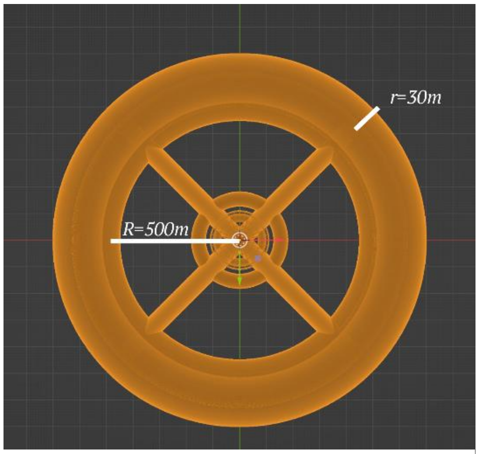

Figure 4 Top View of Polaris

Polaris is composed of two rotating tori with major radii of 500 meters and minor radii of 30 meters. Each of these tori are connected to a 400-meter-long tubular structure with a diameter of 60 meters, via 4 50-meter-long cylinders with diameters of 10 meters. These cylinders are equipped with elevators that connect the tori to the main tube. Unlike the tori, the end-capped main tube does not rotate and, hence, is exempt from an "artificial gravity" effect. Therefore, the tube accommodates various sections that tolerate if not require a microgravity environment.

At the center of this tube, a port where material imports & exports and tourist arrivals & departures will take place is located. The length of the tubular structure enables space shuttles to dock safely, as the port is located a considerable distance away from each torus. Moreover, the tube will also house the magnetic confinement fusion reactors, utility structures (like water storage tanks), microgravity manufacturing facilities, and two high-speed trains connecting the two tori.

Furthermore, the tori compose the habitable zone of Polaris. Hence, the tori are designed to be self-sustaining, with aquaponic systems, housing, commercial areas, and more. The volume of a torus can be calculated from the equation:

$$V_{torus} = 2\pi^2 R r^2$$

$$R: Major\ radius$$

$$r: Minor\ radius$$

Therefore, the volume of a torus in Polaris is:

$$V_{torus} = 2\pi^2 \times 500 \times 30^2 \approx 8{,}900{,}000\ m^3$$

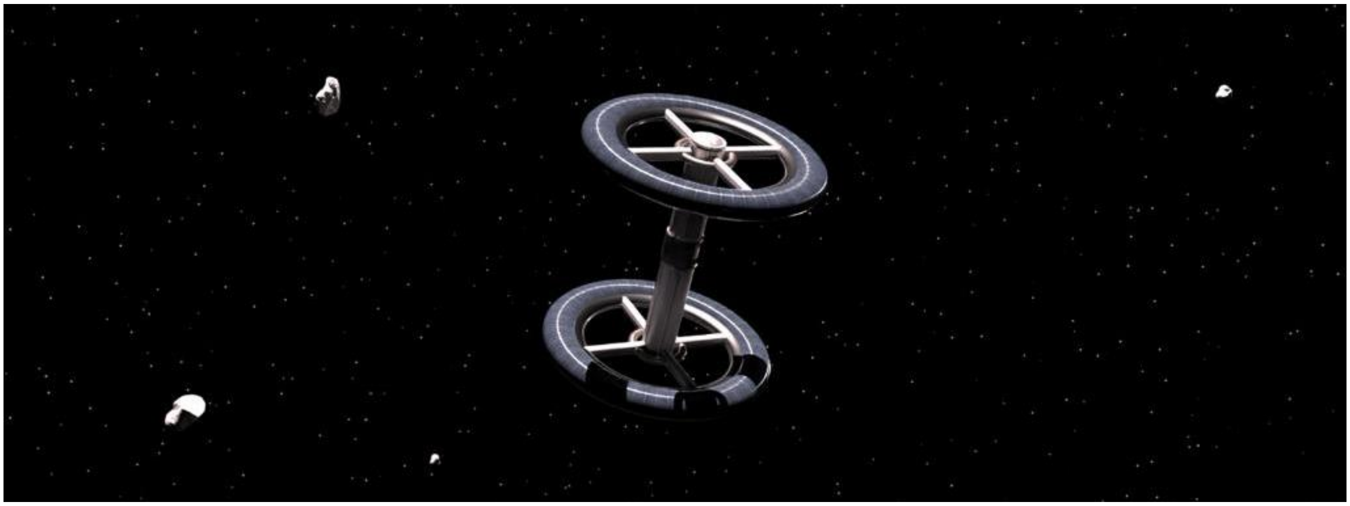

Figure 5 3D Render of Polaris (wide angle) 3D model by Barış İNANDIOĞLU

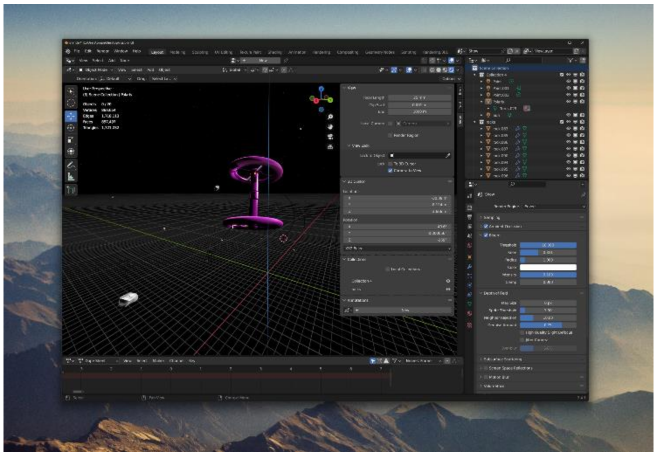

Figure 6 Barış İNANDIOĞLU's In-Progress Blender Screenshot of the 3D Model (Scene)

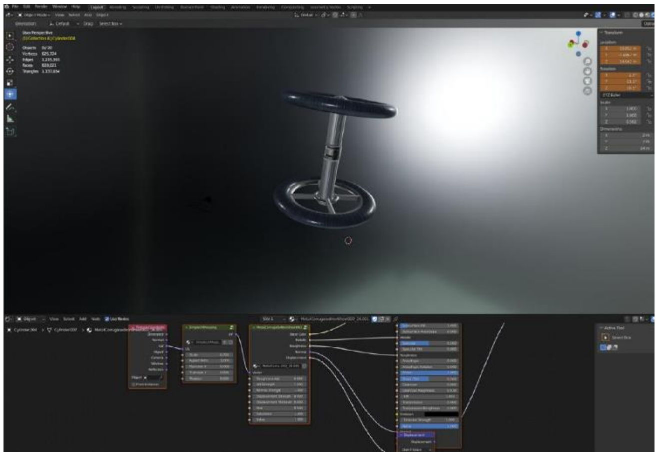

Figure 7 In-Progress Blender Screenshot of the 3D Model (Nodes)

Overall, Polaris was designed to have the least number of edges possible to minimize heat escape, construction costs and micro-meteoroid impacts. Hence, the external structure is fundamentally composed of an end-capped cylinder and 2 tori.

Artificial Gravity

Polaris will be a permanent home for thousands of pioneers, and the safety of these inhabitants is the upmost concern. The human body requires a constant gravitational force of Earth-like magnitude to prevent muscle loss and regulate nasal blockage. An environment of microgravity could also negatively affect the development of children's skeletal structure.

In consideration of such problems, we decided to create an artificial gravity effect in the tori of Polaris for the safety and comfort of our inhabitants. Unlike the fundamental force of gravity that originates from mass, our artificial gravity stems out from circular motion and, hence, is independent from the mass of the settlement. After removing the need for planet-size masses, creating an artificial gravity effect becomes much more implementable.

One way to create an artificial gravity effect is to create constant acceleration. Although constant acceleration eliminates certain undesirable effects caused by rotation, to constantly accelerate an object is not only dangerous but also extremely costly.

Instead, Polaris accelerates the tori to a constant tangential velocity with sixteen hydrogen thrusters (eight on each torus). These thrusters are then turned off, which eliminates acceleration according to Newton's First Law. And, due to the lack of friction in space, the tori will be able to rotate at constant velocity with very minor disruptions.

To calculate the artificial gravity effect in Polaris, we started with the following formula:

$$\ddot{\mathrm{R}} = -2r + 2\omega\dot{\mathrm{r}} + \ddot{\mathrm{r}}$$

$\ddot{\mathrm{R}}$: $Total\ Acceleration$;

$-2r$: $Centripetal\ Acceleration$;

$2\omega\dot{\mathrm{r}}$: $Coriolis\ Acceleration$;

$\dot{\mathrm{r}}$: $Velocity$;

$\ddot{\mathrm{r}}$: $Linear\ Acceleration$;

ω: $rotation\ vector$;

Considering that Polaris will be in a stable orbit, it will not experience linear acceleration. Therefore, the formula can be simplified to:

$$\ddot{\mathrm{R}} = -2r + 2\omega\dot{\mathrm{r}}$$

If a child were to throw a ball up in one of the tori, the ball would follow a different trajectory compared to a counterpart on Earth. Therefore, when the $\dot{\mathrm{r}}$ in the equation cannot be equal to zero and the Coriolis effect will occur. Coriolis acceleration ($2\omega\dot{\mathrm{r}}$) is a natural outcome observed in certain moving bodies, like Polaris's tori. The two components of Coriolis acceleration are the vertical Coriolis and the tipping effect.

If moved along the x axis, a hypothetical person would be traveling along the circumference of one circle within the torus. If that person moves in the direction of rotation, her rotation rate would increase and the downward force she experiences would increase. Whereas, if that person were to move in the opposite direction of the direction of rotation, the force she experiences would decrease. According to certain studies (Nesti et al. 2014), humans are not affected by 5% or lesser change in vertical acceleration. Other studies (Cohen et al. 2000) demonstrate that the upper limit of human tolerance is approximately %25.

If moved along the y axis, the hypothetical person's distance to the center of rotation would change. This change creates an undesirable tipping effect when traveling across different levels in the settlement. In order to minimize the impact of the tipping effect on inhabitants changing levels, Polaris utilizes special elevators that are designed in accordance with the Coriolis acceleration. These elevators are built so that the plane of the ladder or elevator is perpendicular to that of Coriolis acceleration. The elevators are also programmed not move faster than the speed limit for this motion.

Even with the vertical Coriolis and tipping effect addressed, the issue of canal sickness remains. Canal sickness is the result of Coriolis acceleration interfering in the motion of the vestibular fluid inside the inner ear. This interference causes various symptoms like nausea and vomiting. To minimize canal sickness, angular velocity of the tori must be limited. Various studies such as (Hill et al., 1962), (Gilruth et al., 1969), (Gordon et al., 1969), (Stone et al., 1973) and (Cramer et al., 1985) have shown that while 6 rotations per minute was tolerable for short periods of time, 2 rpm was the upper limit of angular velocity to ensure comfort.

With the limit in angular velocity in consideration, we calculated the possible velocity values and radii that created a constant centripetal acceleration of 1 g:

$$V = Rx\omega$$

$$a_c = v^2 R$$

$$V: Tangential\ \ Velocity\ (m/s)$$

$$R: Bigger\ Radius\ (m)$$

$$\omega: Angular\ Velocity\ (rpm)$$

$$a_c: Centripetal\ Acceleration\ (m/s^2)$$

For example, for a major radius of 600. meters:

Angular Velocity is $\sqrt{\frac{a_c}{R}} = \omega \ \rightarrow \sqrt{\frac{9.81}{600}} = \omega, \omega \approx 0.127\ rps \approx 1.22\ rpm$

Tangential Velocity is $V = \sqrt{r \times a_c} = \sqrt{600 \times 9.81} \approx 76.72\ m/s$

Table 2 Comparison of the Effects of Different Radi on Angular and Tangential Velocities

Radius (m)	750	700	650	600	550	500	450	400
Angular Velocity (rpm)	1.09	1.13	1.17	1.22	1.28	1.33	1.41	1.49

Tangential Velocity (m/s)	85.76	82.85	79.84	76.72	73.44	70.02	66.43	62.63

Our criteria for an artificial gravity effect consist of:

- A stable environment with a centripetal acceleration of 1 g
- The graph shown above demonstrates the parameters for health and comfort.
- An environment large enough to sustain 5120 individuals.
- Enough space for socializing and housing
- Having as low tangential velocity as possible to make it safer for the ships to enter the docking station
- Having an angular velocity lower than 2 rpm to avoid the Coriolis effect.
- Providing the tubular structure with as low angular velocity as possible in order to support microgravity manufacturing.
- Minimizing the radius and thus the cost of manufacturing the settlement.

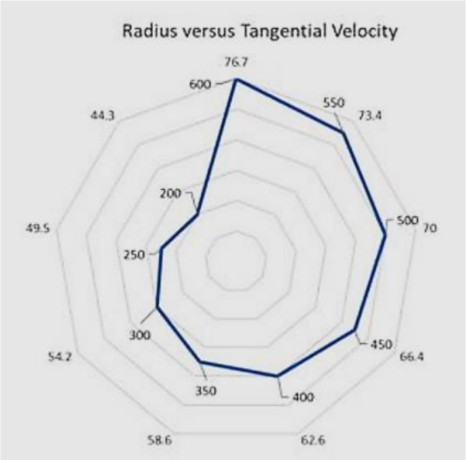

Figure 9 Radius versus Angular Velocity

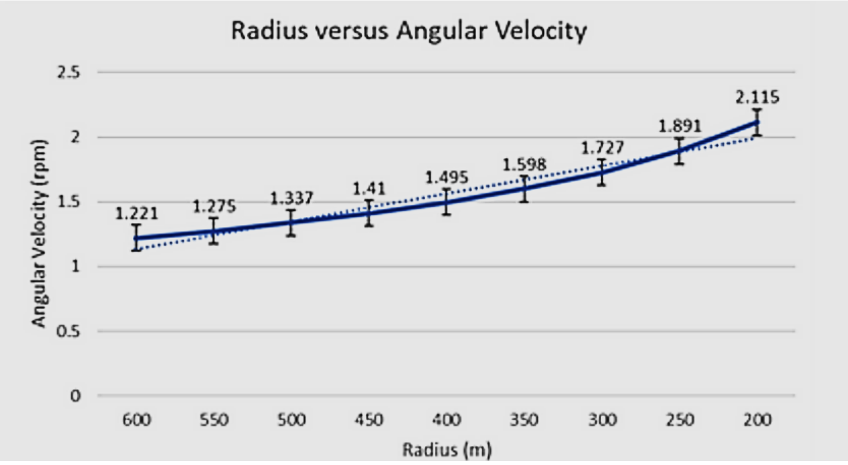

Figure 8 Radius versus Tangential Velocity

Graph "Radius versus Angular Velocity" illustrates that, on average, an increase in radius by 50 meters is followed by a decrease of 0.1 rpm in angular velocity. Meanwhile, graph "Radius versus Tangential Velocity" conveys that, on average, an increase in the bigger radius of tori by 50 meters leads to an increase of 3.6 m/s in tangential velocity. In order to increase the ease of space shuttle docking, both velocities must be as low as possible. Whereas the maximum limit for angular velocity is 2.00 rpm.

$$\omega = \sqrt{\frac{a_c}{R}} \rightarrow 0.0\overline{3}\ rps = \sqrt{\frac{9.81}{R}}, R \approx 223\ m$$

Hence, the minimum value for the bigger radius of the tori is 223 meters. Larger radiuses are not problematic but still deviate from the optimum value due to the increase in tangential velocity. Yet, an increase in radius is followed by an increase in volume, and the optimal volume to sustain 5120 individuals is around 17,000,000 meters cubed. Therefore, the following conditions will be applicable:

Table 3 Physical Properties of Polaris Concerning Artificial Gravity

Outer Radius of the Tori	500 m
Angular Velocity	1.34 rpm
Tangential Velocity	70.02 m/s
Centripetal Acceleration	9.81 m/s (1 g)

Interior and Housing

Interior Design

The interior design of Polaris mainly consists of equally divided "districts" that surround the main body of the settlement. Each district is self-sufficient, meaning every need of people that live in any given district will have access to vital resources. There are a total of 8 districts located in each torus (16 in the entirety of the settlement).[1]

Figure 10 3D Model of a Type B kids' room

Figure 11 3D Model of a Type B Living room

Figure 12 3D Model of a Type B Bedroom

Each district has 126 houses that consist of three "types":

- Type A: 448 units total (28/district), 1 bedroom (with a double bed), $20m^2$
- Type B: 1024 units total (64/district), 2 bedrooms (one double bed, one single bed), $30m^2$
- Type C: 544 units total (34/district), 3 bedrooms, (one double bed, two single beds) $40m^2$

Polaris has the capacity to house 6184 people. However, the population is started from 5120 due to foreseen social issues (divorce, single parenting, etc.).

Each type of house features important properties from such as:

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[1] All 3D models used in these figures are free models provided by HomeByMe, an online 3D space planning service developed by Dassault Systèmes SE. (https://home.by.me)

- Heating: Temperatures in space can be unpredictable, proper heating is essential. Heating is automatically regulated unless manually accessed.
- Power outlets: A limited amount of power for each family. To prevent over-usage, there is a limit for each household's usage.
- Water Access: A limited amount of water is allowed for each family. Similarly, to electricity, it is limited to a specific amount.
- Computer Terminals: Basic computers used to communicate around the facility, store knowledge and communicate with Earth.

Yet, in consideration of the conditions in space, some residential aspects in Polaris differ from that on Earth. One change is that the houses in Polaris are not owned by their inhabitants. Each family is assigned a house by the government, according to the size of the family (which can only be 2, 3, or 4 individuals to manage the population efficiently). Every individual is assigned a new house when they start a family of their own or get married. Hence, families with no kids, one kid, and two kids will be assigned to house type A, B, and C respectively.

Other unconventional aspects of housing in Polaris include:

- The lack of windows: temperature insulation and radiation shielding do not allow for windows. Instead, LED screens are added to every living room in Polaris to serve as a TV and a replacement for windows (with background images being taken from a live feed of cameras outside the tori).
- All furniture is fixed to a surface: every piece of large furniture in Polaris is fixed to at least one surface. This measure is taken for the safety of inhabitants in case of asteroid collisions (which might have an effect similar to that of an earthquake) and artificial gravity effect malfunctions.

New World-360 Transportation System

New World-360 (NW-360) is a collection of multipurpose electricity-powered trains in Polaris. These trains travel at 60 meters per second and in the opposite direction of the tangential velocity of the settlement.

The NW-360 trains are located at the center of both tori, with enough capacity to carry 500 individuals each. For a population of approximately 2600 individuals in each torus, these trains essentially serve as a metro station. And, the shopping centers lining NW-360 stations are the prime social hubs in Polaris.

A NW-360 train completes a full cycle around the torus every 30 minutes, with 4 stops at each quarter of a torus.

The time it takes for one person to walk through the circumference of the torus (t_{person}) is:

$$d_{circumference} = 2\pi \times R \times r \approx 38000$$

where R is the major and r is the minor radius of torus

$$t_{person} = \frac{d_{circumference}}{speed_{avg}} = 38{,}000\ \div 1.42 \approx 256{,}000\ s\ \approx 74\ hours$$

The time it takes for one person to take NW-360 through the circumference of the torus (t_{NW}) is:

$$t_{NW} = 38{,}000 \div 60 \approx 633\ s \approx 11\ minutes$$

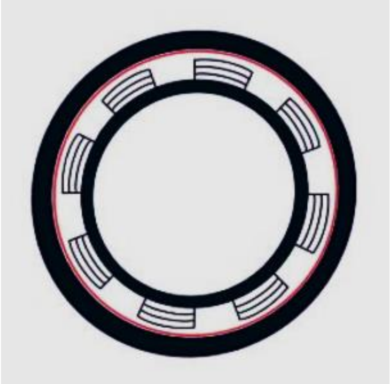

Figure 13 Top view of NW-360

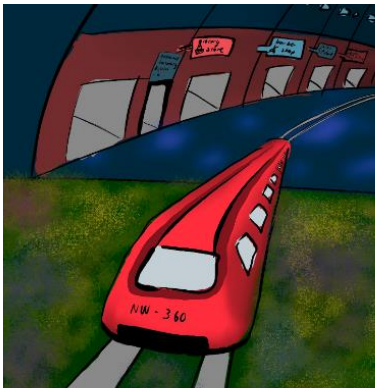

Figure 14 Concept image of NW-360

Thus, the NW-360 trains allow for fast travel inside tori. NW-360 stations are also major tourist attractions for Polaris, as they offer a unique trip around the settlement.

Magnetic Confinement Fusion Reactors

On December 13, 2022, the U.S. Department of Energy announced that ignition for an inertial confinement fusion reaction had been achieved. This major breakthrough demonstrates that fusion as an energy source is becoming more and more viable as technology advances.

Unlike fission wherein the nucleus of an atom is broken into its nucleons, fusion involves fusing two nuclei into one. Overall, fusion-based reactors are theoretically safer, cleaner and more efficient than fission reactors, due to:

- The more stable nature of fusion reactions, with a lack of an exponentially increasing number of free neutrons
- Less radioactivity and amount of waste
- Ease of accessibility of deuterium and tritium compared to enriched uranium.

The process of fusion involves colliding two atomic nuclei at temperatures exceeding 100 million Kelvin. At these conditions, electrons are stripped from the nucleus and enter a plasma state. And, the nuclei combine, producing a helium nucleus of two protons, two stable neutrons, and a high-energy neutron.

$$H_1^2 + H_1^3 \rightarrow He_2^4 + n_0^1 + 17.59\ Mev$$

The energy released during fusion stems from the mass difference between the nuclei and the resulting product. Moreover, unlike fission reactors that require rare elements, fusion utilizes readily available isotopes of hydrogen, Tritium (T) and Deuterium (D), which will be sourced from water extracted from asteroids. The two primary fusion reactors are magnetic confinement fusion reactors and inertial confinement fusion reactors.

In inertial confinement fusion, a strong laser is focused on a D-T fuel pellet, causing the outer layer of the material to heat up and explode. The resulting inward compression then heats the interior layers of the material, rapidly increasing its density and fueling a fusion reaction. The energy utilized to maintain the strong laser significantly decreases the efficiency of the reaction and such reactors are vulnerable to heat escape.

Whereas magnetic confinement fusion utilizes a magnetic field to contain plasma, with the magnetic field directing ions and electrons away from the inner walls of the reactor. Hence, particle and heat (energy) loss due to contact with the reactor walls is minimized and the reaction is more efficient.

Polaris's nuclear fusion reactor will utilize a magnetic confinement fusion technique known as a Stellarator. This type of reactor is characterized by its unique torus-like shape and the use of external non-axisymmetric coils which generate the twisting magnetic fields that help to direct the plasma particles. Unlike other fusion reactors like the Tokamak, the Stellarator does not require toroidal plasma currents, as it relies on permanent magnets to provide the majority of its magnetic field.

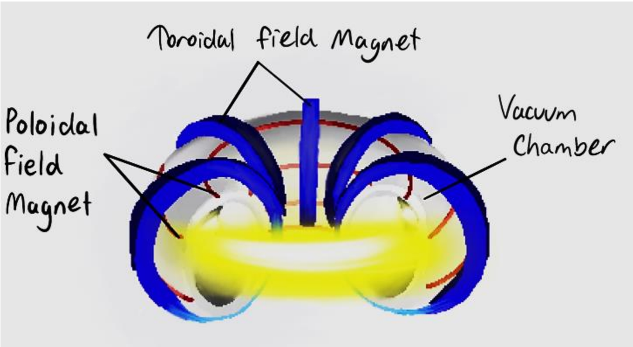

Figure 16 Illustration of Tokamak Reactor

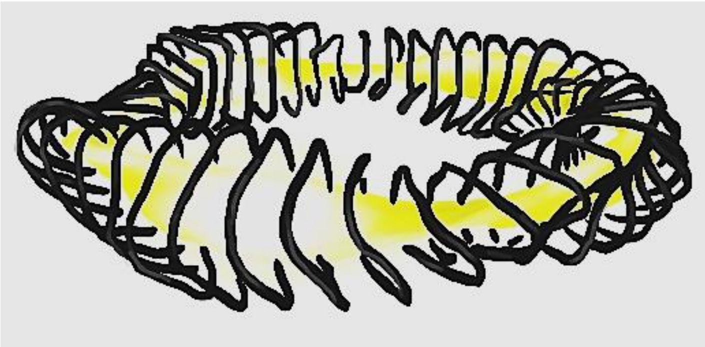

Figure 15 Illustration of Stellarator Reactor

This design offers several advantages, including:

- Increased flexibility in reactor design
- Simplified plasma control
- Increased plasma stability
- Higher cost-effectiveness with a building cost estimated at 1.1 billion dollars, compared to the $22 billion cost of a Tokamak reactor.

Communications

Communication is made with Earth and the mining camp at Mars via the use of ultra-high frequency (400 megahertz) antennas. Although there is an inevitable 5-to-30-minute delay in time depending on the distance of travel, these antennas are currently the most reliable communication method for deep space. In fact, ultra-high frequency antennas have been used by NASA during most of their unmanned Mars exploration missions with an array of antennas called the Deep Space Network (DSN). The only faster alternative to this system is quantum communications; yet, even after the breakthrough that won the 2022 Nobel Physics Prize, quantum communication systems are very expensive and only theoretical.

There will be three separate channels for communication outside of Polaris. The first channel, which has the highest capacity, is the civilian network. The civilian network is designed to be able to support 750 people at once, although the expected average-usage is around 400 calls per hour. This channel is used by the inhabitants of Polaris to communicate with friends and family on Earth.

The second and third communication channels are both utilized by Polaris's government, with one being used for scientific data-sharing and the other one being utilized for diplomatic relations. The scientific channel and the diplomatic channel can support 300 and 100 users at once respectively. The Ministry of Communication experts operating these channels are able to communicate with the both the Earth and the Mars Mining Camp to:

- Transmit regular status updates.
- Exchange information on solar flares and other important events
- Speed-up diplomatic and emergency communications

Communication inside the settlement is also very important, as people working on different tori will need to communicate during emergencies. Hence, Polaris is equipped with fiber-optic cables that run through the tube and radio signal terminals in each torus. The fiber-optic cables use light to relay information from two separate locations incredibly fast. As such, the use of these cables ensures a fast connection between the tori for scientific and emergency data transfers. Whereas the radio signal terminals are utilized for casual communication between friends and family living in different tori.

Shielding

Conditions of the Main Asteroid Belt like the high levels of ionizing radiation, fluctuating temperatures and high-velocity meteoroids pose a major threat to the continuity of Polaris. Hence, these hazards must be properly addressed for the safety of inhabitants. The shielding for Polaris will be composed of layers of various materials of differing properties, which all together will construct a habitable environment inside the settlement.

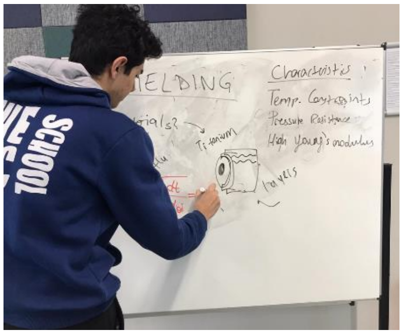

Figure 17 Emre EKİCİ presenting his ideas on shielding.

Materials and Properties

Table 4 List of Potential Materials for Shielding

Material	Potential Use	Necessary Thickness (m)	Density (kg m^{-3})

Aluminum	Structural enclosure	0.4	2710
Graphene (multilayer)	Shielding against meteoroids	1.8×10^{-9}	2000
Kevlar	Shielding against meteoroids	6.5×10^{-4}	1380
Dyneema	Shielding against meteoroids	1.6×10^{-3}	980
Polyethylene Foam	Shielding from solar flares	5.0×10^{-2}	150
Liquid Hydrogen	Shielding against gamma and x-ray radiation	5.0×10^{-2}	71
Lead	Shielding against gamma and x-ray radiation	0.4	11300
Lithium Borate Glass	Shielding against gamma and x-ray radiation	5.0×10^{-3}	2400
AVCOAT 5026-39	Temperature insulation	8.0×10^{-2}	512
Silica Aerogel	Temperature insulation	$3.0\ 10^{-2}$	0.15
Kapton	Temperature insulation	3×10^{-5}	1430

Table 5 Properties of Collision Shielding Materials

Material	Tensile Strength (Mpa)	Shear Strength (Mpa)	Young's Modulus (Gpa)
Graphene	1.3×10^{5}	358000	2400
Kevlar	3.62×10^{3}	474	76

Dyneema	3.87 x 10^2	300	120

Table 6 Properties of Temperature Insulating Materials

Material	Thermal Conductivity (W m^{-1} K^{-1})	Specific Heat Capacity (J kg^{-1} K^{-1})
AVCOAT 5026-39	0.89	1810
Silica Aerogel	0.035	1900
Kapton	0.46	1090

Table 7 Properties of Radiation Shielding Materials

Material	Reflectivity	Emissivity Coefficient (ε(λ))
Liquid Hydrogen	High	0.03
Lead	High	0.06
Lithium Borate Glass	Medium	0.96

Protection from Radiation

To understand how Polaris shields its inhabitants from ionizing radiation, the sources of ionizing radiation in space must be discussed. The two primary sources of radiation, in space are:

- Particles that are displaced across the universe, via solar activities like solar flares. These explosions eject great amounts of energy, in the forms of gamma rays, x-rays, and other types of electromagnetic radiation.
- Galactic Cosmic Rays (GCR) are rays that originate from outside of our Solar system. The majority of GCR reaching Polaris will be from other regions of the Milky Way Galaxy.

The magnetic field of Earth shields the planet from 99.9% of ionizing radiation, by reflecting these charged particles. The effect of Earth's magnetic field can be artificially created to some extent by utilizing the right radiation shielding material.

In the following table, radiation shielding materials are evaluated according to their densities, reflectivity and emissivity. Density is the amount of mass in a unit volume. In the context of radiation shielding, density affects the radiation permeability and the mass-used of materials. Even though high density often parallels high reflectivity, less dense materials are always preferable due to their ease of transport and lower cost per area. Moreover, reflectivity is a material's ability to reflect incident radiation, measured by the ratio of reflected radiation and incident radiation for a given wavelength of light. Materials with higher reflectivity are useful for radiation shielding, as they reflect charged particles. Last, emissivity is a material's ability to emit radiation from its surface. Materials with lower emissivity will emit lesser amounts of previously absorbed radiation, hence less ionizing radiation will penetrate Polaris.

Table 8 Evaluation Matrix for Radiation Shielding Materials

Criteria (Scale 1 to 5, Higher is better)	Weight of Criteria	Liquid Hydrogen	Lithium Borate Glass	Lead
Density	5	5	3	2
Reflectivity	4	4	3	4
Emissivity	4	5	2	5
%Match	Total: 13	**87.1**	55.7	65.7

In evaluation matrix calculations, the percentage match of material for the desired trait is calculated with the following formula:

$$\%Match = \frac{20(\sum_{i=1}^{x} W_i S_i)}{W_T}$$

$$W_i: Weight\ of\ Individual\ Criteria$$

$$S_i: Score\ in\ Individual\ Criteria$$

$$Wt: Total\ Weight\ of\ Criteria$$

$$x: Number\ of\ Criteria$$

For example, the percent match of liquid hydrogen for radiation shielding is calculated from:

$$\frac{20(\sum_{i=1}^{3} W_i S_i)}{W_t} = \frac{20((5 \times 5) + (5 \times 4) + (5 \times 5))}{14} \approx 87.1\ \%$$

Due to its low density, high reflectivity and low emissivity coefficient, **liquid hydrogen** is the best material for gamma and x-ray radiation shielding in Polaris. The dense arrangement of H_2 molecules in liquid state is key to hindering gamma ray penetration. Previous research (Li et al., 2017) has also demonstrated that liquid hydrogen is the most mass-effective radiation shielding material. In Polaris, a 0.05 meters thick layer of liquid hydrogen will be contained in an aluminum tank-like structure.

Protection from Temperature Changes

Regulating the heat flow in Polaris is key in sustaining a habitable environment. The majority of the heat energy in the universe originates from nuclear fusion in stars. In our sun, the core temperature averages 15,000,000K, with a surface temperature of 5800K. Considering that the only method of heat transfer applicable in space is radiation, the sections of Polaris facing the Sun will experience extremely high temperatures, while the sections facing outer space will experience very low temperatures. Therefore, the temperature insulation material must be durable and effective in both hot and cold temperatures.

In the following table, temperature shielding materials are evaluated according to their densities, thermal conductivities, and specific heat capacities.

The thermal conductivity of a shielding material is its ability to transmit heat energy. Less conductive materials are preferable for insulation, as they reduce the amount of heat escaping and entering Polaris. Thermal conductivity is calculated through the equation:

$$K = (QL)/(A\varDelta T)$$

$$K: thermal\ conductivity\ (W/m.K)$$

$$Q: the\ amount\ of\ heat\ transferred\ through\ the\ material\ (W)$$

$$L: the\ distance\ between\ the\ two\ isothermal\ planes$$

$$A: the\ area\ of\ the\ surface\ (m2)$$

$$\varDelta T: the\ difference\ in\ temperature\ (K)$$

Specific heat capacity is the amount of heat required to raise the temperature of a unit mass by a set amount. If the specific heat capacity of a temperature shielding material is high, then fluctuation in the temperature will be less frequent. Hence, materials with high specific heat capacities are typically better insulators. Specific heat capacity is calculated through the equation:

$$C = Q\ /\ (m\varDelta T)$$

$$C: specific\ heat\ capacity\ (J/Kg\ K)$$

$$Q: the\ energy\ added\ (J)$$

$$m: mass\ (kg)$$

$$\Delta T: the\ change\ in\ temperature\ (K)$$

Table 9 Evaluation Matrix for Temperature Insulating Materials

Criteria (Scale 1 to 5, Higher is better)	Weight of Criteria	AVCOAT 5026-39	Silica Aerogel	Kapton
Density	4	4	5	3
Thermal Conductivity	5	3	5	4
Specific Heat Capacity	5	4	5	2
% Match	Total: 14	72.9	**92.9**	60.0

Due to its low density, low thermal conductivity and high specific heat capacity, **silica aerogel** is the best material to shield Polaris against temperature fluctuations. Due to the presence of silica, the material has a hydrophobic nature that is key in preventing corrosion and moisture damage. The gaps between individual atoms illustrated in Figure 18 explains the highly porous structure and low density of the silica aerogel. Moreover, the same porous structure also contributes to silica aerogel's ability to withstand high temperatures without deforming. Hence, silica aerogel requires little to no maintenance while offering high temperature insulation for Polaris.

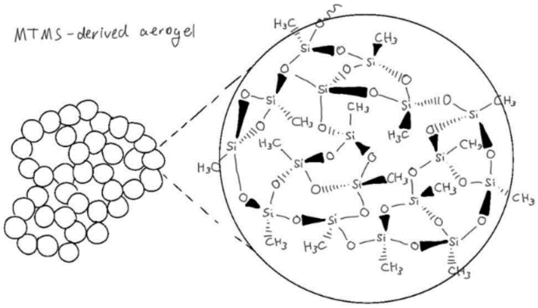

Figure 18 Molecular Structure of Silica Aerogel

Protection from Meteors and Space Debris

Even though the distances between objects in the Main Asteroid Belt is relatively large, a permanent settlement like Polaris will eventually come across asteroid, meteoroid and space debris. For such scenarios, it is vital to avoid collision, while ensuring that the outermost layer of Polaris's shielding can endure impact.

One approach to avoid impact is the standoff approach. This approach is utilized for large meteors capable of causing significant mechanical damage to the settlement. In the standoff approach, the threat is shattered into smaller pieces while it is still at a distance from Polaris. This can be achieved by detonating nuclear explosives alongside the object (a distance of at least 20 meters). After the asteroid is shattered into pieces, the outer layer of Polaris will be able to shield the settlement from minor meteorite collisions.

A hypothetical study (Sandorff et al., 1967) aiming to alter the course of an asteroid named Icarus (18 months distant at the time and 1.4 kilometers wide) evaluated the standoff approach. In the study, modified Saturn V rockets containing nuclear explosive devices were to be utilized to shatter the asteroid into smaller pieces, and the results suggested that the standoff approach could be beneficial in certain, though limited, scenarios.

Additionally, NASA Dart Mission is a key example of planetary defense against near - Earth objects. In 2022, the mission successfully changed the trajectory of asteroid Dimorphous, entering historic records as the first human alteration on the course of a celestial object. The method involves commanding one or more spacecraft into the hazardous asteroid at high speed to change its trajectory. This particular approach is successful over time, as small nudges lead to major changes in the trajectory of the asteroid. All in all, this particular method of planetary defense can be applied to defend Polaris from space debris and meteoroids.

In the following matrix, meteor and space debris shielding materials are evaluated according to their densities, shear strengths, Young's Modulus values and tensile strengths.

The shear strength of a material is the maximum stress that a material can withstand before beginning to rip or tear. This modulus is utilized to determine a material's ability to shield against micrometeoroids and small meteoroids.

Tensile strength is the maximum load that a material can support before deforming. A material with high tensile strength is ductile and preferable for collision shielding. This modulus is used to evaluate a material's ability to withstand caving in upon impact with meteoroids.

Young's Modulus is a measure of a material's ability to withstand compression and decompression upon force without deforming. Materials with high modulus of elasticities can maintain their form under large compressive forces and are hence preferable as shielding materials. Young's Modulus is calculated from the following equation:

$$Young's\ modulus = stress/strain = (FL0) / A\ (Ln - L0)$$

$$F: compressing\ force\ (N)$$

$$L0: initial\ length\ (m)$$

$$Ln: final\ length\ (m)$$

$$A: cross - sectional\ area\ (m2)$$

Table 10 Evaluation Matrix of Collison Shielding Materials

Criteria (Scale 1 to 5, 5 Best)	Weight of Criteria	Graphene	Kevlar	Dyneme
Shear Strength	5	4	5	5
Density	4	3	3	4
Young's Modulus	3	5	3	2
Tensile Strength	4	5	3	2
% Match	Total: 16	**83.8**	72.5	68.8

Graphene has a high shear strength, tensile strength, and Young's Modulus value. Hence, it can easily withstand its impact with meteorites and microscopic space debris. Graphene, like Teflon, can be applied to surfaces and requires little to no maintenance due to its durable mechanical properties.

Graphene itself is a single layer of hexagonally arranged carbon atoms. By utilizing multiple layers of graphene on top of each other, the strong mechanical properties of graphene can be mimicked and, thus, put into macroscopic use. Figure 19 demonstrates the Van der Waals forces between different layers of graphene and the covalently bonded unit structures of graphene.

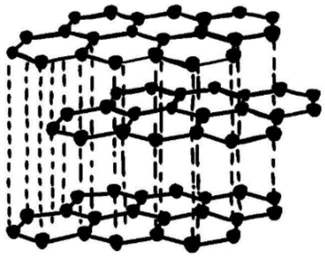

Figure 19 The interactions between layers of Graphene

Arrangement of Layers

Overall, graphene, aluminum, liquid hydrogen, silica aerogel and polyethylene foam will be utilized for meteorite impact shielding, structural enclosure, gamma and x-ray radiation shielding, temperature insulation and electromagnetic interference (EMI) shielding respectively.

- The outermost layer of graphene protects the lower-levels of shielding from abrasion due to meteorite collisions, while the first and thickest aluminum layer offers structural support to prevent the shell from caving in upon impact.
- The silica aerogel facilitates temperature insulation and is located two layers above the temperature-sensitive liquid hydrogen tank.
- After the silica aerogel layer, a layer of polyethylene foam offers protection from the EMI effect of solar flares to delicate circuitry inside the Polaris.
- Then, a tank of liquid hydrogen enclosed by aluminum offers radiation shielding for the inhabitants.

All measures in the following figures are in meters.

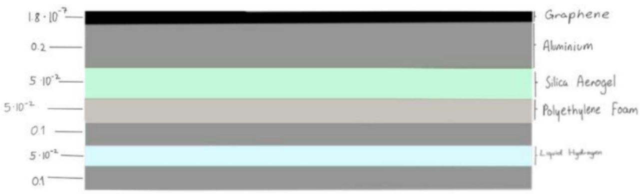

Figure 20 2D Arrangement of shielding layers

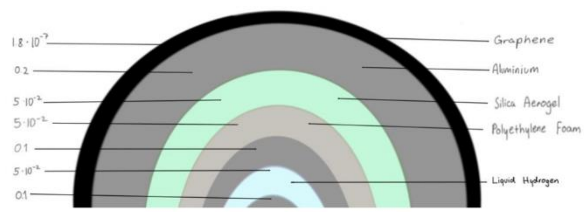

Figure 21 2D Arrangement of shielding layers (bent view)

Sustainability

Water Management

The water requirement of the settlement will be fulfilled with two different sources of water: water obtained from asteroid & planetary mining and water recycled in the settlement. Moreover, the three main uses of water in Polaris are household consumption, agriculture, and industry.

To prevent nitrogen and heavy-metal pollution, water used for industrial and agricultural applications cannot remain in the same recovery cycle as the water used for consumption. Hence, for cost-efficiency, polluted water from the industry and agriculture centers of Polaris is ejected away from the settlement in high velocity and is replaced with fresh water from asteroids and the Mars Mining Camp.

Whereas domestically used water is easily recovered, by filtering various contaminants and solid substances. The first step in the purification cycle is filtering suspended solid particles by running the waste water through a polyurethane film. The porous structure of polyurethane acts like a filter by capturing and holding solid particles. These films will later be cleaned and the solid particles will be utilized as fertilizer in the aquaponics system. Then, the visible particle-free water will be distilled to reduce microbial contamination and contaminant residue. In the last step, the water will be sent to a storage tank to be treated with ozone.

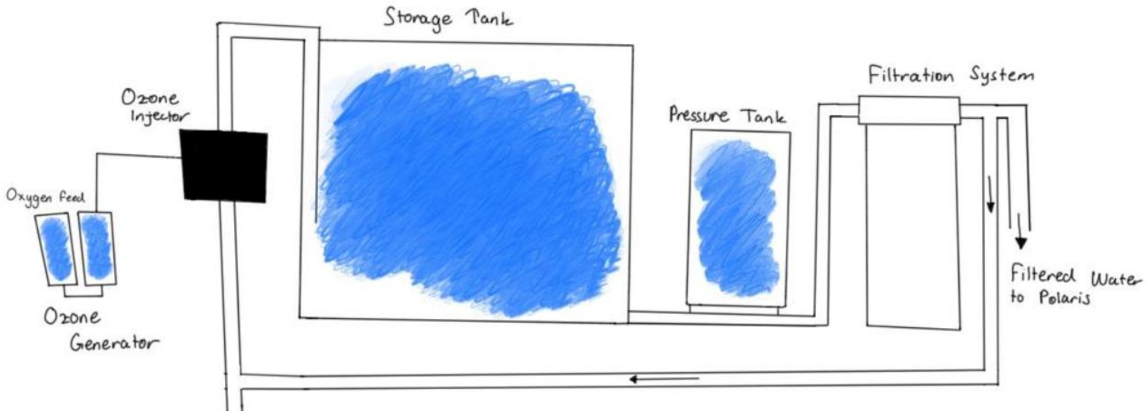

Figure 22 Metal Filtration and Ozone Treatment System in Polaris

Ozone is a disinfectant that eliminates most pathogens. Hence, to sanitize the water supply, Polaris incorporates an ozone-filtration system to its water tanks. Due to its strong oxidizing properties, ozone can also oxidize residue amounts of metal such as iron (found in urine). When oxidized, these materials are much easier to filter-out by a filtration system. Thus, the ozone-filtration system effectively filters out residue amounts of metal, which are later used in Polaris's industry. After these three main steps of filtration, water re-enters the plumbing system of Polaris.

Nutrition and Health

In an environment where resources are scarce, it is essential to build a self-sustaining cycle that can regularly supply for the settlement. A healthy human diet must include carbohydrates, vitamins, minerals, lipids, and various amino acids. A chronically ill human will also require additional chemicals to survive and maintain a regular daily routine. Nevertheless, designing a sustainable system in space that can provide such a variety of nutrition and medicine is a challenging task. Polaris will use aquaponics and bacteria farms to supply a variety of plant and fish-based diets, while also synthesizing various sugars, enzymes, and chemicals for luxury and medicinal use. Numerous 3D printing methods will also allow settlers to consume artificial meat efficiently and without animal cruelty. Additionally, complex nutrition management plans will assure that the settlement will have zero-hunger, by providing all settlers access to a healthy and rich diet.

Aquaponics

Aquaponics is composed of two different parts: hydroponics and aquatic tanks. The reason why hydroponics and aquatic tanks cannot share the same water directly is due to the subtle difference between the optimal temperature for plants and fish. Hydroponics, the section where plants grow, does not require soil. Instead, plants get their nutrients from the fish tank, which they are connected to by air pumps. In aquaponics, both bacteria and fish can enrich the water with nutrients and minerals creating a symbiotic relationship that humans can make use of. Fish that can adapt to crowded environments release feces that are mainly composed of nitrogen and phosphorus. This water is carried to the hydroponics section to get purified and allow plants to obtain nutrition. During this process, the roots of the plants act as biofilters and pick up the residues of feces in the water. Eventually, this cleaned water returns to the aquatic tank where the cycle repeats itself.

The most prominent substance that forms the backbone of the system is nitrate (NO_3). NO_3 is a necessary mineral for plants to sustain their lives, therefore it is vital to maintain a stable NO_3 balance in the water. The optimal NO_3 concentration for the plants to grow sufficiently is between 25ppm to 30ppm (ppm is a unit used for small dimensionless quantities and it can also be represented as mg/L). To keep this level stable, the aquaponic system will consist of different species of bacteria. As an example, the ammonia released by the fish can be converted into NO^-_2 by Nitrosomonas, a species of bacteria. However, NO^-_2 does not play a role in plants' growth or development. Nitrobacteria is a specific type of bacteria that gains energy from oxidizing inorganic compound nitrogen compounds. Therefore, in this case, Nitrobacteria can step in to convert NO^-_2 to a much more useful nutrient: NO3. Another great way to increase is biofiltration, in which hydroponics and bacteria are combined to form a biofilter. The roots of the plants have a high surface area to volume ratio, making them a great region for bacteria to inhabit. However, the unregulated combination of bacteria and plants may result in NO_3 depletion. By providing the bacteria with a passageway to the aquatic tank, the system provides a constant supply of ammonia to the bacteria.

The next step while constructing an aquaponics system is to decide on the plant and fish species. The approximate amounts of nutrition an adult male requires are approximately 275 grams of carbohydrates, 46 grams of protein, 60.5 grams of lipid, and 50 grams of sugar. Plants and fish with high nutritional values must be preferred while making this choice. The most convenient species of fish that satisfies this condition is Tilapia. Tilapia is a freshwater fish that can easily adapt to crowded environments. In addition to its nutritional value, Tilapia only requires 6 to 8 months to reach a mass of 1 pound. Another species that our aquaponics will accommodate is the Catfish. Catfish can live in saltwater, freshwater, or brackish water, hence it is certain that they will have no problem adapting to the aquatic tank. Catfish also have a relatively longer growth span of 18 months. However, this is compensated for by their higher nutritional values in comparison to other aquatic species. Nevertheless, Tilapia and Catfish are not sufficient to satisfy the carbohydrate needs of Polaris's population.

Therefore, the aquaponics system will also grow plants that are rich in carbohydrates. One of the best sources of carbohydrates is fennel, as it has 345 calories per pound. A plant that has similar values is quinoa, with 368 calories. Additionally, even though generic, sweet potatoes cannot produce long tubers in hydroponics, they are still very efficient at supplying the high demand for calories. There are also a lot of different options of green-leafy vegetables that can successfully grow in the hydroponics tank, these include tomatoes, cucumbers, broccoli, cabbage, and cauliflower. Additionally, as the density of fish increases, the number of plants that the system can support increases proportionally. Therefore, the size of the aquatic tank will further extend the range of plants that can be chosen.

For this cycle to sustain itself, the acid-base balance and optimal temperature must be kept stable. The optimal living conditions of both Tilapia and Catfish require water with a pH of approximately 8, while the temperature must be around 80.6°F. To minimize changes in temperature, the tanks will be covered with insulation material. In addition, carbonate involving substances such as $CaCO_3$ and K_2CO_3 will act as buffer solutions, that maintain the water's pH level. The room temperature for the plant will be around 68°F and the corresponding relative humidity will be around 50%.

The table below illustrates the nutritional values present in one pound of a specific organism that will be grown in Polaris. Determining these values is crucial to creating a balanced diet for the settlers.

Table 11 Animal-Based Sources of Nutrition in Polaris

Type of Fish	Calories (kcal)	Proteins (g)	Fat/Lipids (g)	Iodine	Other Vitamins and Minerals
Tilapia	128	26.0	3.00	10 kg/μg	Choline, niacin, vitamin B12, vitamin D, selenium, and phosphorus
Catfish	105	18.0	3.00	Negligible	B12, selenium, Omega-3, and Omega-6

Table 12 Plant-Based Sources of Nutrition in Polaris

Product	Calories (kcal)	Proteins (g)	Fat/Lipids (g)	Other Vitamins and Minerals
Potato	110	3.00	0.60	Potassium, Vitamin C, Calcium, Iron, Dietary Fiber
Sweet potato	100	2.00	0.60	Sodium, Dietary Fiber, Vitamin A, Vitamin C, Calcium, Iron
Fennel	345	15.8	14.9	Sodium, Potassium, Dietary Fiber, Vitamin C, Calcium, Iron
Quinoa	368	14.1	6.10	Sodium, Potassium, Dietary Fiber, Vitamin A, Vitamin C, Calcium, Iron

Broccoli	45.0	4.00	0.50	Vitamin A, Vitamin C, Iron, Potassium, Calcium, Sodium, Dietary Fiber
Tomato	25.0	1.00	0.12	Sodium, Potassium, Dietary Fiber, Vitamin A, Vitamin C, Calcium, Iron

Arduino Temperature and Humidity Detection System

An Arduino circuit we designed and programmed will ensure that these rates are stable. The system utilizes two analog sensors, TMP36 and HOH-4030, that measure temperature and humidity respectively. These values are then reflected on a liquid crystal display connected though an I2C module.

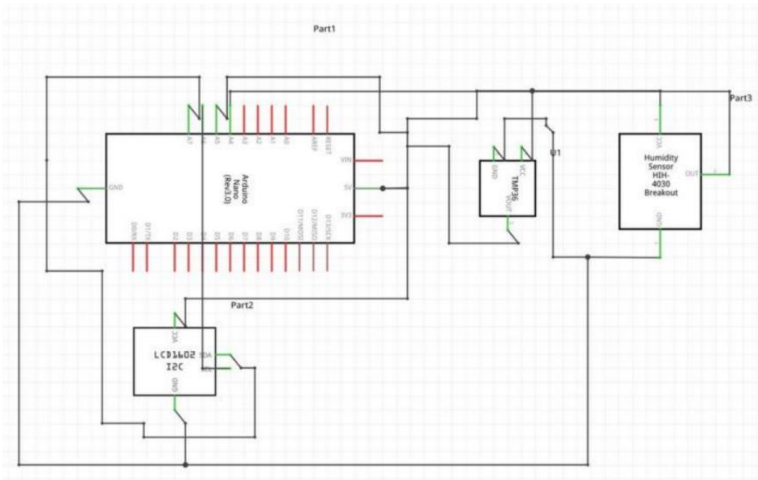

Figure 24 Schematic view of circuitry

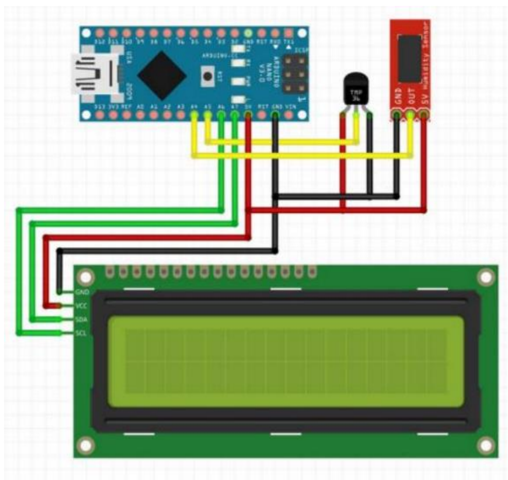

Figure 23 Breadboard view of the circuitry

Furthermore, by writing some code, we can print out the values received from the sensors to the LCD:

```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

LiquidCrystal_I2C lcd(0x27, 20, 4);

void setup()
{
    lcd.init();
    lcd.backlight();
}

void loop()
{
    int temp = analogRead(A5);
    int humidity = analogRead(A4);
    lcd.clear();
    lcd.setCursor(0, 0);
    lcd.print("Temp: ", String(temp));
    lcd.setCursor(0, 1);
    lcd.print("Humidity: ", String(humidity));
    delay(1);
}
// Code by Barış İnandıoğlu
```

Figure 25 Arduino code for reading two analog data streams from two sensors into a liquid crystal LCD.

The final iteration of a system like this can be altered to feature other capabilities. E.g., alerting the aquaponics technicians when drastic changes in temperature and humidity occur.

As seen on the figures below, we have built a prototype similar to the design above using an Arduino Uno. After uploading the code, we have tested and recorded data from the temperature and humidity sensors.

Figure 28 Collecting temperature and humidity data (1)

Figure 26 Collecting temperature and humidity data (2)

Figure 27 Photo from the construction of the Arduino prototype

Bioprinting

In addition to aquaponics, bioprinting will also be used to print 3D meat. By eliminating the need to build factory farms and raise livestock in the settlement, the system will be efficient and cruelty-free. However, small biopsies of livestock embryos are necessary to start the process of bioprinting. The sample cells in these biopsies will then be placed into a layered mold, where conditions will promote rapid mitotic division. As a result, the organism will grow and form tissues that will be used as material for bioprinting, within a repeating cycle of growth and harvest. Later, these ground tissues will be placed in a bioprinter, which will essentially print out a piece of meat in the desired measurements. Thus, creating artificial meat that is visually, tactually and gustatorily indistinguishable from real meat. Whereas bio-printed meat will be much more efficient (as, instead of bones and energy for respiration, only consumable meat will be produced) and animal-friendly. Additionally, bioprinting can prolong the shelf life of the products by up to 30 years. Therefore, in the conditions of space, 3D printing is vital for constant supply of nutrition.

Bacteria Farming and CRISPR

Figure 29 An image of fully grown streptomycin resistant E. coli, from Arda D. ALTINOK's experiment

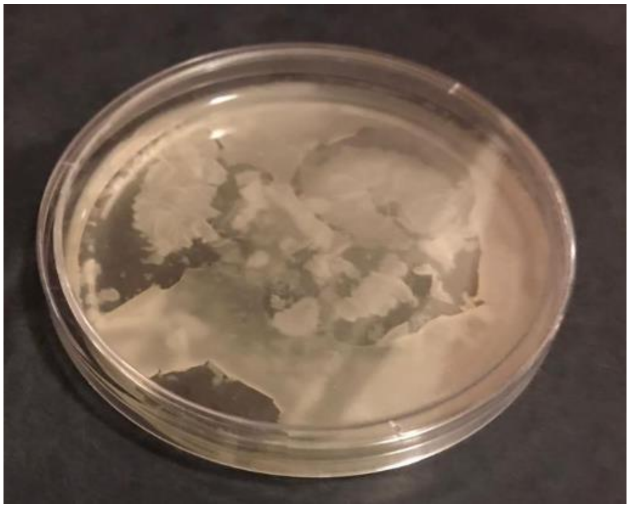

Figure 30 A mixture of Cas-9, gRNA, Template DNA, and E. coli

In an experiment, we utilized CRISPR to change a section of the rspL gene of non-pathogenic Escherichia coli (K12/MG1655). This alteration gave the bacteria the ability to survive in streptomycin media, an antibiotic medium. The experiment functioned by growing E. coli bacterium in lysogeny broth agar plates and, after the mutation process, adding the now-resistant E. coli to LB Strep/Kan/Arabinose Agar plates, to observe their growth. After we observed the plate for two days, our hypothesis was proven correct. Multiple E. coli colonies were visible in the petri dish, as illustrated in Figure 30. Nevertheless, the process of mutation was still a mystery that prompted further research.

The mutation process begins when the guide ribonucleic acid (Trans-activating crRNA and crRNA) finds the 43rd amino acid and activates the Cas-9 protein cascade. The Cas-9 protein cuts out a segment from the deoxyribonucleic acid, hence damaging the cell's DNA. This damage facilitates the activation of the cell's DNA repair cascade, which is named homologous recombination. In this process, the cell looks for a DNA section that is similar or identical to the one that was originally damaged. However, by drenching the bacteria cell with template DNA, we can trick the cell into adding the template into its genetic code. This will create the desired changes in the cell's DNA, which in this case was to replace a single adenosine base with cytosine. Thus, mutating the 43rd amino acid, lysine (AAA), to a threonine (ACA). At that location in the genome, a threonine amino acid prevents streptomycin from binding to and inhibiting the ribosomes of E. coli bacteria. This gives E. coli bacterium the ability to survive in Strep media, considering that ribosomes are a vital organelle for the cell.

This experiment virtually proved that it was possible to alter a very specific section of an organism's DNA, to create desired traits. These same principles will be applied to large bacteria farms, in which genetically modified bacteria will synthesize proteins, sugars, lipids, and enzymes while recycling waste and generating heat and electricity for Polaris. Essentially supplying the settlement with nutrition, medicine, and energy, in return for waste materials.

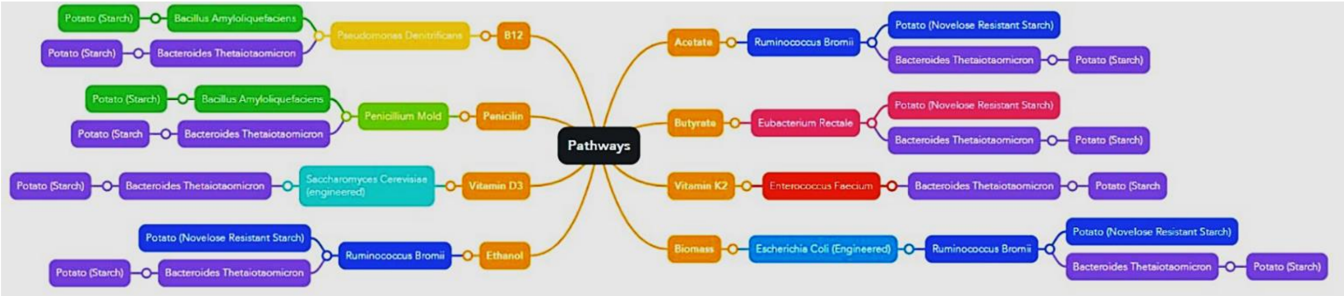

Figure 31 Diagram representing bacterial production.

Table 14 List of Bacteria Species in Bacteria Farms

Species	Product	Required Material
E. Coli (engineered)	Biomass	CO2, Formate
Ruminococcus Bromii	Formate, ethanol, acetate	Novelose Resistant Starch
Eubacterium Rectale	Butyrate	Novelose Resistant Starch
Enterococcus Faecium	Vitamin K2	Glucose
Bacteroides Thetaiotaomicron	Glucose	Starch
Pseudomonas Denitrificans	B12	Maltose

Bacillus Amyloliquefaciens	Amylase (maltose synthesizing enzyme)	Glucose
Penicillium Mold	Penicillin	Maltose
Saccharomyces Cerevisiae (engineered)	7-dehydrocholesterol (Vitamin D3 material)	Glucose

Polaris will be equipped with numerous bacteria tanks, which will house different species and combinations of bacteria, algae, and molds. These tanks will house various pathways, in addition to varying temperatures, humidity, light, and pH levels. Moreover, each pathway demonstrated in Figure 31 leads to the synthesis of the desired product after a sequence of symbiotic interactions between the different species of bacteria. These bacteria have been categorized according to their species, product, and requirements in Table 14. This section will further specialize in the properties of bacteria, as well as the benefits of bacteria farming.

The bacteria species that will be used in Polaris's bacteria farms are not limited to the above table. Whereas the table still provides a more than adequate example of a symbiotic relationship between bacteria --that the inhabitants can profit from. The bacteria species above all produce adenosine triphosphate via aerobic respiration. In this process, the bacteria consume oxygen gas, monosaccharide sugar (in this case glucose) and produce carbon dioxide gas, water, and energy (in terms of ATP). The chemical equation of aerobic respiration is as follows:

$$C_6H_{12}6O_2 \rightarrow\ 6CO_2 + Enery\ (ATP)$$

Henceforth, to allow bacteria to survive (respirate), the bacteria tanks must have a constant supply of glucose and oxygen. The oxygen will be directly provided from the aquaponics system, in which numerous plant and bacteria species produce excess oxygen via photosynthesis. Glucose –which is a monosaccharide sugar– will be derived from potatoes grown in the hydroponics system. The potatoes will be ground and undergo various chemical filtration processes to end up with starch. Since starch is a polysaccharide sugar, it cannot be utilized in its original form by many cells. In order to solve this problem, the species Bacteroides thetaiotaomicron will be made use of. This species will break specific glycosidic linkage bonds that connect the polysaccharide sugar, by a hydrolysis reaction. The broken-up polysaccharides will be turned into monosaccharides. This process of synthesizing glucose is colored purple in Figure 31. In this case, the polysaccharide starch will be broken down into the monosaccharide glucose, which is desired for aerobic respiration by numerous bacteria species.

Another potato derived substance is Novelose Resistant Starch. The prefix "resistant" suggests that this starch is not digestible by the human digestive system. This certain type of starch is utilized by the species Eubacterium Rectale and Ruminococcus Bromii to produce compounds like ethanol, butyrate and formate. The compound formate is utilized in another pathway to produce biomass. Escherichia Coli is a bacterium that is very suitable for genetic modification. In this case, an engineered E. Coli can utilize carbon dioxide and formate in a chemical reaction that produces biomass. This reaction is very similar to and can be counted as photosynthesis. The resultant biomass can be burned in a power plant, which will make use of a standard water vapor-based reaction --with minor changes to adapt to space.

Furthermore, Pseudomonas Denitrificans is a bacterium that synthesizes vitamin B12, which is essential for human survival. However, the cascade for creating B12 requires the disaccharide sugar, maltose, as a reactant. Maltose is made up of two glucose sugars connected by a glycosidic linkage. Hence, if starch is broken up properly, the result can be maltose. By this same principle, the bacterium Bacillus Amyloliquefaciens synthesizes an enzyme called amylase. The enzyme amylase breaks up glycosidic bonds in starch, thus providing maltose for Pseudomonas Denitrificans. Similarly, the Penicillin mold also works in symbiosis with Bacillus Amyloliquefaciens. As a result of this relationship, the Penicillin mold uses maltose to synthesize penicillin, a common antibiotic.

Due to ionizing radiation concerns, the settlement is shielded from solar rays and does not have any real windows. However, vitamin D3 can only be synthesized when UVB rays encounter 7-dehydrocholesterol, which is vitamin D3's precursor. Vitamin D3 plays a significant role in the immune system, as well as the growth and development of humans. Considering that vitamin D3 is essential to human survival and the inhabitants of Polaris do not have access to direct sunlight, D3 supplementation is necessary. In order to provide such supplementation, an engineered form of the bacterium Saccharomyces Cerevisiae will be utilized to synthesize 7-dehydrocholesterol. This precursor will be placed in a template, where the compound will come in contact with UVB rays from the sun, hence, synthesizing vitamin D3 for Polaris.

Waste Management

Every resource is extremely valuable in space, due to its scarcity. In a similar fashion to the saying: "One man's trash is another man's treasure", raw materials harvested from what is considered as waste can prove beneficial to the settlement. Waste management for Polaris will focus on three key points, which are: compostable, solid and harmful waste.

Compostable waste includes human/animal feces, dead plants/bacteria, food waste, and other organic materials. The resulting compost will be used as fertilizer for plants in the hydroponics system, in addition to being utilized as nutrition for certain fish and bacteria. Even though this method is very cost-effective and efficient, implementation is not an easy task.

There are numerous factors that must be considered while composting waste. One of those factors is the nitrogen and carbon balance. All organic matter contains carbon, while the majority of organic matter has a tendency to have nitrogen in its composition. However, the amount of carbon is often much greater than the amount of nitrogen. In fact, the ratio of carbon to nitrogen in composts is often 30 to 1. If the amount of carbon is reduced, the resulting compost will be wet and with a terrible odor. If the amount of nitrogen is reduced, the resulting compost will be much drier and require a longer duration of time before it breaks down into pieces. Henceforth, balancing the carbon and nitrogen balance is crucial in creating good quality compost.

Moreover, oxygen, temperature, and water are also vital ingredients of compost. To assure continuous airflow, waste must be stacked on top of each other in layered structures. Water must be regularly added to ensure that the compost remains humid. Additionally, high temperatures are very suitable for organic compost. This is because high temperatures promote the growth of bacteria that utilize aerobic respiration and also kill other species of bacteria that may harm the intended, decomposing bacteria. Considering that these bacteria are responsible for decomposing organic matter, their number greatly affects the efficiency of the system. The optimal temperature for composting ranges between 55 to 60 degrees Celsius.

Furthermore, solid waste includes scrap metal, plastic, glass, and other inorganic materials. Waste management for this category of waste is based on the "Three R Principles" in ecology, which are: reduce, reuse, and recycle.

Education will play a key part in implementing the first two steps, reduce and reuse. Polaris will teach inhabiting children the importance of conserving raw materials and resources for the continuity of the settlement –beginning from a very young age. This will lead to generations of aware citizens, who will mind their choices and try very hard to reduce their use of unnecessary material. Nevertheless, educating inhabitants is not sufficient on its own. Legislation and infrastructure in Polaris will make it so that single-use objects are reduced to the bare minimum, in order to conserve material. Alternatives for such objects will allow inhabitants to not sacrifice their quality of life, while still maintaining efficiency.

The process for recycling all solid waste essentially comes down to cleaning the object, sorting the material, breaking it down to tiny pieces, and then reusing it as raw material. For cleaning, simple soap or acetone solutions with water will be utilized --depending on the type of material. In stage two, the materials will be sorted out based on chemical composition, and then color. Later, high temperatures and grinding machinery will be used to break waste material into tiny pieces. Last, the tiny pieces will be used as raw materials for a new product. Thus, reducing the amount of solid waste in Polaris.

Last, harmful waste can be categorized as medical, radioactive and industrial waste. Considering that recycling these wastes is very expensive, waste management for harmful wastes is focused on safe disposal. Henceforth, medical waste will be burned, radioactive waste will be encapsulated in cement and industrial waste will be dried before being loaded into a capsule and ejected into deep space at high-velocity.

Population

Administration

An important issue to consider when constructing an independent space settlement is governing the inhabitants and establishing healthy diplomatic relationships with nations on Earth. Considering that Project Gaia was founded upon the principle international collaboration and space is a common heritage of humankind, Polaris's independent government must be unique in the way it fosters further collaboration between nations. To ensure such collaboration and the separation of powers, the representative democracy in Polaris will be founded on five fundamental branches: the Council of Representatives, the Parliament, the Ministers, the Judiciary Committee and the Council of Experts.

To form the Council of Representatives, 75 people will be elected from the inhabitants of Polaris –with no prerequisites other than being older than the age of 20. Every inhabitant over the age of 16 will be able to vote, and a cumulative voting system will be implemented each year to choose the representatives. The Council of Representatives is tasked voicing out the concerns of the inhabitants of Polaris to the Council of Experts. The members of the Council of Representatives still work in their regular jobs and are not be paid an additional salary. The council is also tasked with hosting the weekly meetings wherein inhabitants can voice out their opinions on various decisions.

The second branch is the Parliament. The Parliament consists of 30 senators (15 from each torus) who are tasked with auditing the Council of Experts and legislating in Polaris. Each decade, inhabitants of Polaris vote in a cumulative voting system to elect these senators –all of whom must be over the age of 30 and have applicable degrees in law and ethics. The parliament meets monthly to pass legislation, and the senators have considerably reduced workloads in their regular jobs in addition to an additional salary.

The third branch is composed of Ministers. The Ministers are elected by the Council of Representatives and confirmed by the Judiciary Committee. Ministers are tasked with running their respective ministries. The Ministers hold executive power over their respective systems and work full-time in their ministries for a full salary.

Table 15 List of Ministries in Polaris

Name of Ministry	Jurisdictions of the Ministry
Ministry of Energy	Management of the magnetic confinement fusion reactors and power distribution in Polaris
Ministry of Water	Management of water extraction, sanitization and consumption. Responsible for allocating water to various areas of the settlement.
Ministry of Resources	Management of the Mars Mining Camp and asteroid mining activities. Maintenance of Polaris.
Ministry of Law	Management of laws and policing inside the settlement.
Ministry of Agriculture	Management of food supplies inside the settlement. Overseeing the aquaponics, bioprinting and bacteria farming systems.
Ministry of Transportation	Management of transportation between Earth, Mars Mining Station, and Polaris. Management of communication and the NW-360 train systems.
Ministry of the People	Management of social events, space tourism and governmental services to ensure the wellbeing of inhabitants.

The fourth branch is the Judiciary Committee. The Judiciary Committee is composed of 15 supreme judges who are elected by the Parliament and confirmed by the Council of Experts. Members of the Judiciary Committee serve for life (are exempt from other duties and receive full salary), but can be impeached by a common verdict of Minister of Law and the Council of Experts. The Judiciary Committee is tasked with overseeing the courts run by the Ministry of Law, auditing the Parliament and approving changes made to the constitution by the Parliament.

The final branch is the Council of Experts. Four members in the council are elected by the Parliament and confirmed by the Judiciary Committee, while one member is appointed by the United Nations. These members must be experts in STEM or human sciences. Moreover, the Council of Experts work to ensure that other branches of government are in full collaboration. They can also veto any decision made by the Parliament, the Council of Representatives and Ministers, if in full agreement. Each expert serves for 20 years and cannot be re-elected –yet is paid a full salary and exempt from other duties for life.

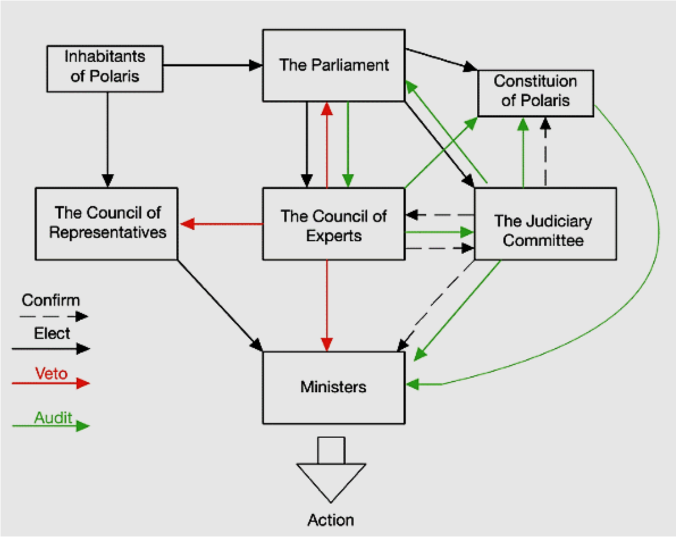

Figure 32 Diagram representing the jurisdiction of Polaris.

The Dual Structure of the Tori

As the main structure of Polaris consists of two separated tori, these two sections may become socially isolated from each other over time. Such isolation may possibly lead to the polarization of the population in the two sections, which may cause further social upheaval and reduce synergy.

To prevent such undesirable outcomes, bi-monthly competitions based on collaboration between the two halves of the station will be held. These competitions will push two inhabitants from different tori (who work in the same field) to work together and achieve a common purpose, while competing against other teams of two. Such teamwork will foster healthy bonds between inhabitants of different tori and create a Polaris spirit.

Furthermore, a monthly tournament between people from the two tori will be held. The tournament topic and contest will be decided by the Ministry of the People and small rewards such as a higher electricity quota or extra rations will be given as reward. Tournaments can be composed of video games, physical activities, or board games, such as:

- Chess
- Tennis
- Zero-G Virtual Reality Games
- Bingo
- Trivia

Finally, to celebrate the full rotation of the settlement around the Sun every Polaris year, a vacation day (for non-essential services and education) will be chosen by the Council of Experts and named the Solar Festival. The Solar Festival will be an event where people can have fun, relax and celebrate the prosperity in Polaris through various activities, like:

- Video Game Tournaments
- Gambling Games
- Wrestling, Tug-of-war, Weightlifting
- Food Buffet
- Karaoke

The Solar Festival will be one of the biggest tourist attractions of Polaris, creating various commercial opportunities and fostering a spirit of unity between the tori.

Zero-G Virtual Reality: A Novel Experience

Polaris, being the first permanent settlement in the Main Asteroid Belt, holds many unique possibilities for entertainment and tourism. One new possibility is using virtual reality technologies in zero gravity. Zero-G VR offers new features that were impossible in VR on Earth, like weightlessness and the ability to easily move in all four directions. All of which will definitely enhance the entertainment component of virtual reality.

The Zero-G VR experience takes place in specialized rooms of 15x15x15 m^3 dimensions, with padded walls to prevent injuries. The walls contain motion tracking sensors which feed the VR goggles information on the whereabouts of the room's boundaries. And, the room is placed in the main tube, so it is not affected by the artificial gravity effect.

Figure 33 Tourists experiencing Polaris' Zero-G Virtual Reality

Moreover, individuals experiencing Zero-G VR will be wearing a bodysuit with motion tracking and VR goggles. To interact with anything inside the VR worlds, the user can simply walk and use their hands. Detectors in their bodysuit will be able to detect such movements, enabling a VR interface without a remote. If the VR world requires items for an enhanced experience, sponge-like soft items with sensors embedded will be available for use.

Some of the Zero-G VR experiences offered in Polaris are listed below:

- Aquatic Expedition: A VR experience where you can float inside of a virtual ocean ecosystem, as if you are swimming! A single-player free world exploration experience in a giant ocean. From giant jellyfish to leviathan beings, a world of marvel and adventure!
- Deep Space: Truly astronomical! An adventure in deep space enhanced with the lack of gravity. Explore alien ruins and shoot at the evil alien AI! A first-person shooter game with 1-2 players, meant for excitement and thrill.
- Battle Box 0: A no gravity VR fighting simulator, where you can fight friends with VR swords while floating! Soft boxes and panels with sensors added to spice up combat! A maximum of 4 people battling out to be victors in a zero-g arena.
- Galactic Ball: A VR ball game with a VR ball, where two teams work to throw balls in the other's goals. The excitement of sports in zero-g, a way to experience ball games in space. With a maximum of 6 players, the game is on!

Conclusion: The Future of the Settlement

Polaris is the last step of Project Gaia. It serves as a beacon of human ingenuity and demonstrates that it is in fact possible to establish a permanent home for humans outside of Earth. The structure of Polaris allows more tori to be added, hence increasing the population that Polaris can accommodate. Yet, by the time the mission is concluded, new technologies developed in Polaris will enable further colonization that is not limited to the Main Asteroid Belt. Over the past year, our team has worked very hard to ensure that Project Gaia is the path to a better and more sustainable future for humankind. We dedicate Project Gaia to Gerard K. O'Neill and those who envision humanity's future in space.

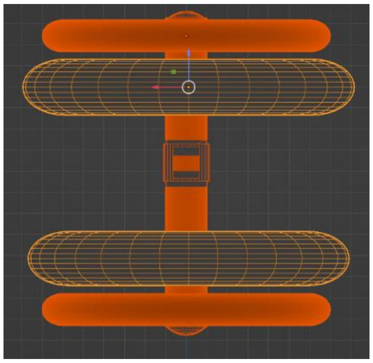

Figure 34 Polaris with two more tori extensions attached

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Epilogue

Project GAIA

is written by:

Arda Deniz ALTINOK, Barış İNANDIOĞLU, Ekin DİRİCAN, Alp DİNÇKOÇ, Ayşesu ÖZDOĞAN, Emre EKİCİ, Ahmed Metin KARAKÖSE

All of whom are 11th-grade students from the Koç School in Istanbul, Turkey.

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