**Gaia**

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“The dinosaurs became extinct because they didn't have a space program. And if we become extinct because we don't have a space program, it'll serve us right!”

-Larry Niven



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# Abbreviations

|  |  |
| --- | --- |
| CHP | Combined heat and power |
| CMF | Composite Metal Foams |
| DPSK | Differential Phase Shift Keying |
| GEV | Gaia-Earth Transport Vehicle |
| GMV | Gaia-Mars Transport Vehicle |
| GTV | Gaia Transport Vehicle |
| HVDC | High-voltage, direct current |
| ISRU | In-situ resource utilization |
| LCRD | Laser Communications Relay Demonstration |
| LDR | Liquid Droplet Radiator |
| LQR | Linear Quadratic Regulator |
| MEMS | Microelectromechanical systems |
| PICA | Phenolic-impregnated carbon ablator |
| PPM | Pulse Position Modulation |
| PRT | Personal Rapid Transit |
| PTFE | Polytetrafluoroethylene |
| RTG | Radioisotope thermoelectric generator |
| TIMU | Timing and Inertial Measurement Unit |
| TSTO | Two-stage to-orbit |
| WDM | Wavelength Division Multiplexing |

# 0.2 Executive Summary

Gaia is meant to be humanity’s first home in the stars. It will serve as a stepping stone for humanity’s eventual expansion into space. Gaia’s primary function is to serve as a “backup” world in the event of an apocalypse on Earth.

Gaia is a toroid space settlement located at the Mars-Sun L2 point, designed to provide a home for 30,000 people. It provides artificial gravity by the rotation of the structure at 1.25 rpm. It has a radius of 575 meters.

Gaia uses an Integral Fast Reactor to provide energy to the entire structure, which includes industry, production of essential resources, and several other human activities. It generates 200 MWe of electricity, along with 450 MWt of heat.

Support activities, mainly ISRU’s, are present on Mars to act as auxiliary structures. Several minerals and metals, some essential for the operation of Gaia and some for commerce purposes, are extracted and processed. Some of the minerals and metals being extracted are iron, deuterium, silicon and calcium among others.

Gaia’s structure consists of 3 tori, surrounding the central cylinders. The outer torus, housing the habitation areas, is present at a minor radius of 200 meters. The second torus, housing the food production centers, the storage facilities and the waste disposal plants, is present at a minor radius of 104 meters. The third torus, housing the nuclear reactor and a section of the industry, is present at a minor radius of around 68 meters. The central core consists of 2 cylinders, one above the other, the lower cylinder being the part of the industry which is non-gravitational, and the upper cylinder is the docking station. The cylinders have a radius of 64 meters.

Considering that Gaia’s construction is expected to take 8 years, the technology used in Gaia are those which are already existing, those which are expected to be available within the next 5 years, or those which already have a successful prototype. However, it has been constructed in a manner in which future technologies can be accommodated into the structure.

As mentioned above, Gaia is meant to be a stepping stone for humanity’s future in space. Considering Mars and its moons, Phobos and Deimos, have positions as a stopover onto the asteroid belt, a plan has been presented for the construction of a skyhook at an indefinite time in the future, to serve as an energy efficient method to mine the asteroid belt and also to facilitate humanity’s expansion beyond the inner planets.

Gaia is meant to be the first in a line of space settlements across the solar system. It should serve as an example for future space settlements, possibly in the outer planets and in the asteroid belt, and perhaps one day, in the very distant future, be remembered as the start of humanity’s voyage beyond Planet Earth and beyond the Oort cloud.

#### Section 1

Gaia

# Background

Gaia is meant to serve as a home for 30,000 people of varying backgrounds, including teachers, engineers and other normal middle class people, not just scientists. It will be completely independent, but having economic and cultural ties with Earth. Gaia’s growth is in several ways similar to the development of America. It will be dependent on its home planet, Earth for a while in the beginning. After attaining independence from Earth, it might expand and establish more settlements and mining structures in the Outer Planets and the Kuiper belt. The establishment of mining structures on the Kuiper Belt will definitely result in an extremely valuable Gold Rush. It’s expansion will also be marked by the development of its own unique culture. The harsh conditions of outer space will result in the rapid development of science on Gaia, which will be necessary for its development and to make life more comfortable for the settlers, thereby establishing a culture of innovation and scientific development Therefore, it can be extrapolated from this that one day in the future, Gaia might be the point from where humanity expands to the rest of the Solar System. Although, the initial conditions might be harsh and rough, braving these tough circumstances for a while would result in the gains we obtain, such as the resources in the Kuiper Belt, outweighing the temporary hardships by a large factor.

## 1.0.1 Purpose

Gaia is meant to be a permanent home in space for 30,000 people. It will be positioned at the Mars-Sun L2 point, a critical point as it has easy access to Mars and could act as a gateway to the Outer Planets.

While Gaia is meant to serve as a standalone, independent human settlement outside Planet Earth, it will also serve as a backup world for humanity in the event of human extinction.

At present, humanity faces several existential threats, including climate change, nuclear weapons, or an extremely contagious and deadly virus. While humanity has the ability to reduce the probability, some events are outside humans’ control, such as an asteroid collision. Thus, to prevent human extinction, Gaia could serve as a “backup” world, in the event of a human extinction scenario. If, unfortunately, certain events on Earth lead to the extinction of humankind as we know it, Gaia will have the minimum viable population required for a potential expansion and eventual de-extinction.

Another purpose is to act as a stopover for human missions to the asteroid belt and the Outer Planets. The asteroid belt, located between Mars and Jupiter, have extremely valuable asteroids, is extremely rich in substances like, iron, nickel, platinum, gold and water. The dwarf planet Ceres, located in the asteroid belt, is estimated to be composed of around 25% water.1 However, at present, it is not feasible, financially, to send a mission to the asteroid belt, only to extract a few kilograms of resources. Sending mining missions to and establishing ISRU’s in the asteroid belt would be easier from Mars, rather than Earth.

An advantage of mining the asteroid belt, is the availability of water, in huge quantities, at a large distance from Earth. In 2002, the Keck telescope provided evidence that Ceres, a dwarf planet in the asteroid belt, could contain as much as 200 million cubic kilometers of water, more than the amount of water on Earth.2 Water can be split into hydrogen and oxygen, which can be used as rocket fuel, reducing the costs of missions to the Outer Planets by a large margin. Water is also one of the most important resources required for human survival. This can be used in the establishment of settlements in the Outer Planets, perhaps on Europa or Titan. Rocket fuel would not be an issue, as it would be easier to produce rocket fuel closer to the outer planets, and water for the settlers would be easy to procure.

Therefore, Gaia as a space settlement, has two main purposes, to act as a “backup” world for humanity in the event of a human extinction event, and to serve as a base for further expansion and utilization of the resources of the asteroid belt and the Outer Planets.

## 1.0.2 Naming

In Greek mythology, Gaia is the personification of the Earth and one of the first goddesses to be born from the void of Chaos. She was the original deity ruling the Universe before the Titans were born.

According to Hesiod’s Theogony, Gaia “arose to be the everlasting seat of the immortals who possess Olympus above”. At the time of her birth, the Earth was shapeless, but Gaia led the Gods in the creation of Earth and all life on it. She was also believed to be the mother of all life on Earth.3

Gaia was the deity who was responsible for the creation and spreading of life on Earth. She was believed to be the actual life force of Earth. This is similar to our space settlement, which is responsible for the spreading of life in the solar system, from the Earth to Mars, in the beginning, and perhaps one day in the future, beyond Mars as well. She took a land believed to be shapeless and barren, and turned it into a land where all living beings could live. The space settlement too is responsible for the spreading of life onto Mars, a land considered today to be harsh and barren, but perhaps, due to Gaia become a land where living beings can survive and thrive for generations to come.

As we build a space settlement, the first thought that arises is of the harsh and barren emptiness of space. But humanity still chooses to venture into space and live. The final characteristic of humans which is similar to the goddess Gaia, is that we are willing to take a harsh, inhospitable land and convert it into a place where life can not only survive, but also thrive.

## 1.0.3 Location

Gaia, as a space settlement, must have a location factoring in several requirements. As a space settlement must be completely independent, it must have the ability to procure and process the resources required for the operation and maintenance of all of its component structures, along with the resources required by the human settlers. Another important factor would be the distance between the settlement and Earth. Although Gaia must be as independent as possible, it would be impossible for it to be completely independent from Earth, as certain essential minerals, such as the rare earth metals, have to be obtained from Earth. Another reason Gaia should not be too far from Earth is so that the cost of transport of material for the construction in the initial stages are reduced.

As several factors should be included, some of the primary factors considered for the choosing of a location were:

1. Distance between Earth and the space settlement
2. Availability of the resources required for the operation and maintenance of the settlement and the ability to extract them
3. Communication time
4. Presence of water in significant quantities on the closest celestial body
5. Ease of living for humans on the surface of the closest celestial body
6. Potential for the terraforming of the closest celestial body

|  |  |  |  |
| --- | --- | --- | --- |
| Location | Distance from Earth | Communication delay | Availability of water |
| Earth LEO | 2000 km | 0.06 s | Earth only |
| Low Lunar Orbit | 384,400 km | 1.28 s | Lunar poles |
| Low Venus Orbit | 55.283 million km | >3 min | None, except for 0.02 % in the atmosphere  (Earth atmosphere’s water vapor composition=0.40%) |
| Mars Sun L2 Point | 35.8 million km to 401 million km | 3 to 21 minutes | Martian north and south poles, plenty of water can be obtained |
| Asteroid belt | 330 million km | 25 minutes | Plenty of water on Ceres |
| Moons of the Outer Planets, like Titan or Europa | 1.4 billion km(Titan)  628.3 million km (Europa) | 1 hour 17 min (least for Titan)  35 minutes  (least for Europa) | Titan and Europa’s surfaces are made mostly of water ice |

After analyzing the table, it becomes obvious that some options, like Venus and the moons of the outer planets, cannot be considered as potential locations.

Venus has an extremely high surface temperature, an average of 462 degrees Celsius. The high temperature of the surface of Venus, combined with the presence of sulphuric acid in the atmosphere of Venus (25 ppm) and sulphuric acid clouds4, prevents the establishment of ISRU’s on the surface of Venus. ISRU’s made of PTFE can be used though, as they would be resistant to corrosion by sulphuric acid.5 However, PTFE has a melting point of 327 degrees Celsius. Venus also has an atmospheric pressure of 9.3 MPa, compared to Earth’s atmospheric pressure of 0.1 MPa. The presence of water on Venus is negligible, as mentioned above. It is evident that it would be extremely difficult to establish a permanent settlement on Venus without being dependent on Earth for a wide range of materials.

The Moons of the Outer Planets, such as Titan and Europa, have sufficient quantities of water. However, their large distance from Earth and the huge communication delay makes establishing a space settlement difficult. Another factor involved is the lack of resources on the surface of these moons. Europa and Titan have surfaces made of liquid ice, of a thickness of around 30 km on Europa and Titan’s surface is made of water ice, beneath which there is probably an ocean of liquid water. Due to the lack of resources, a space settlement near these moons would likely need to import essential metals and minerals like iron, aluminum and silicon from Earth. The establishment of a space settlement becomes even more difficult near Europa, due to the extremely high levels of radiation. Jupiter’s radiation belt is almost 10x stronger than Earth’s Van Allen radiation belts. Europa receives almost 540 rem of radiation every day.6 Compared to the average radiation on Earth of 0.0017 rem per day, a space settlement on Europa is exposed to almost 320,000 times more radiation! The effects of this radiation were felt during the Pioneer 11 mission, which lost all images of Io and suffered glitches in commands due to the radiation.

A settlement in Earth LEO would be completely dependent on Earth, and in the event of an apocalyptic event on Earth, it would become redundant as the main source for the resources required would be no longer available. Thus, although a space settlement would be easier to construct in Earth LEO, it would be of no use in the event of a human extinction event.

The asteroid belt has several characteristics which favor the construction of a space settlement there, such as the presence of large quantities of water and metals. However, the asteroid belt is at an extremely large distance from Earth of around 330 million km. Due to this huge distance, it becomes difficult for transport between Earth and the space settlement, and the distance also gives rise to a communication delay of almost 25 minutes.

Thus, the potential locations for a space settlement would either be Mars or Low Lunar Orbit.

Although, the Moon is located closer to the Earth and has a smaller communication delay than Mars, it has several challenges. Mars has several compounds required for living beings, like carbon dioxide, nitrogen and water, in sufficient quantities. However, Moon on the other hand does not possess these resources, excluding oxygen, which also has to be extracted from the lunar regolith using the molten salt electrolysis process, which is highly energy intensive.7 Another problem is the low amount of water present on Moon, compared to Mars. The Moon also has a high temperature variation of 250°C compared to the 83°C temperature variation on Mars. There is also a deficiency of important light metals, such as copper, on the Moon, whereas Mars has a higher quantity of light metals.

However, the primary advantage of Mars is its similarity to Earth and its potential for terraforming. Although terraforming is a rather difficult process, in the not so distant future, it might become possible to terraform Mars. Some ideas which have been proposed could be executed within the next 30 or so years. One such example is the placing of a magnetic dipole of strength 1 to 2 teslas, preventing the solar winds from stripping away the Martian atmosphere.8 This might result in the restoration of the Martian atmosphere and the sublimation of the frozen carbon dioxide at the polar ice caps, thereby increasing the Martian average temperature, which might result in the melting of the ice caps, filling up a fraction of the prehistoric oceans. Therefore, while it may be likely for Mars to be terraformed for the establishment of permanent Earth-like colonies, it might be very difficult to achieve the same on the Moon

Another factor to be considered is the financial gains. The Moon has Helium-3, an extremely valuable resource, while Mars has deuterium and its oxide D2O, a valuable resource costing around $10,000 per kilogram. Deuterium, an important fuel required in nuclear fusion reactors, is 5 times more common on Mars than on Earth. Another overlooked valuable resource on Mars is opal, which costs almost $15,000 per gram. Opal was first discovered in 2008 by the Mars Reconnaissance Orbiter, in small quantities and has been confirmed by numerous Martian meteorites.

Therefore, it can be concluded that although Moon wins with distance and communication delay, Mars is a better choice for a long term, more independent settlement. Mars has potential for terraforming and has several important and essential resources in high quantities, unlike the Moon.

The potential locations for Gaia are either Mars Areosynchronous Orbit or the Mars-Sun Lagrange Points. The Mars-Sun L2 point was chosen over the Areosynchronous Orbit due to a lower station keeping budget and high radiation protection. Although the Mars-Sun L2 point is slightly unstable, whereas the L4 and L5 points are stable, the Mars-Sun L2 point has certain advantages which outweigh the small stationkeeping budget:

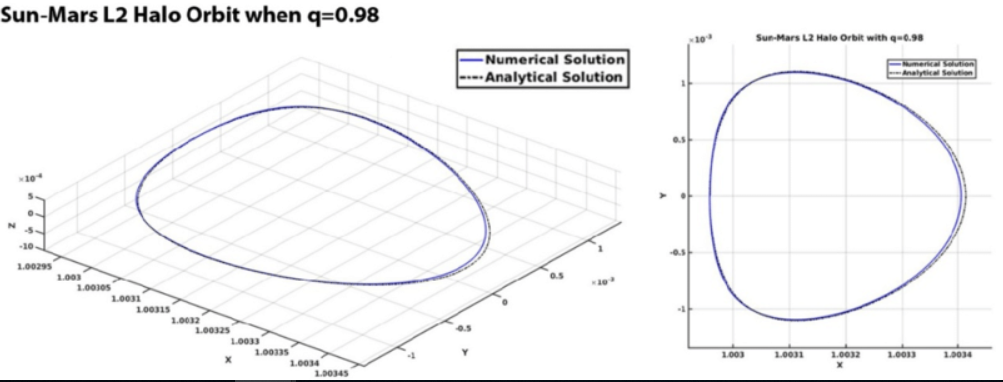
1. Protection from the solar wind and line of sight radiation from the Sun
2. Better communication between Gaia and Earth ( will be seen in Section 2.3.2)
3. Increase in information about the solar system and beyond from the telescopes on board Gaia (probably even better than the JWST or Hubble), due to low solar radiation interference.

If we consider the Mars and Sun system as a right cone, with the base radius ‘R’ being the radius of the Sun, Mars being located at some distance ‘d’ from the Sun, and the radius of Mars being ‘r’, the calculation for the distance between the ‘vertex’ of the cone, or the maximum extent of the solar umbra of Mars, ‘D’ is given by,

Plugging in the values, it is found that at perihelion, the end of the umbra is at a distance of 1,012,830 km from Mars and 1,221,080 km from Mars at aphelion. The Mars-Sun L2 point is located at a distance of 981,000 km from Mars at perihelion and 1.183 million km at aphelion. Thus, it is seen that the Mars-Sun L2 point is always in the solar umbra of Mars, protected by all line of sight radiation from the sun and the solar wind.

At the Mars-Sun L2 point, Gaia follows a halo orbit about the Mars-Sun L2 point. Halo orbits are periodic orbits about either the L1, L2 or L3 points. A Halo orbit was chosen over a Lissajous orbit due to the fact that a Lissajous orbit requires higher amount of orbital stationkeeping than a Halo orbit.

In the case of Gaia, the halo orbit followed has an amplitude about the Z axis (i.e. perpendicular to the plane formed by the Sun and Mars) of 100,000 km and has an , with a time period of 225 days. The radiation pressure q is considered to be 0.98±0.01 and the oblateness of the orbit is taken to be 5e-6.9 The eccentricity of the orbit is around 0.041.The delta-v required for orbit insertion from Mars is 1.75 km/s.

Figure 1 : Halo Orbit of Gaia9

# 1.1 Structure

The structure of a space settlement is always its most integral property as the structure determines several important aspects of the operation of a space settlement. Gaia's structure would determine the population, the size of the industry on Gaia, and the costs of its construction. These three factors determine the profits from and the operation of Gaia. Therefore, the structure of a space settlement is one of the most important decisions during the planning of a space settlement.

Gaia would, obviously, be required to rotate so as to provide artificial gravity and it would also require a non-rotating part and also a part with lower rates of rotation so as to facilitate non-gravitational industry and some amounts of zero-g recreation. This is an advantage of a space habitat where it becomes easier to have an industry in zero or micro-g which is not possible on Earth or a planet like Mars. Therefore, the structure of Gaia must have distinct regions for 1g and zero g

The material used in the construction of Gaia must also be carefully chosen, so as to reduce the costs of construction, but also to provide the maximum amount of strength and durability to Gaia. During the choosing of the material, the availability of the material, the strength of the material and the density of the material must all be considered, which will be done below.

## 1.1.1 Structural analysis

The basic factors which determine the shape of Gaia are:

1. Amount of area for human habitation
2. Amount of material used in construction
3. Cost of construction
4. Strength of the structure
5. Line of sight

The possible shapes for Gaia are:

1. Sphere:

A spherical space settlement would have one advantage over either a toroidal or dumbbell-shaped space settlement, such as a larger population capacity(by almost 7.5 times). However, spherical space settlements are undesirable due to the large surface area and high amounts of stress in the walls, which would result in a wall which has a larger surface area and more thickness, adding to the material costs by a large factor. Another problem is the large amount of volume wasted in the middle of the sphere. Compared to either a torus or a dumbbell, the line of sight in a sphere is 3.3 times more. In the case of a sphere, the artificial gravity would vary across the human habitation area, where it would undoubtedly cause problems for humans to walk around the sphere without experiencing the side effects of change in gravity.

Another problem would be the lower area of the zero-g area, as the only zero-g area would be the North and South poles of the sphere. This would reduce the size of the zero-g industry, adding to the costs of industry and cutting the profits of Gaia.

2. Dumbbell

A dumbbell shaped settlement would have the same population capacity as a torus, but it would have a higher mass due to the surface area remaining high. A comparison of a dumbbell shaped space settlement (radius = 895 m)and a toroidal space settlement (major radius=830 m) show that the surface area difference is almost 4 x 10^5 m2. Therefore, the disadvantages of a dumbbell compared to the torus is that for the same population capacity, a dumbbell requires higher mass and a large amount of area is wasted in the habitation areas, where the interior of the spheres cannot be used.

3. Cylinder

A cylindrical space settlement would have several advantages over the other shapes. A cylinder can effectively utilize the entire 1g area. Although it tends to have a much larger surface area than either a dumbbell or a sphere, it requires only half of their shielding mass. It also has the longest line of sight among tori, cylinders, and dumbbells. However, it tends to have an extremely large surface area for the same radius as a torus. Another disadvantage of cylinders, compared to a torus, is that the increase in stress on the walls. This is because rounded bodies like a torus are able to withstand pressure difference much more easily. Thus, a cylinder would require more reinforcement in its upper and lower walls. Compared to a torus, a cylinder has a smaller radius for the same surface area, which results in a higher rate of revolution for a cylinder for attaining 1g. This might result in higher rpm, causing discomfort for the settlers.

4. Torus

In the case of a torus, the stress on the walls is reduced by a significant margin as mentioned above. However, a torus has no zero-g area for docking and zero-g industries. This problem can be solved by concentric tori. In a concentric tori structure, the central core will be a zero g region, whereas the outer tori can be used as a 1g human habitation area. Due to a torus' curved walls, it tends to experience less stress on its walls compared to a cylinder as mentioned above. The fraction of a torus visible from the inside tends to be around 0.3. Thus, the line of sight of a torus is the shortest among dumbbells, cylinders and spheres, thus preventing disorientation among settlers.

Another important factor would be the mass of the structure. If we take a cylindrical, spherical and toroidal space settlements, having the same radius of rotation, the mass required for a cylinder or a sphere is almost 4 times more than that required for a torus. Thus, a torus requires almost a fourth of the material required by a cylinder or a sphere.

Thus, after the analysis of different shapes, a concentric tori shape was chosen for Gaia's structure of the form below.

<insert diagram here>

The walls of Gaia are of a stressed skin form, so as to evenly distribute the tension applied on the surface. As a stressed skin is of a semi-monocoque form, the stiffness of the walls is increased due to the application of stress. Another advantage is the cladding in a stressed skin wall also behaving as a bracing, thereby reducing the framing and making the wall lighter.

## 1.1.2 Materials analysis

The usage of the right materials is vital to the planning and construction of Gaia, as it would be important to choose a material which has high strength but also low density. It is vital that the material used in the construction of Gaia have high strength so as to bear stresses. It is also extremely important to consider the density of the material being used. If a material of high strength and high density is chosen, the settlement might be able to bear high stresses, but the costs would increase to high amounts, as it would take more rocket launches to transport a high density material than a light density material.

Another important thing to consider when choosing the material is its availability near the settlement. At this point, Graphene as a construction material would be the best option. However, large scale production of Graphene has not yet begun on Earth, let alone Mars. The material would also have to be present in large quantities near the settlement so as to reduce the import of vital construction materials from Earth.

An important aspect of the materials analysis for Gaia is the radiation shielding. As the Mars-Sun L2 point has the advantage of being in the solar umbra of Mars, it is protected from the radiation of the Sun (x-rays, gamma rays, etc.) and the solar wind. Therefore, the radiation affecting Gaia primarily consists of Galactic Cosmic Rays. Therefore, it is important when choosing the materials for the radiation shield, that the primary sources of radiation are considered as well.

### 1.1.2.1 Walls of the structure

The materials chosen for the construction of the walls of Gaia must be able to bear a rather large load, the main load being the atmospheric pressure. Gaia's structural integrity must be of highest importance as a failure on part of the walls to bear the loads might lead to disastrous consequences. Although measures to evacuate will be in place, it will be extremely difficult to recoup the losses suffered from such an accident, both profit wise and morale wise.

While several measures, such as the use of load bearing elements in the different structures of Gaia, along with the optimization in the shape of Gaia will be taken, it is vital that the material itself be able to bear the load. Several factors were considered for choosing the right material, including the specific strength and the Young's modulus of the material.

Specific strength was chosen so as to compare the ratio of the ultimate tensile strength and density of various materials. This is important considering that while a strong material is required, the density must not be too high as well. Consider an example such as steel. Although using steel would eliminate all material problems, its higher density (8 g/cm3) translates into higher construction mission costs. On the other hand, using a metal such as copper would reduce mission costs by several magnitudes, but its low tensile strength(220 MPa) would not be able to bear the load, resulting in a failure of the space settlement.

It should be noted here that the volumetric thermal expansion coefficient is not being considered when choosing the materials. This is because Gaia is positioned at the Mars-Sun L2 point, where it does not face the Sun. Thus, the entire external surface is roughly at the same temperature at all times. The average temperature calculation of the external surface will be provided in 4.4.

|  |  |  |
| --- | --- | --- |
| **Material** | **Tensile Strength** | **Density(g/cm3)** |
| Graphene | 130.5 GPa | 2.09 |
| Polyethylene | 80 MPa | 1.35 |
| Concrete | 3.5 MPa | 2.3 |
| Zylon composites | 5.8 GPa | 1.56 |
| Titanium Beta-C | 1.25 GPa | 4.81 |
| Aluminum 7075-T6 | 572 MPa | 2.81 |
| Stainless steel | 505 MPa | 8 |
| Kevlar | 3.62 GPa | 1.44 |

As seen in the table, Graphene would be the best construction material, due to its high tensile strength(130.5 GPa) and low density(2.09 g/cm3). However, it is not possible to produce graphene in large quantities on Earth, let alone Mars. Therefore, due to lack of availability, graphene was not chosen as the material for Gaia.

Polyethylene as a material is easy to produce on Mars, as Mars has a high amount of carbon and hydrogen in the form of methane. It also has a low density of 1.35 g/cm3. However, it has a low tensile strength of 80 MPa, which might result in it cracking under high stress. It is estimated that at a stress of around 50 MPa, which is really low compared to its tensile strength, the use of polyethylene would result in the wall having a thickness of around a 1.75 m or a mass of 2275 kg/m2, which is clearly untenable. The same goes for concrete, which has a density of 2.3 g/cm3, higher than polyethylene, but also an extremely low tensile strength of 3.5 MPa. Therefore, polyethylene and concrete are not used.

Another option would be Zylon composites. Zylon has a high strength of 5.8 GPa, almost 5.8 times more strong than stainless steel, for almost a fifth of the density. It has a high amount of abrasion resistance, almost 1.5 times more than aramid fibers. However, it is highly sensitive to low temperatures. Zylon's tensile strength decreases rapidly in low temperature. Thus, Zylon is instead used for the interior of the walls of the Gaia.

As a metal is required for the exterior of the wall of Gaia (for heat rejection and for the metals' ability to withstand temperature changes), aluminum alloy (7075-T6), stainless steel, Inconel and the titanium alloy Beta-C are the primary metals being considered.

Among these metals, titanium alloy (Beta-C) is clearly the best, having a higher tensile strength than stainless steel and the aluminum alloy (almost 2.5 times more) and the same tensile strength as Inconel. However, titanium has a lower density than Inconel and a higher emissivity(0.31) than Inconel (0.25). Another disadvantage for the usage of Inconel is that the materials required for its production, mainly nickel, are not present in large quantities on Mars.

Therefore, Titanium (Beta-C) is the metal chosen for usage in the walls of Gaia.

As a standard throughout all the walls of Gaia, the thickness of Zylon will be 2 cm, whereas the thickness of the titanium will be determined based on the pressure on the walls and the minor radius of the torus or the radius of the cylinder.

### 1.1.2.2 Radiation Shielding

As mentioned before, the Mars-Sun L2 point is in the solar umbra of Mars, thereby reducing the amount of radiation incident on Gaia by a large factor. Gaia is protected from solar radiation (gamma rays, x-rays, etc.) and solar wind. Therefore, the main source of the radiation incident on Gaia are galactic cosmic rays. They primarily consist of protons (90%) and alpha particles (9%), with extremely small amounts of electrons (<1%).

Graded Z shields are radiation shields consisting of layers of different materials, with the materials having the low atomic numbers at the top, with a high Z material/s in the middle, followed by a low Z material at the bottom. Graded-Z shields are highly effective against electrons, reducing penetration by almost 60%. The Graded Z shield is highly effective against electrons and different forms of radiation like gamma rays, but these shields also produce large amounts of bremsstrahlung when preventing penetration by protons. They produce large amounts of secondary protons and neutrons, along with X-rays.10 A Graded-Z shield is also not really effective against protons. Therefore, a two-layered composite shield was designed for use in Gaia.

As the primary objectives of the shield will be to reduce proton penetration to low, acceptable levels and to lower the amount of secondary radiation produced. Therefore, the materials which are being used are composite metal foam, to reduce the proton penetration, and carbon fibers, to lower the proton penetration and to lower the secondary radiation.

CMF’s consist of metallic foams with several spheres (which are 0.26 mm in size). Due to the high Z of the metals, the protons are deflected and due to the hollow spaces in the form of spheres, any secondary radiation produced is deflected back into space. Out of the two different types of composite metal foams which can be used for radiation shielding, steel-steel CMF’s were chosen over aluminum-steel CMF’s due to the high Z of steel-steel CMF’s. It is also seen that steel-steel CMF’s are 275% more effective compared to aluminum. It is also seen that the use of high Z material also maintained the energy absorption capacity and the density of the metal foam.11 CMF’s are seen to be just as effective as lead without the secondary radiation and weight. Therefore, one of the materials chosen was steel-steel CMF’s. The steel used is T15 steel, due to their tungsten and vanadium concentrations.

Another material chosen was a MTM57-M40J epoxy-graphite fibers composite material. Graphite-epoxy composites have a low density, but provide 30-40% less radiation attenuation than an equal mass of aluminum. As this is due to the lack of high Z materials, the graphite-epoxy composite is doped with tungsten (100 µm wafer for every 1 mm of graphite fiber).12 It has been seen that this form of graphite-epoxy composites are more effective than tungsten at radiation shielding and produce less bremsstrahlung, while having a much lower density (2.26 g/cm3, compared to tungsten’s 19.3 g/cm3).

Thus, the radiation shield for Gaia consists of the outer layer having a 7 cm thick steel-steel CMF and an inner layer of 3 cm thick MTM57-M40J epoxy-graphite fiber, with an overall mass of 27.08 g/cm2.

## 1.1.3 Divisions

The different tori of Gaia, along with the central cylinder core, are designed to perform different tasks. The outer torus acts as the habitation torus, whereas the lower cylinder core contains the zero-g industry. Therefore, it is imperative that each of these tori or cylinders be designed in an optimal way such that the function of those tori or cylinders are performed at their best capacity, while maintaining the structural integrity of Gaia.

Therefore, some of the divisions of Gaia have a different atmosphere. An example of this is the industrial torus and the Central Core. During the refining of the metals, the processes require little human action. Thus, as the requirement for humans is low in this torus, it is possible for the atmosphere to be different than that on the habitation torus, where it is required that the torus have an atmosphere like that of Earth. In the industrial torus, inert gases, like argon, are used. Argon is already used in titanium processing as a component of the atmosphere during the separation of titanium chloride from other chlorides in the Kroll process. It is mainly used in the metal refining industry as it is the most abundant noble gas and it is also highly unreactive. Therefore, to prevent attack on the metals or other products, argon is used as a component of the atmosphere, along with nitrogen. Argon is the third most common noble gas on Mars, with a volume percentage of 1.9%.

### 1.1.3.1 Central Core

The Central Core consists of two cylinders stacked one above the other, surrounded by Torus 1. The two cylinders are similar in all manners, except for their functions. The Central Core’s cylinders have different functions, with the lower cylinder consisting of the zero-g industry and zero-g research, along with the second IFR nuclear reactor, and the upper cylinder acting as the docking port and Mars-Gaia transfer vehicle construction area.

The Central Core consists of two cylinders, one above the other. Due to the lack of artificial gravity in the Central Core, normal elevators would not work. Therefore, a maglev based and rope-free elevator, based on Thyssenkrupp’s MULTI is used for the transport of large amount of materials between the docking port and the rest of Gaia. The elevator uses linear induction motors for the movement of the elevators, following the idea used behind trains like the Transrapid. The MULTI is a highly complex machine, which would require a more in-depth study to be analyzed and is beyond the scope of this project.13

**Functions and Facilities**

The Central Core also has the least amount of artificial gravity, due to its small radius from the axis of rotation. Due to this, the Central Core would be the best section of Gaia for the docking port. Due to the low amount of artificial gravity, it would also be easier to construct large structures, like the transfer vehicles mentioned above.

It may seem that the Central Core would be the division where the metal refining industry would be based, due to the ease of movement of heavy loads, such as the metal ores. However, the metal refining facilities are not located on the Central Core. This is mainly due to the fact that metal refining processes do require gravity. One example for this would be the refining of aluminum by the Bayer process. In the Bayer process, bauxite is heated in a pressure vessel with NaOH solution at temperatures of 150 to 200°C. After this, the aluminum is dissolved in the NaOH solution.14 The residue is separated out by filtering, which requires gravity. In another step in the Bayer process, carbon dioxide is bubbled through a sodium aluminate solution, which also requires gravity. It is obvious that the metal refining processes require gravity. One of the solutions used on the International Space Station is a centrifuge, used in the Environmental Control and Life Support Systems. However, a large scale metal refining industry would require huge centrifuges with a lot of power consumption. Therefore, the metal refining industry is not located in the Central Core.

The processing of minerals like silicon dioxide, the production of semiconductors and transistors, along with zero-g research laboratories are present in the Central Core.

Research laboratories in the Central Core will be important primarily due to the lack of radiation interference. Space telescopes on Gaia will be present in the Central Core. Space telescopes are highly efficient on Gaia due to the lack of radiation interference from the Sun.

The second IFR reactor will also be located in the Central Core, acting as the primary energy source for the zero-g industry. The operation of the reactor will be mentioned in more detail in Section 1.2.

It is to be noted that due to the different atmosphere inside the Central Core, facilities are constructed inside the Central Core, where almost 100 humans can stay in one chamber for a week, with around 385,000 liters of oxygen gas stored in the liquid form. It is rather easy to store oxygen in the liquid form as it has a high expansion ratio of 1:861 at 20°C. Due to the high expansion ratio, 385,000 liters of oxygen gas can be stored in a volume of 447.15 liters. The nitrogen gas required will be around 1,833,333 liters of nitrogen gas, or 2641.7 liters (expansion ratio of 1:694 at 20°C).

**Structure**

The cylinders have a radius of 64 m and a height of 21 m, with 8 elevator systems connecting them. Each of the elevator systems consists of 4 elevators, each of length and breadth of 3 m. The Central Core is connected to Torus 1 by 6 spokes, each of length 21 m, height 10 m and a breadth of 20 m.

The cylinders have walls of thickness of 7 cm, where 5 cm of wall is titanium Beta-C and 2 cm is the Zylon composite. Therefore, the volume of the cylinder will be 268,000 cubic meters. The volume of the wall is 2000 cubic meters and the mass of the wall is 9620 tons.

The curved surface area of the cylinder is around 8440 square meters and the volume is 270,000 cubic meters.

The atmosphere inside the cylinders is different. As the industries require as less chemical attack as possible, the atmosphere consists of the noble gas, Argon, and nitrogen. The cylinders have an atmosphere of 58.3 % N2  gas and 41.7% argon gas. According to the ideal gas equation,

the pressure on the walls is 96 kPa, for a temperature of 293 K.

The mass of the atmosphere is 346525 kilograms, with 183382 kilograms of nitrogen gas and 163143 kilograms of argon gas.

The stress on the walls of the cylinder is given by the equation,

Plugging in the values, the stress in the walls is calculated to be 87.7 MPa. This is way below the tensile strength of titanium of around 1250 MPa.

The artificial gravity in this division is almost zero.

### 1.1.3.2 Torus 1

Torus 1 is the innermost torus, surrounding the Central Core and surrounded by Torus 2. It is attached to the inner Core by 8 rectangular spokes for transport of materials and personnel. It is the torus which consists of the artificial-gravity based industry and the first IFR nuclear reactor. Here too, the atmosphere is the same as that of the Central Core, so that the corrosion and oxidation of the metal refining units, among others, can be prevented and the production capacity of the metal refining units is improved when there is less maintenance required.

Torus 1’s industrial activities are primarily focused on artificial-g industry, such as metal refining. The different metals and their respective refining processes will be detailed in Section 5.

The IFR reactor is located here because this is the highest energy consuming division of Gaia. Metals refining, especially of metals like titanium and aluminum, are highly energy intensive.

**Functions and Facilities**

The primary function of Torus 1 is to serve as the industrial sector of Gaia. As mentioned above, it is extremely difficult to operate metal refining units in zero-g environments. The perfect environment for metal refining would be a micro-g region with an inert gas atmosphere, as it would be easier to transport heavy loads, while not having to install large, costly and power consuming centrifuges. The inert gas atmosphere will also not attack the metals or the operating parts. The only disadvantage in this kind of an environment would be the difficulty for humans to operate comfortably. However, most of the industrial processes of Torus 1 can easily be handled by robots, with limited human intervention. The only human activity required will be the maintenance and repair of the robots. Therefore, the aim in this sector, as well as the Central Core, will be to minimize human activities to the maximum extent by automating as many activities as possible.

In the metal refining industry, the metals being refined primarily are iron, aluminum, titanium. Silicon will also be refined on board. Plastics will also be produced in Torus 1. More details on these processes will be mentioned in Section 5.2.

The first IFR reactor is also located in Torus 1 as this is the highest energy consuming division of Gaia. It is estimated that almost two-thirds of the energy consumption on Gaia is by the industry. Therefore, it is vital that the energy source is located as close to the industry as possible. The energy consumption of the torus is high mainly due to the high energy consumption during the refining of titanium and aluminum, chief of them being aluminum. In the Hall-Heroult process, by which alumina is refined to produce aluminum, alumina dissolved in molten cryolite undergoes electrolytic reduction, due to which high amounts of energy are consumed.

Humans will be unable to survive in the event of any accident in the Torus, due to the atmosphere. Therefore, emergency chambers have been constructed in the Torus. There will be 2 chambers on either side of the Torus, with the same specifications as mentioned above in 1.1.3.1.

To prevent carbon dioxide from reaching toxic levels, a series of electrodes, coated with polyanthraquinone, are charged and placed at an exit. The air inside the chambers are frequently circulated through the electrodes. These electrodes react readily with carbon dioxide when charged, while being unreactive with the other components of air. After one cycle of circulation, the electrodes are discharged, releasing the carbon dioxide gas which is removed from the chamber after collection.15

**Structure**

Torus 1 has a major radius of 100 m and a minor radius of 68 m. It has 8 rectangular spokes connecting the Torus 1 with Torus 2. Each of the tunnels are of length 21 m, breadth 20 m and a height of 10 m.

The Torus has a volume of 424,472 cubic meters, with a surface area of 53,060 square meters.

The Torus has an atmosphere composed of 58.3 % N2  gas and 41.7% argon gas, pressurized to 50 kPa, half its value at a temperature of 293 K.

The mass of the atmosphere is 313980 kilograms, with 288300 kilograms of nitrogen gas and 25680 kilograms of argon gas.

The stress on the walls of a torus is given by the sum of the hoop stress and the axial stress as the stress on a wall will be both applied along the radius of the torus and along the length of the wall, i.e. a compressive force. The net stress acting on the walls is equal to their sum, which is equal to,

Assuming a stress of around 100 MPa, the thickness of the wall would come to around 5 cm, with 2 cm being zylon composite and 3 cm being titanium Beta-C alloy.

The volume of the shell is 26,900 cubic meters. The mass of the walls will be 60,300 tons.

This torus has an artificial gravity of 0.2g

### 1.1.3.3 Torus 2

Torus 2 is surrounded by Torus 3 on the outside and surrounds Torus 1 on the inside. It is attached by 10 spokes, which are rectangular. This torus has not one, but three main functions. It contains the food production units, the waste disposal units and the storage sectors. It also houses the Command Center and the main communication station between the habitation torus and the Central Core and Torus 1

Therefore, due to the high load of this torus, the thickness will be 150% of the required thickness, so as to keep a safety margin of around 50%.

This torus is attached to Torus 3, the habitation torus by 10 spokes, and the not the usual 8 is due to the large amount of load transfer. Another reason is for easier flow of electric power to the settlers in the habitation torus.

In this torus, the atmospheric composition is different from that of the Central Core and the Torus 1, due to the growth of plants, along with the permanent human presence required at the Command Center. The atmospheric composition will be briefly mentioned below, with a more detailed explanation in Section 3.1.1.

**Functions and Facilities**

The waste disposal units are mostly used for the extraction of important metals from appliances used by the settlers, the melting of plastic for recasting and the treatment of organic waste. The storage units are positioned next to the waste disposal units so as to reduce the amount of time taken to transport recycled waste or products created from the wastes to the storage sector.

The food production units are one of the most important structures on Gaia. The crops are grown in the food production units using aeroponics. They occupy a very small area for the growth of food sufficient for 30,000 people. Therefore, the food production units have been designed to produce enough food for 45,000 people. The units do not require a lot of resources, but require a lot of human supervision.

Torus 2 also houses the Sabatier Reaction units, where the required methane for a space launch vehicle will be produced. The methane produced will be liquefied for use in a launch vehicle. The water produced will undergo electrolysis to produce oxygen and hydrogen gas. The oxygen produced will be liquefied for use on the space launch vehicles, whereas the hydrogen will be stored in the storage sector for its usage in the industry.

The storage units will be used mainly for the storage of excess food and water, along with the storage of liquefied forms of gases which are components of the atmospheres of the different divisions. The storage units will also store excess scrap metal and plastics.

Food storage will be in low temperature chambers, as a large scale version of vacuum packing and freezing. It will be constructed of aluminum ribbed skin walls of thickness 1 cm. The chambers will have a length of 20 m, breadth of 10 m and a height of 40 m. Due to the combination of techniques, food will not be spoilt and can be stored for extended periods of time, perhaps up to 2 years at a time.

Water will be stored in the liquid form, and not in the solid form of ice. It would seem that any fluid, such as oxygen gas or water, must be stored in a form which occupies as little volume as possible. While this is true, and is applied when storing the atmosphere’s components, this is not applied to water. This is because water tends to increase in volume upon freezing by almost 9% of its initial volume. Therefore, water is stored in the liquid form in aluminum canisters, each of radius 30 cm and a height of 1 m. The water will have to be transported in large quantities in little time. Therefore, to make it easier for transportation, the water is stored in canisters.

The components of the atmosphere are also stored in the storage torus as a backup measure. The amount of gas stored is 10%(by weight) of the atmosphere. The primary components of the atmosphere are argon, nitrogen, oxygen and carbon dioxide. These gases are stored in the liquid form so as to reduce the volume occupied.

**Structure**

Torus 2 has a major radius of 194 m and a minor radius of 104 m. It has 10 spoke-like rectangular tunnels to connect it to Torus 3, the habitation torus. Each of the tunnels have a length of 20 m, breadth of 5 m and a height of 15 m.

The torus has a volume of 6,088,900 cubic meters and a surface area of 267,643 square meters.

The torus has an atmosphere composed of 4% carbon dioxide or 216150 kg of carbon dioxide, 21% of oxygen or 825300 kg of oxygen gas, 5% of water vapor or 110530 kg of water vapor and 70% of nitrogen or 1547430 kg of nitrogen. The total mass of the atmosphere is around 2700 tons. This composition was determined to be the optimal choice of atmospheric composition for a greenhouse.17 As it also has an atmosphere suitable for humans, this particular composition was chosen. The atmosphere is kept at a temperature of 25°C and at a pressure of 50 kPa.

Using the stress equation, and assuming a stress of 120 MPa,

the thickness of the wall comes to 0.065 m or 6.5 cm, with 2 cm composed of Zylon composite and 4.5 cm of Titanium Beta-C alloy.

The mass of the shell comes to around 78390 tons and the volume of the shell is around 133,086 cubic meters.

The artificial gravity in this torus is around 0.5g, using the calculations, which will be mentioned below.

### 1.1.3.4 Torus 3

Torus 3 is the most important division of Gaia, as it acts as the habitation torus. It will consist of 2 halves, along the axis of symmetry along the plane of Gaia. Each half will be identical to the other in terms of buildings and population.

Torus 3 is the outermost torus. The outermost torus acts as the habitation torus, mainly due to the large surface area and the artificial gravity. Artificial gravity at any radius of a rotating body can be calculated using the equation,

where a is the acceleration, or acceleration due to gravity in this case, v is the tangential velocity and r is the radius of the rotating body. Plugging in the values for acceleration and radius, it can be calculated that the required tangential velocity is 75 meters/second. Using the equation for tangential velocity,

Using the values of tangential velocity and radius, it can be calculated that the number of revolutions per minute are around 1.25. This value of angular velocity is in the comfortable range for humans, i.e. below 2 rpm.18 Therefore, little adaptation is required by the settlers.

Gaia’s habitation torus is the largest, as it contains most of the facilities and amenities for the settlers. It contains most of the life support systems, habitation spaces and workspaces.

**Functions and Facilities**

The primary and only function of Torus 3 is to act as a habitation area for the settlers. Therefore, almost all of the life support systems are in this torus. The hospitals, houses and the government’s center are all located in this torus. This torus contains an atmosphere of 79% nitrogen gas and 21% oxygen, like on Earth. The interior of this torus has a large surface area so as to accommodate the life support systems and the habitation spaces of the settlers. The interiors will not be discussed in-depth here. However, it can be expected that the interiors will have to be designed in a manner in which the settlers feel at Earth. Several design aspects are included to make the settlers feel like they are on Earth, such as a torus’s low line of sight (0.3) and the artificial illumination (detailed in Section 3.1.2), among several other.

The life support systems including water purification units, human waste disposal, the humidity control systems and the temperature control systems.

Water purification units are actually used for adding vital salts to the pure water obtained from the various industrial processes, or they are used for the purification of water obtained from the Martian ice caps. The addition of vital salts to pure water is required because pure water is the most hypotonic solution, due to which, the red blood cells are killed by osmosis, where all the cellular material is transferred to the water. Pure water causes internal bleeding and is, at times, highly corrosive as well.19

Human waste disposal consists of disposal of human waste and dead bodies. This is described in detail in .

Humidity control is one of the most vital, yet overlooked, life support systems. Humidity is required by all animals living on the surface, as humidity determines the rate of perspiration, thereby regulating the body’s internal temperatures. However, high humidity is also a problem, as high humidity results in the heat exchange dropping, as the rate of sweating decreases.

The temperature control is also important to maintain the comfort of the settlers and to prevent medical conditions from high temperature or low temperature. The temperature control systems’ actions can be divided into 2 basic functions; heat distribution in Gaia and heat rejection in Gaia. While it will not be that hard to distribute the heat for maintaining a high enough temperature, the heat energy which will not be required will have to be disposed of. This is done in mainly two methods, heat radiation from the outer surface of Gaia (albeit in low quantities), and using liquid droplet radiators. This will be detailed in Section 2.4.

**Structure**

Torus 3 has a major radius of 575 m and a minor radius of 200 m. It has a volume of 268,908,200 cubic meters, almost as big as 20 Boeing Everett factories, the largest in the world. It has a surface area of 2,868,353 square meters.

It has an atmosphere composed of 79% nitrogen gas or 208,756,290 kg and 21% oxygen gas or 63,419,630 kg, therefore resulting in the atmosphere having a mass of 272,175,922 kg. The atmosphere is kept at a pressure of 90 kPa, which is almost 13 times the Armstrong Limit, the lowest pressure the human body can bear. This division is maintained at temperatures between 25°C to 30°C.

Using the stress equation and assuming a stress of 140 MPa,

the thickness of the walls of the torus is found to be around 18.5 cm, where 2 cm is composed of zylon composites and 16.5 cm is composed of the titanium Beta-C alloy.

The mass of the shell comes to around 2,400,000 tons and the volume of the shell is around 1,436,100 cubic meters.

The artificial gravity in this torus is 1g. This can be shown using the equation for centripetal acceleration,

where v is the tangential velocity and r is the minor radius of the torus. It is found that in the habitation torus, the centripetal acceleration or the artificial gravity is 9.81 m/s2..

# 1.2 Power

Power production on Gaia is one of the most important functions. It is estimated that a colony of 30,000 people consumes 1010 GWh per year, including all the industrial activities and the life support systems. Therefore, if 1.5 times the electricity required is produced, the power required by Gaia comes to around 200 MW. After consideration, the Integral Fast Reactor was chosen to be the power source for Gaia. It is a reactor based on two fundamental principles; the neutrons involved in the fission of the metallic fuel(mainly composed of plutonium-239 and uranium-235) are not thermal neutrons, but fast neutrons, and the reactor reprocesses the nuclear waste using electrorefining. It produces 200 MWe and 480 MWth.

**Power Source Selection**

The main power sources which are considered are solar, RTG’s, nuclear fission, nuclear fusion, wind, fossil fuels and biomass. Solar and wind cannot be chosen as the power sources because: 1. Gaia lies in the solar umbra of Mars, where there is no solar energy, and 2. Wind energy is not present in space.

It might be possible in the future that satellite-based solar power can be used as a secondary power source. However, it is not feasible at this point as the wireless power transfer through either cavity magnetrons or klystrons require a large receiving rectenna (covering an area of almost 1.5 square kilometers). The microwave beam is assumed to be of frequency 2.45 GHz and a power intensity of 5 mW/cm2. Another disadvantage of satellite-based solar power is the deviation in the angle of the beam. Considering a satellite solar power station in geostationary altitude. A beam with an angle of 7.2 arc seconds is required to stay within a one kilometer target area if it is to successfully transfer power by means of microwaves.21 This problem is aggravated at larger distances. This will be the main obstacle for the usage of satellite based solar power on Gaia. As Gaia is in the Martian solar umbra, the solar power will have to be obtained from a satellite or constellation of satellites, perhaps at the Mars-Sun L4 or L5 points. These points are at an extremely large distance of almost 228 million kilometers. Controlling the deviation of the beam within a certain angle would be almost possible using today’s technology.

Therefore, potential power sources for Gaia are nuclear fission, nuclear fusion, RTG’s and fossil fuels.

**Fossil Fuels**

Fossil fuels, like coal or oil, are not present on Mars. Although thiophenes, important constituents of crude oil, have been found in trace quantities on Mars, it is likely not oil, but instead kerogen. Therefore, any fossil fuel required for Gaia will have to brought from Earth. It is estimated that 1 ton of coal produces around 2500 kWh of electricity.22 Therefore, large quantities of coal in the hundreds of tons would have to be shipped between Gaia and Earth every month. Along with this, coal produces around 3 kg of carbon dioxide for every kg of coal used in electricity generation. It would be extremely difficult to dispose of the large amounts of carbon dioxide produced. Therefore, it is unfeasible to use fossil fuels as a source of power for Gaia.

**Nuclear Fusion**

Nuclear fusion is an extremely attractive choice as a power source, as it produces a large amount of electricity for a low amount of mass. One of the most common fuels for fusion power, deuterium, is extracted in large quantities by Gaia’s ISRU’s. Hydrogen and Boron-11 fusion reactions are also possible on Gaia, as Mars has boron-11 in large quantities.23 Thus, the availability of fuel is not a problem for the use of nuclear fusion.

At present, there are two main methods for the production of fusion power. Magnetic confinement is one method, where the hot plasma produced as a by-product of heating the fuel at large temperatures is confined using magnets. Tokamaks are an example of nuclear fusion reactors using magnetic confinement. Inertial confinement is a method in which the fuel pellets, generally consisting of tritium and deuterium, are heated and compressed to the size of a pellet.

However, even using the best methods for nuclear fusion, the temperatures required for the fusion reactions to occur are extremely high, requiring around 100 million degrees Celsius. The amount of energy required to start a nuclear fusion reaction is large. The energy required for the fusion reaction exceeds the energy produced, as the power produced is 16 MW at best today for an input of 24 MW. Therefore, for several reasons, primarily the power production deficit, nuclear fusion was not chosen.

At this point, the only options are RTG’s or a nuclear fission reactor. RTG’s, however, produce extremely low amounts of energy. The MMRTG is the RTG which produces the most amount of power at 110 W. RTG’s are also highly inefficient, having an efficiency between 3-7%. Therefore, the final choice is nuclear fission.

**Reactor**

The reactor used in Gaia is an Integral Fast Reactor, which produces 200 MWe and 480 MWth. It uses metallic fuel(U-Pu-Zr), composed of 20% plutonium-239, 67% uranium-235, 10% zirconium and 3% composed of various transuranics such as americium, neptunium and curium. Martian soil has an abundance of Uranium, with a concentration of around 1.9 ppm, with larger concentrations in Utopia Planum.28 The main use of zirconium is to raise the melting point of the fuel, preventing nuclear fuel meltdown.25 The reactor uses fuel rods made of steel cladding. Steel is used instead of zirconium mainly due to the low amount of hydrogen release in the event of loss of coolant.

The reactor requires an initial fissile material of 110 kg. The IFR reactor, initially, uses a fuel assembly in the form of 18 fuel rods and 1 carrier rod, following RBMK Fuel assemblies. It is expected that the IFR reactor will require 180 fuel assemblies per year.

The reactor has a breeding ratio of 1.5 and a large burnup of 68.8 GWd/t. The burnup can be calculated by the formula,

The IFR is highly efficient fuel cycle, where 99.5% of uranium undergoes fission, compared to the 0.65% of Light Water Reactors.27

The IFR uses two nuclear fission reactions,

[[1]](#footnote-1)

**Operation**

The reactor core is placed in a pool of liquid sodium coolant. The pool based design has the advantage of being maintained at normal pressure. Thus, they require low power and low maintenance.

Upon fission, the heat generated is transferred to the first heat exchanger. The heat exchanger is a helical coil heat exchanger, which tends to occupy lower volumes than other heat exchangers with the same efficiency and heat transfer capacities.

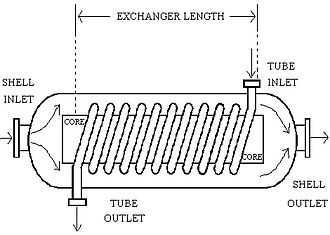


Figure 2. Helical Coil Heat Exchanger

The first heat exchanger includes the intermediate coolant loop to reduce the risk of leakage of water, which would result in an explosive reaction between the liquid sodium and water. In the event the water does get leaked, the explosion would be limited to the heat exchanger and not to the reactor itself. The heat is then transferred to the second heat exchanger, following which the heat is transferred to the turbines. In both the heat exchangers, the fluids flow countercurrent to each other, so as to achieve the maximum efficiency. In countercurrent flow, the heat transfer is maximum due to a higher temperature difference along a fixed length, as compared to either a cross-flow heat exchanger or a parallel-flow heat exchanger.

The turbine system used in the IFR is the combined cycle gas turbine(CCGT). This system uses two turbines, one of which uses the Brayton cycle, while the other uses the Rankine cycle, i.e. one gas turbine cycle, where the gas, an ammonia/water mixture, passes through a compressor, a combustor, and then the turbine, following which, the gas is heated to high temperatures(around 550°C), which then acts as the source of heat for the steam in the second steam turbine(operating the Rankine cycle). The CCGT uses a heat recovery steam generator(HRSG) for this process, which uses a heat exchanger to transfer heat from the first gas turbine to the steam turbine, which then produces the steam.

The CCGT uses a multi-shaft configuration, consisting of 3 gas turbines and 1 steam turbine. The system uses two-stage steam turbines, where the steam is passed through a loop twice, so as to heat it to higher temperatures. It uses high pressures in the steam turbine, therefore increasing the efficiency of the Rankine cycle. Another important aspect of the CCGT is the use of duct burners. Duct burners are used to burn supplementary fuel after the flue gas has left the gas turbine, due to which the temperature of the flue gas is raised by almost 200 to 400°C. Thus, the use of duct burners greatly improves the efficiency of the CCGT.

The CCGT system produces electricity at two points, one at the end of the gas turbine, where the flue gas is used, and another at the end of the steam turbine, where the steam is used.

The electricity generation is dependent on the efficiency of both the Brayton and the Rankine cycles. Therefore, the efficiency of the CCGT can be calculated using the equation,

where ηCC is the overall efficiency of the CCGT system, ηB is the efficiency of the Brayton cycle, i.e. the gas turbine, and ηR is the efficiency of the Rankine cycle, i.e. the steam turbine. The efficiency of the Brayton and Rankine cycles can be calculated by using the following equations.

The gas turbine is maintained at an initial temperature of 299°C(572 K) and a final, output temperature of 650°C(923 K). The efficiency for these temperatures comes to around 62.3%. As waste heat lost to friction is not factored into the calculation, a reasonable efficiency is around 41%.

The steam turbine gives off a heat energy of 61 kJ/mol for 1 mole of water to be converted into steam of temperature 450°C. After the steam passes through and gets condensed in the condenser, it rejects a heat energy of around 43 kJ/mol. Using these, the efficiency of the Rankine cycle can be calculated to be around 41.3%. Adjusting for the heat lost due to friction, the efficiency of the steam turbine can be calculated to be around 32%.

Using both the efficiency values, the total efficiency of the CCGT comes to around 59.8%. This is the biggest advantage of using the CCGT system. If individual cycles were used, the efficiency would have been low, perhaps around 45%, but if the CCGT system is used, the efficiency rises to around 60%.

**Coolant**

The coolant used in the IFR reactor is liquid sodium. Liquid sodium has a high heat capacity of 32.3 J/mol.K, low density and a high boiling point. Although liquid sodium has a slightly lower heat capacity than other liquid metals like lead, the reason sodium is preferred over the other options is due to the low density of sodium results in the coolant having low pressure difference, reducing maintenance costs. Another reason for the usage of sodium is to prevent the usage of water in the reactor’s core. The main advantages of using liquid sodium is to absorb the large amounts of decay Heat, preventing any form of fuel meltdown. However, one disadvantage of using liquid sodium as a coolant is the positive void coefficient. As the void content in the coolant increases, the reactivity increases, making the reactor prone to overheating, which in extreme cases might lead to a core meltdown. To achieve negative void coefficient, technetium is used along with the liquid sodium in small quantities.26 The technetium is readily available as technetium-99 is a fission product of the IFR.

A potential danger of using sodium is its flammability. Thus, the EBR-2, a prototype of the IFR, used an intermediate coolant loop to minimize the risk of the sodium catching fire, which will also be used on the IFR’s aboard Gaia.

The reactor is estimated to be operating at an average temperature of 510°C and the coolant, liquid sodium is maintained around a temperature of 283°C. The coolant can easily be maintained at this temperature as the boiling point of liquid sodium is 882.8°C.

Liquid sodium has a heat transfer coefficient of 4.85 kW/m2.K. Therefore, the heat flux density of the IFR can be calculated using Newton’s Law of Cooling,

where h is the heat transfer coefficient, q is the average heat flux density and ΔT is the difference in temperature between the reactor temperature and the coolant temperature.

Therefore, the average heat flux density between the reactor and the coolant is around 2.425 MW/m2.

**Pyroprocessing and waste disposal**

The disposal of the waste generated in the nuclear core is extremely important, as it would be very difficult to construct containment chambers for the waste generated in the core. Disposal of the waste into space is also not possible, as there is a high probability that the waste might enter into the same halo orbit as Gaia, which might lead to impacts in the future. Therefore, there are two methods in which the waste of the IFR is disposed of; pyroprocessing and disposal of the remaining waste on Mars.

The waste products of the IFR mainly constitute transuranic waste(americium-241 and plutonium-233), uranium-234, noble metals, cesium-135(6%), palladium-107, technetium-99, zirconium-93 and iodine-129. The IFR produces only 5% of the waste generated by a Light Water Reactor.29

Some wastes, like technetium-99 and zirconium-93, are directly used in the IFR. Technetium-99 is an unstable isotope, but can be transmuted to isotopes with a short half-life of 12.3 hours by neutron absorption. Technetium is also useful for reducing the positive void coefficient of the liquid sodium. Therefore, the technetium is added to the IFR directly, which results in a reduction of the void coefficient of the liquid sodium. Zirconium-93 is also useful as a fuel rod cladding, due to which, it is directly separated and used for the fuel rod cladding.

The rest of the waste is made to undergo pyroprocessing, which consists of 3 stages,

Stage 1: Electrorefining

Stage 2: Cathode processing

Stage 3: Injection casting

Electrorefining uses a molten salt electrolyte, composed of lithium chloride, potassium chloride and traces of uranium at 500°C.30 The nuclear waste is introduced into the electrolyte, following which, cadmium chloride salt is added for oxidization of the rare-earth elements and the actinides to their chlorides to enable their transport to the cathodes. After electrolysis, the uranium is deposited onto the solid metal cathode, whereas the plutonium, along with the transuranic waste(including americium-241, neptunium-237 and some amount of curium) are deposited onto the solid aluminum cathode. A solid aluminum cathode is used instead of a cadmium cathode mainly due to the abundance of aluminum. The remaining fission products, mainly cesium-135, palladium-107, zirconium-93, and technetium-99, along with the stainless steel cladding, are present in the electrolyte and are extracted and processed. The technetium-99 is introduced into the liquid sodium coolant pool, the zirconium is transported to the injection casting section, and the other elements are either used on board Gaia, or are stored temporarily for disposal on Mars.

The salt contains several wastes in it, such as the noble metals and the several fission products(excluding rare earths and actinides). The salt is made to react with a Cd-Cu-Li mixture, where the alkali metals, alkaline earth metals and the noble metals are reduced to chlorides. Then, the waste salt undergoes ion exchange with zeolite and then undergoes occlusion at 500°C.30 This results in the chlorides in the salt being reduced from chlorides to their respective alkali metals, alkaline earth metals or noble metals. The atoms of the zeolite turn into either sodium or lithium chlorides as a result of the ion exchange. The sodium or lithium chlorides are then disposed on Mars.

After electrorefining has taken place, the cathodes are removed and the actinides and the rare-earths, which are actually chlorides at this point, are separated out. The cathodes undergo cathode processing, where the cathode is heated in vacuum under high temperatures of around 1200°C.31 The chlorides and cadmium salts are melted, and the cadmium and the chlorine evaporate after a while. The liquid, comprising of uranium, and several other rare earths and other actinides, is distilled and solidified. After this process, the uranium, plutonium and all the actinides and rare-earths are separated out and obtained in the solid form.

In the third stage, the uranium, plutonium and zirconium, along with trace amounts of transuranics like americium, are blended to form the nuclear fuel and are then injected into the fuel rods, which are made of minor amounts of zirconium and steel which has been reprocessed in Stage 1.

As a result of pyroprocessing, the waste which has to be disposed of is in an extremely low quantity, as almost 30 kg of waste has to be disposed of every year, most of which consists of sodium and lithium chlorides, along with non-radioactive material like iodine. Materials like palladium could be used on board Gaia for processes like hydrogenation. Several elements can be re-used on board Gaia. The remaining waste can be disposed of on Mars, using a small area of Martian land, using a combination of dry cask storage in steel cylinders and geologic disposal, burying the waste underground at a depth of around 750 meters at a distance of around 2 km from the ISRU’s.32 It is important that the waste not be disposed of near the Martian polar ice caps. This is done to prevent the radioactive contamination of the ice, which is Gaia’s primary source of water.

# 1.3 Resource management

The several resources present on Gaia need to be stored in a manner in a suitable manner, including those held in reserve.

Therefore, each of the different resources on Gaia are stored in a different manner on Torus 2, where there are several storage units for different storage units, each specialized for the particular resource being stored.

The largest storage units are for the storage of food, air, water, and different materials(comprising of metals, plastic, and so on). Another “resource” being stored in the storage torus is electricity. The different storage units and their function are mentioned below.

## 1.3.1 Food

Food storage can use several techniques, such as canning or salting, to name a few. However, it would be more economical to use techniques which do not rely on using other materials on a large scale, such as salt.

Gaia’s food storage units are low-temperature chambers, maintained at temperatures of -18°C. Food stored at temperatures below -18°C are safer, as most microbes tend to become more active above this temperature.33 This mainly takes place as any residual moisture in the food is turned into ice, depriving any microbes of water. The food is frozen by initially passing the food through large mechanical freezers, where ammonia is passed through the vents, acting as a refrigerant. The heat is transferred to the ammonia and then to the condenser, where the heat is dissipated in the form of heat of condensation. The ammonia is then passed through an expansion valve, where it is vaporized, following which the gas can be re-introduced into the cycle.34

A food storage chamber on board Gaia has a length of 20 m, breadth of 10 m and a height of 40 m. The walls are made of aluminum ribbed skin(thickness of 1 cm). The main advantage of vacuum storage, like in the hermetic chambers, is that anaerobic bacteria cannot decompose the food in this environment. The individual foods are stored in vacuum packing. The food storage units use thermoforming vacuum packaging. The food is stored in large vacuum bags, made of the polymer polyvinylidene chloride(PVDC). The effectiveness of the vacuum bags can be measured using the shelf life and the permeability of air per square meter of material in one day. PVDC allows almost 10 cc of oxygen to permeate.35

It is estimated that the shelf life of food stored in these chambers will be around 2 years. If techniques like freezing are used alone, the shelf life of the food might have been 6 months. However, the combination of these techniques proves to be highly effective, extending its shelf life by almost 4 times.36

## 1.3.2 Water

Water is one of the most important resources on board Gaia. Its storage process is vital, as materials such as sodium chloride cannot be introduced to enable the storage of water at lower temperatures.

Water cannot be stored in the form of ice due to the anomalous expansion of water and the high heat of fusion(333.55 J/g). Due to these factors, it makes sense that the water on board Gaia is stored in the liquid form.

Water is stored in the liquid form at a temperature of 3.98°C, as water has the least density, and therefore, the least volume at this temperature. The water is stored in the form of stainless steel containers, with a thickness of 0.5 cm.

## 1.3.3 Atmosphere

10% by weight of the air of Gaia is stored as a reserve in Torus 2. The air stored consists of 70% nitrogen, 20% oxygen and 10% carbon dioxide. In the event of an accident in a section of Gaia, the gases(at this stage in a liquid form) are transported to that particular sector and introduced into the atmosphere using the atmospheric control systems of that sector, where the liquids are passed through a heat exchanger, which receives stored heat from the local TES(Thermal energy storage) system. The TES system uses molten silicon to store heat, as 1 MWh of heat energy per cubic meter of molten silicon, when the temperature is maintained at 1400°C.37 The TES system uses a combined heat and power(CHP) output system, which is activated only in case of an accident. The advantage of using a CHP system is that the heat energy can be released for the temperature maintenance of the sector, along with providing electricity in lower quantities and the heat required to vaporize the liquid form of gases.

The obvious method for the storage of the gases is liquefaction. The volume reduced after the liquefaction of these gases is large. This is seen by taking the example of oxygen. Oxygen has an expansion ratio of 1:861, meaning that 861 cubic meters of oxygen gas when liquefied occupies just 1 cubic meter. Therefore, it becomes obvious that storage of the gases must be in the liquid form. An exception for this is carbon dioxide, which will be stored in the form of dry ice

As it is required for gases to be liquefied in order to be stored, the storage sector also contains a liquefaction/deposition plant. The liquefaction process uses the Linde cycle to liquefy the gases. The Siemens cycle is not preferred over the Linde Cycle so as to remove the usage of moving parts.

The Linde Cycle uses the Joule-Thompson effect to cool the gases as it moves from a region of low pressure to high pressure. The Joule-Thompson coefficient is used to determine the temperature variation for a particular change in pressure. The coefficient determines when the gas starts to cool upon expansion, thereby determining the change in pressure required for the liquefaction of the gas. The temperature at which the sign of the coefficient changes is the temperature at which the gas begins to cool on expansion. This temperature is known as the inversion temperature.

Using the equation,

where µ stands for the coefficient, α stands for coefficient of thermal expansion of the gas and CP stands for the specific heat capacity of the gas.

Using this, it is determined that the inversion temperature of oxygen gas is 491°C, 348°C for nitrogen gas and 1227°C for carbon dioxide, at an enthalpy of 30.8 kJ per kg.

During the liquefaction, the gases are compressed to a pressure of around 50 atm. Then, the gas is cooled by passing it through pipes surrounded by brine at 10°C.The gas is cooled again using heat exchangers, using countercurrent techniques , similar to those used on the IFR nuclear reactors. Then, the gases are allowed to expand, following which a portion of the gases are liquefied. Note that a portion is liquefied and not the whole gas, due to which the gases are passed through the process again for several cycles. It is estimated that the liquefaction of 20 liters of nitrogen gas would take an hour.

The same process is used in the conversion of carbon dioxide to dry ice. The carbon dioxide is liquefied, following which, some of the liquid CO2 is allowed to vaporize, due to which, there is rapid cooling, causing the liquid to solidify into dry ice. Calculating the heat of vaporization, almost 570 kJ of heat energy is absorbed by 1 kg of liquid CO2.

The liquefied gases and the dry ice are stored at a temperature of -20°C. As the temperature is too high for the maintenance of the liquid stage of the gases, the pressure of the containers is just above the critical pressure of nitrogen, which requires the maximum amount of pressure for liquefaction. The critical pressure is calculated by the equation,

where a and b are the Van der Waals constants, in this case 1.37 and 0.0387, respectively. The critical pressure of nitrogen, and thus the pressure of the container comes to around 85.6 MPa. Therefore, the containers need to extremely durable and strong to withstand the pressure, due to which the containers are made of the Titanium Beta-C alloy used in the walls of Gaia.

## 1.3.4 Power

The electricity generated by the IFR’s is not completely used. Around 15 MW out of the 200 MW generated by the IFR is stored in reserve. The storage of this reserve power is vital as this will be the source of power in the event of accident, along with smaller CHP-utilizing TES systems mentioned above. The power storage units will be in both Torus 3 and Torus 2, as these sectors contain the vital life support systems, along with the reserve food, air and water.

Power storage can use several techniques, including mechanical storage, generally by Compressed air energy storage(CAES). CAES uses energy to compress air, after which, it is stored. The air is then released into a combustor, where the exhaust is used to generate electricity. However, this technique would be difficult to implement on Gaia. Using CAES as an energy storage method would result in large amounts of air being wasted. Another disadvantage of CAES is the large volumes of gases and the low efficiency of the power storage.

Another technique which can be considered is the hydrogen storage system. In the hydrogen storage system, hydrogen gas is liquefied, using electricity in the electrolysis of water. The hydrogen is then liquefied and stored at low temperatures. When the electricity has to be used, the hydrogen is used in a hydrogen fuel cell, which is releases energy to power an electricity generator(a CCGT system). However, hydrogen liquefaction is extremely difficult as the liquefaction point is extremely low(-252.882°C). Another obstacle would be the power deficit of this method of storage compared to other methods. The production of 1 kg of hydrogen using electrolysis requires 52.5 kWh, whereas the use of 1 kg of hydrogen in a hydrogen fuel releases around 39 kWh of electricity. Thus, almost 13.5 kWh of electricity is lost per kg, or a loss percentage of almost of 25.7%. Therefore, this form of storage is clearly infeasible.

The two other methods considered are the Thermal Energy Storage and supercapacitors. Thermal Energy Storage systems use the electricity which needs to be stored to melt salts. The molten salts are maintained at a fixed temperature above their melting point. When electricity needs to be obtained, the molten salts are passed over a steam generator(along with other heat sources), to produce super-heated system for a steam turbine. This method can be used on board Gaia so as to act as a small scale heat disposal unit, an important component of the emergency atmospheric support system(see 1.3.3), as well as providing a method to dispose of the salts produced in the ion-exchange process with zeolite in the IFR waste processing systems(see 1.2, pyroprocessing). The only disadvantage of this method is the inefficiency in the steam turbine. Thus, this is not Gaia’s primary energy storage system, but is instead used for secondary storage of power, which is used in events of emergency.

The primary method of power storage onboard Gaia is the use of supercapacitors, more specifically, a Lithium-ion hybrid capacitor(LIC). A Lithium-ion hybrid capacitor is called so because the anode of the capacitor is that of a lithium-ion battery, whereas the cathode is that of a double-layer capacitor. Lithium-ion capacitors have one of the highest discharge energy densities(55 Wh/kg), as well as the one of the highest specific energies(20 Wh/kg).38 The capacitor consists of pre-lithiated(lithium-doped) graphite anode and an activated carbon cathode, having a potential difference of 3.8 V, with a lithium-ion salt being used as the electrolyte. The capacitor is maintained at a temperature of 60°C. The capacitor is maintained at a higher temperature to increase the power density of the capacitor, as the electrolytic resistance decreases at higher temperatures. The capacitance is around 3300 F.39

The energy stored on one Lithium-ion capacitor can be calculated by,

where U is the energy stored, C is the capacitance, and V is the voltage. Using the equation, the energy stored by one capacitor comes to around 6.7 Wh/ capacitor. As the weight of one capacitor is estimated to be around 350 g, the energy density of the capacitor matches with the value for the energy stored by one capacitor.39

Almost 15 MW of reserve power has to be stored, or 131,400 MWh of energy per year. Taking the energy density of the lithium ion capacitor, along with the mass and approximate volume of each capacitor, the area to be occupied by the storage units comes to around 20,000 square meters, with a height of 10 meters. However, the storage units are not concentrated in only one torus. The power storage units are located mainly in Tori 3 and 2, with smaller storage units in Torus 1 and in the central core.

#### Section 2

Operations

Gaia’s operations are vast and complex, ranging from stationkeeping to communication. These operations will be managed by different units, each decentralized, but reporting to a central hub. The operations described are not only those conducted onboard, but also include operations between Earth and Gaia. Several support structures of Gaia, such as the communication satellites at the Martian orbit, which are gravitationally locked with the Sun, are detailed, along with the stationkeeping methods and the inertial navigation systems on board.

# 2.1 Transportation

Transportation is one of the most important operations of Gaia, as Gaia’s survival depends on transportation between Earth and Gaia initially, followed by transport between the Martian surface and Gaia, later. Another important aspect of transportation on Gaia will be the transportation on board Gaia.

## 2.1.1 On Gaia

It would be impossible to use fossil-fuel based transportation structures on Gaia, mainly due to the lack of fossil fuels and the large amount of exhaust fumes produced. Therefore, it is obvious that the transportation system on board Gaia will have to powered with electricity.

Several systems were considered, including electric cars and personal rapid transit systems.

Electric cars, more specifically, electric autonomous cars, are one option for transport on board Gaia. The electric production of Gaia is sufficient for operating such a vast network of cars. Along with the electric production, the material for the batteries of the cars are also readily available. The Tesla Model S uses lithium-ion batteries, with lithium cobalt oxide as a cathode and silicon-treated graphite as an anode.40 These materials are produced by Gaia in large quantities, with lithium, cobalt and carbon easily available on Mars. However, Gaia will need to have a much larger surface area for building the required larger roads and charger stations. The use of electric cars would also result in a larger metal requirement, which will be larger than the current metal production capacity. The electricity requirement would also increase by around 20 MW.

The Personal Transit System consumes low amounts of electricity, requires less metal and is a personal public transport system, whereby a passenger can use a podcar to customize their route and destination, using the system as a personal transportation system.

The Personal Transit System is completely automated, with each PRT vehicle being around 0.374 m long, 0.21 m wide and 0.25 m high.41 A single PRT vehicle has the capacity of 2 passengers, with provisions for 2 extra passengers, albeit at slightly lower levels of comfort. Each PRT has a load capacity of 2500 kg, with an average speed of 70 kmph, and a deceleration of 4.9 m/s2. The individual PRT vehicles are made of aluminum matrix composites, preferably in combination with titanium. The PRT vehicles use linear induction motors for forward propulsion, with the power source being the lineside conductors. Linear induction motors use a flat magnetic core, with coils on each side, where the coils give alternating polarity, generating an alternate polarity magnetic field. The PRT’s are also provided with small lithium-cobalt batteries as a backup energy source. Lithium-cobalt batteries have the highest energy density of 1.04 MJ/kg. This energy, while not sufficient for longer durations of transport, is useful for shorter durations. This will be mainly be used in the event of a breakdown, providing just enough energy to move the PRT vehicle to the nearest station.

The Personal Transit System uses a guideway system, running in the center of roads, with the sides of the road left as large sideways, with 2 cycle tracks on the extreme ends of the roads. The transportation system of Gaia is designed in such a manner that each section is divided into rectangular blocks, with each street of a block having one stations at one of the ends. The stations are expected to be small, occupying an area of 75 square meters.

The headway between two PRT vehicles will be 2 seconds. The headway time is important as it determines the maximum number of people on a line. A Personal Transit System line with a PRT vehicle headway of 2 seconds and a capacity of 4 people has the capability of transporting 7,200 passengers per hour, which is almost 2.6 times higher than the average road’s capacity of 2,700 passengers per hour.42

## 2.1.2 With Earth and the Martian surface

Gaia uses a launch vehicle modeled on the SpaceX Starship as its primary workhorse. The launch vehicles for transportation between Earth and Gaia, along with transportation between Gaia and Mars, use the same launch vehicle. This is mainly due to the extremely low costs of around $2 million. Comparing this to other super-heavy-lift launch vehicles, the SpaceX Starship has a cost almost anywhere between 25 to 450 times less than launch vehicles like the under-development SLS Block 2 or the GSLV Mk III. It also has the highest payload capacities to Trans-Mars injection of around 150 tons, whereas the SLS Block 2 has an expected capacity of 45 tons.

The GTV is a fully reusable super heavy-lift launch vehicle, with a cost ranging between $1.5 million to $2 million, for Gaia-Mars transport and Gaia-Earth transport, respectively.43 The slightly lower cost of the Gaia-Mars transport launch vehicle is due to the lower number of rocket engines(24) compared to the Gaia-Earth transport vehicle with a higher number of engines(34). Apart from the difference in number of engines, the two launch vehicles are similar in all other aspects.

The GTV has a payload capacity of 100 tons between Earth and Gaia and 150 tons between Mars and Gaia. The GTV has a total mass, including the first and second stage, of 5000 tons. The GTV has a height of 100 m, with a mass of 5,000,000 kg. The crew of the GEV will be around 25 people, with a habitable space of around 900 cubic meters. The private quarters of the crew are instead modified into a solar storm shelter, resulting in around 200 cubic meters of habitable space being used more efficiently.

The GTV is a TSTO launch vehicle, where the two stages, the first and the second stages have 29 engines and 5 engines, and 19 engines and 5 engines, in the Gaia-Earth transport vehicle, and Gaia-Mars transport vehicle, respectively. The two stages have a specific impulse of 330 seconds and 380 seconds respectively.43 1 rocket engine of the GTV can produce a thrust of 2 MN. Therefore, the thrust of the GEV will be around 68 MN, whereas the thrust of the GMV will be around 48 MN.

**Orbital refueling, aerobraking and heat shields**

The GEV uses orbital refueling using tankers at LEO during transport from Earth to Mars, and at the LMO for a mission from Mars to Earth. If orbital refueling is skipped, the GEV will require not two, but three stages for transporting the same amount of payload, also requiring almost 7.5 times the cost. There are different refueling configurations for Earth and Mars. Earth origin missions use 4 full tankers, which are smaller versions of the Starship. It is estimated that the payload of 4 smaller Starships is sufficient for the complete refueling of the GEV. With Mars-origin missions, 3 tankers are used for the refueling of the GEV. The reason for the difference in the number of tankers is due to the larger gravity well of Earth when compared to Mars, along with the lower amounts of fuel required for retropropulsion during landing on Mars compared to Earth due to aerobraking. This particular amount of refueling results in the delta-v of the GEV being equal to 6.4 km/s for a payload of 150 tons.44 This figure is far above the delta-v required for launch vehicle transfer between Earth and Gaia is 6.2 km/s.45 It is to be noted that refueling is not required for the GMV.

The GTV uses aerobraking upon entry into the Martian atmosphere. Aerobraking results in the amount of fuel required for landing being reduced by 50%. The vehicle is expected to experience a drag force of around 49 N and a temperature of 170°C.43,45 While the aerobraking might decelerate the vehicle, the temperatures also need to be accounted for. The thermal protection systems for the GTV will have to be powerful for the heat experienced during aerobraking and re-entry will be extremely high(up to 1700°C). PICA is used for the heat shield for the GTV, which consists of carbon fibers impregnated with phenolic resin. It has a low density and a capability to handle high heat flux. It is known to be able to withstand mission re-entry into Earth at 12.7 km/s, where it can withstand a high heat flux up to 1.2 kW/cm2. PICA can withstand temperatures of as much as 1850°C.50 The only disadvantage is a slight loss in re-usability, as the heat shield has to replaced frequently, perhaps once every two missions. However, due to the ready availability of carbon and methane on Mars, the essential materials required for the production of PICA, the cost of replacing the shield is reduced by a large factor.

**Fuel and burn operations**

The fuel used on board is a liquid CH4/LOX mixture, with around 240 tons of CH4 and 860 tons of liquid oxygen.43 The methane is maintained at a temperature of around -177°C, just below the condensation point of liquid methane. They are maintained at a slightly lower temperature, mainly because the density increases by about 10-12%.43

The main reason methane is used over other propellants like RP-1 or hydrogen is due to availability, ease of storage and higher density. Methane has a higher specific impulse than RP-1 of almost 10 s. It is also possible to obtain methane on Mars using the Sabatier reaction, utilizing the millions of tons of water and carbon dioxide on Mars, whereas there is no kerosene on Mars. Methane has a lower density as well as a lower liquefaction point than RP-1 and liquid hydrogen. Another advantage of using liquid methane is the re-usability of the methane. Methane does not embrittle or react with the engines, whereas liquid hydrogen embrittles metals by mechanisms like hydrogen-induced cracking(HIC), where the adsorbed hydrogen try to recombine, reducing the steel’s ductility, or hydrogen-enhanced decohesion, where the hydrogen atoms reacting at points of high stress, such as those in the injectors, lead to weakening at those points, causing fracture. Therefore, engines using methane are more re-usable than engines using liquid hydrogen.

The GTV will use 3 sea-level pressure optimized engines and 3 vacuum-optimized engines. The primary difference between the engines is their pressure, which is obvious. The result of the difference in pressure is the specific impulse and the thrust. Sea-level optimized engines are at a higher pressure, but provide a lower expansion ratio of 40, a thrust of 3050 kN and a specific impulse of 334 s, whereas the vacuum-optimized engines have a lower pressure, but provide a higher expansion ratio of 200, a thrust of 3500 kN and a specific impulse of 382 s.

Using the equation,

where ΔT is the time for which the rocket burns on Earth, M is the gross mass of the rocket, E is the exhaust velocity, F is the thrust for the rocket, and ΔV is the delta-v of the rocket.47 Considering a gross mass of 3.53 million kg, an average exhaust velocity of 3034 m/s, thrust of 62 MN for the first stage and 6 MN for the second stage, and a delta-v of 6.4 km/s, we get a burn time of 136.18+611.07 seconds of burn time.

**Radiation protection**

The radiation levels experienced by a Mars mission of 120 days is around 131 mSv, compared to the 6.6 mSv acceptable for the same duration.48 The main sources of the radiation are solar particle events(SPE). Solar particle events consist mainly of protons, with small quantities of helium ions and a smaller quantity of high-Z ions. Protons can be easily deflected by low-Z material with high hydrogen content, due to the high amount of deflection when the proton encounters hydrogen nuclei. The liquid methane on board the GTV’s could act as good radiation shields. Therefore, the GTV is set in a longitudinal axis away from the sun, i.e. in the windward side direction of the radiation. This results in the liquid methane tank providing the GTV with a measure of protection from the solar radiation. Another measure taken is to reduce the travel time of the mission for humans from an average of 7 months to 4 months, using ballistic capture over a Hohmann transfer orbit (see below). Along with these two measures, there is a large solar storm shelter for up to 20 people for a short duration of time.

**Mission path**

The missions to Mars follow different trajectories based on their function. A payload delivery mission without humans follows the ballistic capture method, whereas the human missions between Earth and Mars will use conjunction-class trajectories.

The main factors which are considered in the two types of missions are; mission time and exposure to radiation for human missions, and window for transit to Mars and fuel costs for supply and cargo missions.

Based on these, it makes sense for a human mission to send humans in the shortest time possible, as it also reduces radiation exposure. This type of a mission can be achieved via a conjunction-class mission. However, the only disadvantage of a conjunction-class mission is the window of time during which the launches will have to be made. This problem can be easily solved by sending large numbers of people on numerous missions during the launch windows. Opposition-class missions are not considered due to the Venus swing-by, taking large amounts of time to transport from Earth to Mars(around 360 days just for the swing-by), along with exposing humans on board to large amount of intense radiation exposure, primarily from the Sun. The main requirement of the cargo and supply missions is the ability to be launched at any time, instead of waiting for a window of opportunity. This is especially important in cases where resupply of essential items from Earth are required, such as medical supplies. Therefore, ballistic capture is used for such missions.

Cargo and supply missions use the ballistic capture method for the mission trajectory. Ballistic captures generally tend to occur in regions called weak stability boundaries. In ballistic captures, the GTV is inserted into the planet’s orbit, enabling the planet to capture the spacecraft using its gravity. Thus, insertion burns are not required, reducing fuel costs. Another advantage is that the insertion of a spacecraft into Mars’ orbit can be done at any time, without having to wait for a window during conjunction. Thus, this enables more cargo to be transported at any time.

The ballistic capture point chosen is at a distance of 23 million km from Mars in its orbit, to where a spacecraft can be launched at any time from Earth. Mars requires 11 days to meet with the spacecraft after the GTV has been inserted into Mars orbit. Two burns are performed by the GTV, once on Earth, i.e. VE, and another time during insertion into the orbit, VI. The captures are expected to take place when the spacecraft are at a distance of 49,900 km from Mars. For this distance, the velocity for the insertion burn can be calculated,

where V is the approach velocity(3.4 km/s), µ is the gravitation parameter of Mars, r is the distance between Mars and the spacecraft during insertion (49,900 km), and e is the eccentricity of Mars orbit(0.09341).51 Using these values, the insertion delta-v comes to around 2.116 km/s.

The ballistic capture orbit is elliptical, with an eccentricity of 0.99 and the spacecraft is at a distance of 49,900 km from Mars during orbit.

The time for transfer can be easily calculated, using Kepler’s third law.

where P is the transfer period, a is the average distance between the spacecraft and the sun(as Mars follows a heliocentric orbit, the insertion orbit does as well), and GM is the standard gravitational parameter. According to these calculations, the time duration comes to around 433 days for transfer from Earth to Mars, including the 11 days for landing on Mars after capture into the orbit.

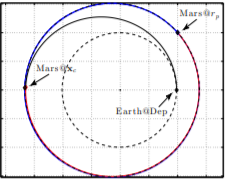


Figure 3 Ballistic Capture Orbit

The second type of mission is a human mission. Human missions use conjunction-class trajectories, which reduce travel time to around 100 days between Earth and Mars and vice-versa. The conjunction trajectories follow a simple direct transfer of the spacecraft to the orbit of Mars during the Earth-Mars conjunction, at which Earth is farthest from Mars. The human GTV missions use the semi-direct conjunction-class trajectories, where a direct docking with Gaia is involved after orbiting Mars once. The capture orbit around Mars, where the GTV orbits before docking with Gaia, is at a distance of 300 km from Mars’ surface. The ΔV for the capture burn can be calculated using,

where V is the velocity at infinity in the transfer orbit’s hyperbola (2.8 km/s), µ is the gravitational parameter of Mars, and r is the periapsis radius above the surface of Mars(350 km). For a human mission to arrive in 130 days, the departure ΔV comes to around 5.11 km/s. The Mars approach velocity will 9.7 km/s.52 As the approach velocity is slightly more than normal supply missions, the GEV will require slightly more fuel than other rockets.

The extra fuel required can be calculated using the rocket thrust equation,

where F is the force required(2904 kN, for an acceleration of 2.2 m/s2 and a burn time of 1000 seconds), m is the mass flow rate, V is the exhaust velocity(3034 m/s), pe and po are the exit pressure(say, 0.1 MPa) and free stream pressure(equal to exit pressure, 0.1 MPa), and A is the area of the exit of the exhaust(64 square meters, for a diameter of 9 meters). The mass flow rate comes to around 43.6 kg/s. Therefore, the amount of fuel mass required is around 43600 kg or 43.6 tons, which can be easily resupplied by a single GTV in half capacity.

It is to be noted that VASIMR is not used as it has not yet been developed completely yet, with its maximum power present right now being 200 kW. However, this technology might be used in the future after development.

# 2.2 Maintenance

Maintenance on board Gaia primarily consists of external repairs and damage control. The main reason for repairs to be conducted are due to micrometeorite impact and air leaks. The internal maintenance is mainly for pressure maintenance and repair of internal structures.

The external surface of Gaia will face relatively low amounts of solid impacts from meteoroids or asteroids, and no space debris impact. The space debris around Mars is almost nil. As there have been few human missions to Mars, the debris/defunct orbiters or satellites are in extremely low numbers, with all of them being found within 500 km from the Martian surface, whereas Gaia is at around 980,000 km from Mars. At this distance, the probability of impact by larger meteoroids increases, with an average influx of meteoroids (sizes between than 3 mm and 7 cm) at rates around 3,000 tons per year at a distance of 50,000 km from Mars.53 It is to be noted that this is for the entire circumference at this distance. A rough estimate for Gaia would be around 40 tons per year. The figure will be even lower as the number of meteoroids in the umbra of Mars decrease due to Mars, which will act as a shield of sorts. This figure is extremely low compared to Earth’s estimate of around 40,000 tons per year. The thickness of Gaia’s walls is also thick enough to prevent rupture of the walls. The average pressure exerted by a meteoroid of a diameter of 5 cm, approaching at a velocity of 20 km/s is around 4 kPa, which is much lower than the modulus of rupture for 1.3 MPa need to tear through 7 cm of titanium. Therefore, the threat of meteoroids is not high.

However, there is a small probability of larger meteoroids (sizes of 50 cm to 3m) striking Gaia. In the event of such an impact, it is highly likely that the large rupture will cause air leaks. The air leaks could result in pressure loss and cause large amounts of damage to not only the settlers but also to the interior’s structures.

For such events, the external maintenance teams will always have telemanipulators at close proximity to all the airlocks. Upon any impact, the telemanipulators can be instantly deployed to the exterior, where one of them will survey the damage, whereas another robot will move along the external surface for repairs. Only in the event of large scale impact will humans be sent out for repair operations.

The telemanipulators are small, mobile robots, which are three-armed. They have a mass of around 200 kg, with large arms of around 3 m. The robots move on the surface using Van der Waals forces between the “feet” of the robots and the external surface of Gaia. This is achieved through covering the lower surface of the robots with tiny bristles of radius of around 2.5 µm, numbering around 300,000 in number. As a result of the Van der Waals forces, the small bristles have a weak electrostatic repulsive force of sorts, mainly due to the polarization caused between the molecules. The surface of Gaia provides an amplifying factor of sort for this force due to the higher amount of electrons polarizing the surface of Gaia, where the electrons come from the electron radiation. The Van der Waals force provides a repulsive force, acting opposite to the direction of motion of the robots, thereby acting as a weaker form of friction, to provide a rough analogy. The robots communicate with the controllers from the interior, using the repeater network on the external surface of Gaia, which are partially embedded in the walls of Gaia, and are covered with polyethylene to prevent radiation interference. The repeaters used are microwave relays, 4 of which are used, at 4 equidistant points on the circumference of Gaia. They operate at frequency bands between 50 and 60 GHz, using the plesiochronous digital hierarchy to transport large amounts of data at once to the different controllers within a specified radius to be decided during operations.

The next major maintenance operation is the air leak and pressure control. Air leaks mostly occur due to the impact of meteoroids. Although the damage due to the meteoroid impact can be repaired within an hour or so at best, the damage which will be caused will have to bed reduced. The primary damage which will occur during the impact of meteoroids is due to the air leaks. After an impact has been detected, all settlers will be immediately evacuated. After the evacuation of settlers, maintenance teams will send in drones to assess damage, so as to prepare the number of people required as well as to estimate the material required. The teams, while moving in to repair will always have on their person oxygen and nitrogen tanks, sufficient for 4 hours. They will also wear pressurized suits, similar to EVA suits, to account for pressure drop. However, the pressure drop is not anticipated to be high. This is because several air leaks on board the ISS, which has a wall thickness of 0.25 cm, have not had a significant pressure change. The change in pressure during the 2004 air leak on board the ISS resulted in a pressure drop of 4.8 kPa. Gaia has far more thick walls, preventing the rupture from increasing in size by large factors. Thus, the pressure suits are only a safety precaution.

There will evidently be far more maintenance issues on board Gaia. However, the most common and threatening dangers have been described here. As a method of prevention and civilian responsibility, all the settlers will undergo basic maintenance training for 1 month, with mandatory active service in the maintenance team for 3 months.

# 2.3 Communication

Communication systems are an integral part of Gaia, as they are responsible for connecting Gaia from within and connecting it to the outside world, mainly Earth and in the future, with settlements beyond Mars. Gaia’s external communication systems have to factor in the Earth-Mars conjunction as well, as the disabling of communication systems once every 780 days, for a month or so at a time, might lead to complications in Earth-Mars missions, along with making it impossible for Gaia to request for aid during times of emergency. Therefore, a method for preventing this is also detailed. The internal communication systems are primarily used for providing internet connections to the settlers, along with acting as a means of communication between the different sections of Gaia.

The internal communication systems use fiber-optic communication, using light pulses, with a frequency comb as the laser source, where the laser is stabilized using a pulse train. It uses a chip-based feedback loop, to fix the repetition rate of the laser to a particular frequency. The internal communication systems have high rates of data transfer of around 7.7 Tbit/s.

The external communication systems use communication satellites placed at a Mars orbit, detailed below, instead of being placed at the Mars-Sun L4 or L5 points. The two reasons for this are that a communication satellite placed at the L4 or L5 points would be at a distance of around 228 million kilometers from Mars. According to the inverse square law for the strength of the communication pulses, the strength would be a small fraction of the strength of a satellite in Mars orbit. The second reason is due to the Trojan asteroids at the Mars L4 or L5 points, which might lead to collisions between the communication satellites and the asteroids. The communication satellites use the LCRD technology, which has a data transfer rate(both uplink and downlink) of 2.88 Gbit/s. While this is a substantial decrease in the data transfer rate on Earth, it is sufficient for the settlers, as will be seen below. The LCRD uses a 2+2 configuration of differential phase shift keying modems and pulse position modulation, which will be detailed below. Each of the satellites have a mass of around 175 kg. The ground stations on Earth for the communication systems will be in 3 locations around the world, such that the communication ability is always present, without the need for another satellite at the Earth-Moon L2 point.

## 2.3.1 Internal Communication Systems

The internal communication systems of Gaia are decentralized and all primary components, excluding the cables for communication, are placed in a 2N configuration, with the mirror component always being on stand-by, to enable immediate active usage during breakdown of the primary component.

The communication systems are decentralized to as large an extent as possible, with all the communications on board passing through the communication hub in Torus 3. However, the 2N configuration enables the communication systems to still operate at normal rates even in the event of a breakdown in the communication hub, thereby achieving the dual purpose of decentralization as well as enabling control over the flow of data.

The internal communications systems consist of optical fiber systems, with the source of light being a frequency comb, using an AlGaAsOI nano waveguide. The optical fiber cables use four wave mixing, where the light generated by the mode-locked laser are mixed using four wave mixing. Four wave mixing is a process where light of three frequencies interact with each other to produce a fourth wave with higher frequency and more data transfer rates. The use of four wave mixing is the reason for the usage of the nano waveguide, as it increases the efficiency of the mixing process.54

The cables use wavelength division multiplexing, where the light generated by the laser is multiplexed into a single wavelength. The reason for WDM to be used on board Gaia is due to the space and material constraints. As it would require large amounts of material to construct a two-way optical communication system, WDM is used to enable two-directional communication, along with increasing the capacity of data transfer by almost 12%. The WDM used has the capacity to handle an input of 160 signals, resulting in a large increase in the data transfer rate, by a factor of almost 2000.55 The input light for the WDM’s are of wavelengths 1530 and 1560 nm. These wavelengths, while unsuitable for a glass fiber optic communication system, are within the absorption bands for a single mode fiber-optic cable, used on board Gaia, mainly due to the material factor.

The laser used is a titanium-sapphire laser. The laser uses sapphire(Al2O3) doped with titanium ions as the lasing medium. The main reason for their use is due to their ability to generate pulses of the required wavelength at a low power consumption of around 90 mW. The pulses produced are of a 5 GHz repetition rate with pulses operating at a length of 1 picosecond.

This mode of data transfer inside Gaia has a high data transfer rate, carrying around 7.7 Tbit/s. If we consider an average of 15 searches per day per person, a settlement of 30,000, with a potential capacity for another 5,000 people, would conduct around 525,000 searches per day.56 Considering the average website size of 4 MB, the total amount of data transfer comes to around 200 Mbit/s. The other uses for the internal communication system are the industrial co-ordination or the communication between the settlers of Gaia.

## 2.3.2 External Communication Systems

The external communication systems utilize communication satellites to communicate with Earth, and in the future, with other human settlements on the Moon or beyond the asteroid belt. An important factor to be considered during the design of the external communication system is the Earth-Mars conjunction. During the conjunction, it is not possible for communication between Earth and Mars to take place. As this occurs once every 780 days, lasting for one month, the lack of communication between Earth and Gaia during this time might be harmful, as certain materials have to be procured from Earth, and in the event of a catastrophic event on board Gaia, which has resulted in irreversible damage, the evacuation of the settlers will prove to be a difficult challenge. Communication between Gaia and Earth is also necessary for the economy, as Gaia’s exports and imports from Earth will be severely curbed in the event of a lack of communication.

### 2.3.2.1 Comsats

Communication satellites, or comsats, are used to enable communication between Gaia and Earth. NASA’s LCRD communication setup is used on board the comsats. The comsats are placed at an orbit around Mars, with an orbit around the Sun, having the same period as Mars, except for the eccentricity of the Martian orbit. The orbit of the comsats has an eccentricity of 0.05, and completes one orbit around Mars on one Martian year.57 This type of an orbit is generally stable, as the perturbations caused by the Mars’ gravity tend to be cancelled out. This is because the comsats has a heliocentric orbit, resulting in Mars gravity being cancelled out by the Sun. Such an orbit would result in an alternative lead/trail between the satellite and Mars, where the satellite is initially ahead of Mars, but as it progresses on the orbit, it gradually begins to trail Mars’ orbit.57 This kind of an orbit is suitable for Gaia as the comsats have high stability and avoid the problems which they would have faced in the Mars-Sun L4 or L5 points due to the Trojan asteroids. However, there will be a different communication problem faced by such an orbit during the comsats’ transit. This problem is solved by using two satellites on either side of Mars, i.e. at any time, there will be two satellites orbiting Mars, each facing the opposite faces of Mars, due to which, the satellite constellation used will always ensure Gaia’s communication channels with Earth. The comsats will have an average distance from Mars of around 26.3 million kilometers(during non-conjunction period) and 22 million kilometers(during conjunction period). For comparison, a comsat placed at the L4 or L5 points would be at a distance of 141.6 million kilometers. Therefore, such a great difference in distance would result in the signal strength being reduced by a huge factor. The propulsion system used by the comsats is a magnetoplasmadynamic thruster, which can use argon as a propellant. It is estimated that the propulsion duration will be for 93 days, with an average thrust of 300 mN, which will be mainly to switch orbits, from around the Sun to around Mars. This is because the difference between the synodic period(once every 780 days) and the sidereal period(687 days) is 93 days. As the communication satellites would be at the same location again exactly during the conjunction, the thrusters would have to fire for 93 days to maintain the satellites orbit around Mars. As the sidereal period is for 687 days, the satellite would be at the same location again every 687 days, which is when the firing of the thrusters is to begin.58 Although the satellites orbit closer to Mars at this period and provide a shorter communication time, the satellites can be used even during the time when there is no conjunction. The only difference will be the distance, which will be around 4 million kilometers.

The number of satellites to be used are 6 satellites on each side of Mars during conjunction, i.e. 12 satellites in all.

### 2.3.2.2 Comsats communication systems

The communication systems onboard the comsats use a modified version of NASA’s LCRD laser communication system. The system weighs around 175 kg, relatively low for a communication system.59 It uses 130 W of direct current electricity for the communication transfer. The LCRD system consists of 4 DPSK modems, and 4 PPM modems, along with 4 optical communication modules and 3 optical mode controllers(including both the optical communications terminals). However, as DPSK modulates the carrier wave by changing the phase to conduct the data by modifying transmissions by using the previous signal as a reference signal, its range is severely limited. Using DPSK over shorter distances is highly effective, due to which the Gaia-Mars communication modules will use DPSK systems. However, for Gaia-Earth communication, PPM modems will be used. PPM modems modulate the signals transmits a single pulse, with a fixed amplitude and wavelength, with the position of each pulse varying according to the reference pulse, which is generally the first pulse in a fixed time shift. Due to the fixed amplitude and wavelength, the pulse tends to have larger range, as the distortion over longer distances is extremely minor, as compared to DPSK modulation. Therefore, PPM modems are used for Gaia-Earth communication. However, the drawback is that DPSK has a data rate of 2.88 Gbit/s(uncoded) and 1.244 Gbit/s(coded), whereas the data rate of the PPM modems is 622 Mbit/s(uncoded) and 311 Mbit/s(coded). However, this is more than sufficient, as seen in 2.3.1, where it can be seen that the average required data rate is around 50 Mbit/s.

The wavelength used by the communication system is 1550 nm. The system consists of 2 reflective telescopes to produce the downlink beam, using a three-axis inertial navigation system with angle rate sensors for automatic rotation to specific angles facing Earth.

The receiving stations onboard both Gaia and Mars, have 60 cm receiving aperture, and a 15 cm receiving aperture, coupled with an erbium doped fiber amplifier, which are C-band amplifiers, as the input signal’s wavelength is 1550 nm, between the wavelengths of 1528 nm and 1565 nm. The signal to be amplified, along with a pump laser of a wavelength between the above two wavelengths mentioned above, are multiplexed into the erbium doped fiber, where the interaction with the Er+3 ions amplifies the signal.

# 2.4 Heat Rejection

Heat rejection on board Gaia is mainly conducted through the external surface and using liquid droplet radiators. A significant portion of heat is used in maintaining internal temperature.

The main sources of heat on Gaia are the IFR reactors. The IFR reactors produce around 480 MW of thermal energy. However, there are some other sources of heat as well, such as the human activities. Therefore, the heat to be rejected is slightly above 480 MW. It is to be noted that the sun’s heat is not considered for the external surface as there is almost no solar radiation is incident on Gaia.

The main method for heat rejection on board Gaia is the use of liquid droplet radiators. However, several other methods of heat rejection are used, including the use of heat in several industrial processes, mainly the Sabatier process and the Hall-Heroult process(for aluminum production). The Hall-Heroult process is a highly energy intensive process, as it requires the aluminum oxide to be heated to higher temperatures of around 960°C OR 0.03 kWh/kg of aluminum produced.

## 2.4.1 Liquid droplet radiator

A liquid droplet radiator uses a droplet generator, a collector, a pressure regulator, and a heat exchanger. The droplet generator produces droplets, preferably from silicone oils or siloxane. The droplets undergo pressure reduction, following which, they are passed through the heat exchanger. The heat exchanger will transfer the waste heat to the droplets, following which, the droplets are ejected into space, where the heat is rejected by radiation. The amount of heat rejected by one droplet can be given by the equation,

where q is the heat rejection rate, a is the radius of the droplet, σ is the Stefan-Boltzmann constant, F is the view factor and T is the temperature of the droplet before the rejection. It is estimated that the average heat expelled is 0.0003 Wh/droplet, which has a diameter of 1 µm . It is estimated that the time between the transfer of heat to the droplet and the rejection of heat is around 2 seconds. One LDR produces around 250,000 droplets per second.60 Therefore, the amount of heat rejected per second is around 75 Wh per second. As around 130,000 Wh of heat is produced by Gaia per second, it is estimated that around 1700 radiators will be required by Gaia for the heat disposal. The liquid droplet radiators used are triangular LDR’s. They use centrifugal force to collect the droplets after rejection, due to which the size of the collector tends to reduce, and therefore, the size of the LDR reduces by almost 40%.61

It is to be noted that although it is mentioned above that 1700 LDR’s will be required for heat rejection, the number of radiators will be significantly less, as heat rejection on board Gaia takes place through radiation from the surface as well as heat being used in industrial processes. The reduction in radiators due to the industrial processes can be expected to be around 200 radiators, resulting in 1500 LDR’s being used. The decrease in the number of radiators due to radiation from the surface is seen below.

## 2.4.2 External surface radiation

Gaia has the capability to reject heat on a large scale by radiation due to its large surface area and also because its external surface is made of titanium, which has a high emissivity(0.31).

The amount of heat radiated can be calculated using the Stefan-Boltzmann law for grey bodies,

where j is the energy radiated per second per square meter [[2]](#footnote-2), ε is the emissivity of the material which is radiating the heat(0.31), σ is the Stefan-Boltzmann constant(5.67e-8) and T is the absolute temperature of the surface. The absolute temperature can be easily calculated using the equation,

Q=mcΔT

where Q is the amount of heat energy supplied per square meter(assumed to be around 70 Wh or 126,000 joules), m is the mass per square meter(315 kg), c is the specific heat capacity of the material, in this case titanium’s specific heat capacity(0.523 J g-1 K-1). Using these values, the change in temperature can be calculated to be around 16 K or 16°C. If the initial temperature is considered to be -60°C, the temperature of space around Mars, the temperature of the external surface of Gaia can be estimated to be around -42°C.

For an external temperature of -42°C or 231 K, the amount of energy radiated is calculated to be around 49.4 J/m2.s, using the Stefan-Boltzmann equation mentioned above. Therefore, the entire surface radiates around 138 MWh per hour, or 138 MW of heat is radiated by the surface of Gaia, which is around 28.3% of the heat energy to be rejected.

As mentioned in 2.4.1, the number of liquid droplet radiators is bound to decrease due to the large amount of heat being rejected by the external surface of Gaia, as seen above. Therefore, as the LDR’s will have to reject only 71.7% of around 110,000 Wh per second, i.e. around 80,000 Wh, the number of radiators required by Gaia will be around 1060 radiators, placed on the exterior of Gaia. Each radiator weighs around 10 kg, which will place little stress on the external surface of Gaia.

# 2.5 Stationkeeping

Stationkeeping is one of the most important operation on board Gaia. Gaia, as mentioned in 1.0.3, follows a halo orbit. Halo orbits tend to be unstable, due to which spacecraft or stations following a halo orbit around a Lagrange point require stationkeeping. The main reason for the instability is due to the large perturbations exerted on the object by the gravity of the planet or the Sun. Thus, if an object is placed on a halo orbit, it can deviate from its path and enter into an orbit around either the planet or the Sun. The L4 and L5 points, on the other hand, are stable due to the Coriolis force acting on the objects at these points when rotating. The Coriolis force at the L4 and L5 points results in the bodies being unable to attain a trajectory around either the planet or the Sun. Although perturbations do act on objects at the L4 and L5 points, the deviation in their orbits is countered by the Coriolis force. Although the Coriolis force acts at the L1, L2 and L3 points, the force acting is lower due to the lower rotation vector at these points. Therefore, the L1, L2 or L3 points are unstable whereas the L4 or L5 points are stable.

The Coriolis force acts perpendicularly to the axis of the body. Therefore, if a force acts perpendicularly to the body, it can provide stability to the body. Therefore, a body in a halo orbit around either the L1, L2 or L3 points requires a perpendicular force acting on it to maintain its stability. The exertion of this force is the stationkeeping required by Gaia.

Gaia requires a stationkeeping cost of 0.2 m/s, where every stationkeeping maneuver is conducted once every 200 days.62 Stationkeeping is conducted through a combination of several techniques, including using liquid hydrogen for propulsion and rocket launches. The reason for the use of liquid hydrogen is due to its high specific impulse. Although costs might increase, primarily due to maintenance, liquid hydrogen would reduce the amount of fuel required. The amount of fuel required can be calculated using the Tsiolkovsky rocket equation, as the reaction force of the rockets will be the primary thrust applied on Gaia for stationkeeping, due to which, the delta-v required for Gaia, along with the mass of Gaia are used in the equation.

In this equation, the change in the mass(mf-m0) is equal to the amount of fuel required for the stationkeeping maneuver. The amount of liquid hydrogen required for the stationkeeping maneuver is around 133,330 tons of liquid hydrogen, which will used in 200 rocket launches over a time of 1 month, or 200,000 tons of liquid methane which will be used in around 250 rocket launches over a time of 2.5 months. The liquid hydrogen will be easy to obtain from the electrolysis of the water on Mars to produce oxygen. As around 20,000 tons of oxygen are required every 1 month, 25,000 tons of hydrogen are produced during the electrolysis of water, adding up to 170,000 tons of liquid hydrogen between every stationkeeping maneuver, providing an excess of 37,000 tons of liquid hydrogen, which is stored for usage in the next maneuver, thereby reducing the costs of stationkeeping due to liquefaction.

The stationkeeping technique used for Gaia is the LQR stationkeeping technique, where the required direction and amount of time for which the burn for stationkeeping has to be done and several other criteria are calculated by an automated regulator, which calculates the required values based on several weighted values, such as position and current velocity. This technique automates the entire process, using a state-feedback controller.

The navigation and attitude measurement systems on board Gaia have to be inertial navigation systems. This is mainly due to the lack of a navigation system near Mars, due to which, Gaia cannot use an external point as a reference for the navigation systems. The inertial navigation systems on Gaia are based on the combination of two systems, which are independent during operation. The inertial navigation system uses the MEMS vibrating structure gyroscope for determining the angular velocity and rate of rotation. MEMS uses two vibrating proof masses and their out-of-plane motion to measure the rate of rotation. The second navigation system is the TIMU navigation system which is used to calculate the position of Gaia and its acceleration.

#### Section 3

Habitation

Gaia’s structure and most of its critical operations have been described in the above sections. In this section, the operations of Gaia essential for the habitation of the settlers, such as food and water production, along with several features of Gaia which are required for human comfort, such as illumination and artificial gravity, are detailed.

The living areas, along with the primary life support systems, such as air supply, or water production, are located in Torus 3, where the artificial gravity due to the centripetal force. The living areas are of primary importance, as their design is an important factor in enabling the settlers to live in relative comfort, and provide an environment which is earth-like to a large extent.

The medical facilities on board Gaia are also highly important, as the medical treatment of the settlers will have to be done with resources available on Mars, while some medicines and equipment will have to be imported from Earth, due to which, the maximum amount of re-using of medical equipment will have to be done, along with the development of alternate methods of medical equipment production which will reduce dependency on Earth for technology and material.

# 3.1 Human adaptability

An Earth-like environment condition is highly necessary for settlers, as the mental condition of settlers is directly related to their surrounding conditions. Gaia’s structure as well as interior design create an almost Earth-like condition. While the design of the interior is not discussed, the structural implications on human comfort are.

The toroidal structure of Gaia results in the line of sight at any one point in the torus being the lowest, as compared to a sphere or a cylinder. The line of sight can be easily calculated, as it is the length of a tangent of the inner ring of the torus which intersects 2 points on the circumference of the larger ring. For Gaia, the length of the chord, or the line of sight, comes to around 342 meters. Another important factor is the fraction of the settlement which can be viewed at a time. If a large fraction of the settlement is viewable at a time, along with a large line of sight, the settlers will undergo discomfort due to unusual surroundings, and quite potentially, dizziness. Only 15% of the settlement can be viewed at any time, as opposed to 100% in a cylinder or a sphere.

The other important factors when considering ease of living and the maintenance of Earth-like conditions are the amount of illumination, the atmospheric composition, and artificial gravity. Artificial gravity on Gaia, along with the optimum rotations per minute, has already been discussed in 1.1.3.4.

## 3.1.1 Atmosphere

The atmospheric composition is vital for several life processes in humans, as well as essential for humans’ comfort. The composition of air is maintained on board Gaia, in a manner which is similar to the atmosphere on Earth. Gaia’s atmosphere consists oxygen(21%), nitrogen(78-79%), around 1% carbon dioxide, and humidity in trace quantities.

Oxygen is necessary for respiration in the human body. Therefore, it is vital that oxygen is present in the body. However, the presence of more than 75% oxygen is impossible. This is due to several reasons such as combustion of the surroundings, but also due to its direct effect on the human body. In the event that humans breathe in large amounts of oxygen, the lungs’ capacity to handle transfer of gases is overwhelmed, which might result in severe brain damage, along with damage to the central nervous system. Prolonged exposure might also result in damage to the retina as a result of hyperoxia and death within a few days.63 Therefore, the oxygen composition is maintained at 21%, similar to the percentage of oxygen on Earth.

Nitrogen is a component of the atmosphere not required by humans, but it is necessary in the atmosphere because it is the main component of the atmosphere which is responsible for neutralizing the effects of oxygen in the atmosphere. As this is one of the most abundant gases present on Mars, it is used for the same reason nitrogen is present on Earth. Therefore, nitrogen composes 78-79% of the atmosphere on Gaia’s Torus 3, along with being present in different quantities in the other sections. However, in the other sections, such as the industrial sections, it is used mainly due to its non-combustibility and its relative inertness.

Argon is a part of the atmosphere in Torus 1 and the Central Core, as most of the processes in these sections are automated, requiring little to no human intervention. Thus, it is possible to maintain an atmosphere in these sections which is not suitable for human living, but is instead suited for industrial purposes. As argon is a major component of the Martian atmosphere, it can be easily obtained. Along with this, argon is highly inert, non-flammable and non-toxic. Therefore, it is highly useful as a major atmospheric component as the maintenance of industrial equipment is reduced along with being easily procurable, as compared to a 100% nitrogen atmosphere.

Carbon dioxide is a component of the atmosphere which is not required by humans in any way. Therefore, it is not used in Torus 3. However, it does have a presence in Torus 2, where it is needed in significant quantities by the plants in the food production sectors.

Water vapor is a component of the atmosphere which is required in trace quantities by humans. Water vapor is important as low to zero levels of atmospheric humidity might result in drier and itchier skin. It might also result in the eyes becoming irritated. Apart from the effects humidity has on the human body, low levels of humidity result in the mucosal membrane being dried out, resulting in inflammation and the risk of flu and other airborne diseases being increased, along with their duration in the body increasing. It is also responsible for damage of electronics, as low levels of humidity will result in buildup of static electricity, due to which there might be damage of electrical components.64 Therefore, the humidity levels in the air have to maintained ideally above 40-50% relative humidity, which is done onboard Gaia.

**Atmospheric components’ generation systems**

The different components of the atmosphere have to be obtained from Mars, as transportation of the components of the atmosphere from Earth to Gaia is unfeasible and would result in extremely large costs. One advantage of Mars is that all components of the atmosphere can be extracted, either from the atmosphere, from the water present in Mars’ polar ice caps, or from the perchlorates present in the soil.

**Nitrogen, carbon dioxide and argon**

The nitrogen required on board Gaia is procured easily, as the Martian atmosphere contains sufficient quantities of nitrogen. The liquefaction process of the Martian air is required, as the Martian atmosphere contains most of the required components which are needed on Gaia. The liquefaction process followed is the same as the process mentioned in 1.3.3, where the Linde cycle is used to liquefy the air. The nitrogen on Mars, though, is molecular. However, it turns into nitrogen molecules upon liquefaction.

**Water vapor and oxygen**

Water vapor and oxygen are easily available from the Martian poles, primarily in the north pole, along with a significant presence in the south poles, under an 8 meter-thick dry ice sheet. It is estimated that around 21 million cubic kilometers of water are present on Mars. These are the primary sources of water and water vapor. Another use for the water, apart from its direct use for settler’s uses and industrial processes, is the use of its constituents, hydrogen and oxygen. The water is electrolyzed in an ISRU on Mars. The water which undergoes electrolysis has to be acidified before electrolysis, to enable the release of hydrogen ions which will result in increased electrical conductivity of the water. Although nitric acid is stronger than sulphuric acid, the acid used is sulphuric acid, instead of nitric acid. This is mainly because nitric acid is a strong oxidizing agent, which will oxidize the liberated hydrogen gas.

Gaia requires hydrogen and oxygen for two different reasons. Oxygen is needed as it is a vital component of the atmosphere, whereas hydrogen is required as it is one of the primary reactants of the Sabatier reaction, which is necessary for the production of liquid methane, the propellant required by the launch vehicles used on Gaia. As hydrogen must react with carbon dioxide in the Sabatier reaction, it is advantageous to situate Sabatier reaction plants in the South pole of Mars, where large amounts of carbon dioxide cover the water ice sheets, resulting in large amounts of carbon dioxide being extracted, which can be used in the Sabatier reaction.

Another source of oxygen, at least during the initial years of Gaia, will be perchlorates present in Martian soil. Martian soil is needed by Gaia for the construction of the ISRU structures. Thus, the Martian soil will have to be purified of all toxic components before being used as a material for the construction of the ISRU’s. The main toxic component in the Martian soil are the perchlorates, which are present at concentrations of around 1%, which is highly toxic for humans. Therefore, the perchlorates will have to be removed from the Martian soil. Instead of disposing off the perchlorates, they are used for obtaining oxygen. The decomposition of perchlorates, in the presence of a mixture of steel slag and water, at temperatures of around 250°C, produces oxygen and chlorine ions.65 The oxygen can be liquefied and stored for usage on board Gaia or in the ISRU’s, whereas the chlorine ions can be disposed of. 100 g of perchlorate yield around 64 g of oxygen, which provides large amounts of oxygen for the ISRU’s alone.

A backup source of oxygen is always present in Gaia to provide sufficient amount of oxygen for 40,000 people for 72 hours. The backup source used on Gaia is a solid-fuel oxygen generator, which uses lithium perchlorate as the source for the oxygen. It is easy to produce, as lithium and perchlorate are abundant on Mars, composing around 3% and 1% of the Martian soil. It is estimated that 1 liter of lithium perchlorate provides sufficient oxygen for 1 person for 24 hours, due to which, it can be estimated that around 120,000 liters of lithium perchlorate are present at any one time on Gaia. However, there won’t be any need to maintain these SFOG’s, as lithium perchlorate is highly unreactive. These backup SFOG’s are positioned at the evacuation chambers, where they will be used in the event that the oxygen supply is disrupted.

## 3.1.2 Illumination

The lighting of Gaia is required as lighting influences human hormone levels, thereby controlling stress levels, and therefore, human productivity and stress levels. One of the examples where illumination is required, without which, humans would undergo intense stress, is in the production of the hormones cortisol and melatonin. Cortisol is required for maintaining blood pressure and stress, along with being responsible for increasing alertness, whereas melatonin is required for regulating the human circadian circle. High amounts of cortisol production will result in excessive stress and alertness, reducing the amount of sleep, with low amounts of cortisol can cause weakness, fatigue and several medical conditions like low blood pressure. Melatonin in high or low quantities cause sleep problems. It is seen from this that not just illumination, but maintaining the light cycle is also required.

The light cycle requires at least 8.5 hours of sleep, along with 10 hours of bright light, and 5.5 hours of dimmer sunlight(2.75 hours before and after the period of bright light). The light cycle will be completely automated, with the control center for the lights located at the command centers of the respective sectors.

The light sources on board Gaia are 21.5 W LED retrofitted for T8 fluorescent tubes, therefore providing the high efficiency of fluorescent tubes, along with providing the reliability of the LED tubes, as compared to fluorescent tubes. These have a high luminous efficiency of around 172 lumen/watt of electricity. The average solar irradiance on Earth’s surface during the noon is around 1000 W/m2, or 98,000 lumen/m2. The retrofitted T8 tubes have an efficiency of 172 lumens/watt.

The amount of power required by Gaia can be calculated by,

where P is the power required, I is the illuminance, A is the area and E is the luminous efficiency. The power required for a lighting system providing an illuminance of 20,000 lux, which is the average illuminance on a day with a clear, blue sky is estimated to be around 48.7 MW.66

# 3.2 Food

Food production on Gaia is one of the most essential processes, as the production of food has to be completely localized, being produced completely on board Gaia. While it may be possible to obtain other resources in minor quantities from Earth, and in large quantities from Mars, the food supply chain has to be completely based on board Gaia. This is for two reasons, one being the economic and logistical difficulties associated with shipping large quantities of food from Earth over longer periods of time, and the other being that a disruption in the supply chain between Earth and Mars might result in large-scale starvation. Therefore, the food supply chain of Gaia is completely located on board Gaia.

The main disadvantage of complete localization is that the choices in the food will be severely restricted. An example of this is the supply of meat. Meat or animals cannot be transported to Gaia from Earth. However, it is possible to produce meat, in moderate quantities, on board Gaia using invitro cell culture of animal cells, which can be imported quite easily from Earth. The only obstacle is the high costs associated with culturing, along with the lack of a suitable growth medium for the starter cells. However, using modern techniques, it might be possible to limit prices and make it easier to culture meat.

Crops are grown on board Gaia in vertical farms to reduce the space occupied and to gain larger amount of control over the resources expended in the growth of crops. The technique used in the growth of the different plants is aeroponics. The plants which have to be grown have to be chosen carefully, mainly due to space constraints. Although the use of vertical farms increases the average yield per square meter, there is still a considerable limit on the space which can be used for the growth of crops. Therefore, the crops to be grown have to be chosen carefully, so as to meet the required amounts of nutrient intake of the average settler, while growing the crops in the smallest possible area. However, while the crops grown might be limited, it will be possible for settlers to buy sections of a vertical farm and grow any food of their own.

## 3.2.1 Crops

The options for the crops which can be grown on board Gaia are limited, primarily due to space constraints. Another reason for the constraint in options is the level of difficulty in the growth of certain crops. For example, certain crops such as wheat and grain can be grown easily, compared to plants which require high nutrient intake such as corn and oats. Therefore, a shortlist of crops which can be grown onboard Gaia has been created, which includes:

1. Amaranth grain
2. Emmer wheat
3. Savoy spinach
4. Sweet potato
5. Romanesco broccoli

Although all 5 crops are grown on Gaia, the crops are grown in different proportions, based on their requirement. Crops like Amaranth grain and Emmer wheat are grown in larger quantities compared to sweet potatoes.

|  |  |
| --- | --- |
| **Nutrients** | **Amount found** |
| Carbohydrates | 65 g |
| Fat | 7 g |
| Protein | 14 g |
| Vitamin B1 | 0.1 mg |
| Vitamin B2 | 0.2 mg |
| Vitamin B3 | 0.9 mg |
| Vitamin B5 | 1.5 mg |
| Calcium | 159 mg |
| Magnesium | 248 mg |
| Phosphorus | 557 mg |
| Potassium | 508 mg |

Major nutrients’ content in Amaranth grain(100 g)

|  |  |
| --- | --- |
| **Nutrients** | **Amount found** |
| Protein | 12.5 g |
| Fat | 2.4 g |
| Carbohydrates | 71 g |
| Calcium | 38 mg |
| Phosphorus | 360 mg |
| Iron | 4.7 mg |

Major nutrients’ content in Emmer wheat(100 g)

|  |  |
| --- | --- |
| **Nutrient** | **Amount found** |
| Carbohydrates | 3.6 g |
| Proteins | 2.9 g |
| Fat | 0.4 g |
| Sodium | 25 mg |
| Vitamin A | 6.2 g |
| Vitamin E | 2 mg |
| Iron | 2.71 mg |

Major nutrients’ content in Savoy spinach(100 g)

|  |  |
| --- | --- |
| **Nutrient** | **Amount found** |
| Carbohydrates | 20.7 g |
| Fat | 0.15 g |
| Protein | 2 g |
| Vitamin B1 | 0.11 mg |
| Vitamin B2 | 0.11 mg |
| Vitamin B3 | 1.5 mg |
| Vitamin B6 | 0.29 mg |
| Vitamin C | 19.6 mg |
| Vitamin E | 0.71 mg |
| Calcium | 38 mg |
| Magnesium | 27 mg |
| Phosphorus | 54 mg |
| Potassium | 475 mg |
| Sodium | 36 mg |

Major nutrients’ content in sweet potato(100 g)

|  |  |
| --- | --- |
| **Nutrient** | **Amount found** |
| Carbohydrate | 5 g |
| Fat | 0.25 g |
| Sodium | 19 mg |
| Protein | 2.42 g |
| Calcium | 27 mg |
| Iron | 0.6 mg |
| Potassium | 246 mg |
| Vitamin C | 72.2 mg |

Major nutrients’ content in Romanesco broccoli(100 g)

The combination of crops is chosen in such a manner that this particular combination, in different quantities obviously, provide the average settler with all of the nutrients. The Romanesco broccoli provides vital nutrients like potassium, Vitamin C, and sodium, while providing low amounts of iron and carbohydrates. These nutrients are made up for in the emmer wheat, which provides iron, carbohydrates, calcium and phosphorus. Sweet potatoes were preferred over potatoes as sweet potatoes provide higher amounts of carbohydrates and minerals as compared to potatoes. It can be observed that out of the 5 primary crops grown, only Amaranth grain contains high amounts of fats. This is because the fat content in food has been decreased, with the extra energy generally provided by them in a human diet, being provided by carbohydrates. The minimal amount of fats required are provided, with one crop having moderate amounts of fat, with the remaining crops having low amounts of fat. All the vitamins, in the required quantities, are provided by a combination of Amaranth grain, Savoy spinach and sweet potato.

The crops which have been chosen to be grown on Gaia contain all the nutrients required by the human body. These crops also consume low amounts of water and nutrients. An example of this is Emmer wheat, which is known for surviving drought conditions for months at a time. An important factor which was used to determine which crops were to be selected was the amount of nutrients which the plants require during growth. These 3 factors, amount of water required, nutrients present in the crops and the nutrients required by the crops, determine which crops are grown on board Gaia. Although crops which do not fit these criteria can be grown, the costs would rise by a large amount, due to which, these crops’ seeds or cells would be stored on Gaia, and are grown for the consumption of a settler or a group of settler when the settler or the group pays a special cost for growing these crops.

**Aeroponics**

The crops are grown on Gaia in vertical farms, which employ aeroponics to grow the crops. The main reason for the use of aeroponics is to reduce water and nutrient usage, along with reducing the area occupied for the growth of crops. Compared to other methods such as hydroponics, it is highly efficient in its use of water and nutrients. It provides a greater degree of control over the use of different resources and also enables increased air exposure, providing the roots with more oxygen and carbon dioxide. The nutrient intake of plants can also be controlled to minimize the amount which needs to be given to the roots. Therefore, aeroponics is used for growing crops on Gaia.

Aeroponics uses a material which has been sterilized, generally plastic, as a bed for holding plants in place. The plastic bed holds the plants in such a manner that the shoots are above the bed, with roots dangling below. The dangling roots are sprayed with an atomized nutrient-rich, water solution spray, whereas air supply containing 75% nitrogen, 20% nitrogen, 5% oxygen, along with small quantities of methane and water vapor, are introduced into the growth chambers via pipes, which obtain the air from the tanks storing the different atmospheric constituents. The advantage of this atmospheric composition is that all the constituents can either be directly obtained from the Martian atmosphere or are by-products of major industrial processes.

The water spray system uses reverse osmosis for the treatment of the water to be used. This is done to eliminate all the minerals present in the mineral, both unnecessary and harmful ones. Following this process, the water is passed through pipes, where a regular pulse, operating at an interval of around 4-5 seconds, injecting the nutrients into the water passing through the pipes. The concentration of some important nutrients present in the water, which undergo nutrient uptake are67:

|  |  |
| --- | --- |
| **Constituent** | **Concentration(ppm)** |
| NO3- | 1980 |
| H2PO4- | 180 |
| K | 1260 |
| Ca | 234 |
| Mg | 144 |

Other nutrients, such as iron, boron, and sulphur are also present, though they are in low quantities. Plants can only take in minerals at a certain limit, which is calculated by the solution’s electrical conductivity. Certain crops, like potatoes, grow best at an electrical conductivity of 2.1 decisiemens/meter.68 The conductivity of pure water is around 0.3 decisiemens/meter. The mineral content required as a percentage can be calculated by dividing the electrical conductivity of pure water and the electrical conductivity of water at ideal levels, and multiplying it by 100. For potatoes, this value comes to around 14.3% mineral/nutrient content required in the water.

The water is sprayed at pressures of around 75-80 psi, using ultrasonic transducers to supply the water to the plants. The plants have a solution input of 1.5 milliliters per minute. The system is generally maintained at a temperature of around 18.3°C and 32°C.

The aeroponics system requires light to enable photosynthesis and several other important plant functions. The light required by the plants is provided by LED’s operating at a fixed wavelength. Light of wavelength between 640 and 680 nm, within the red spectrum, are seen to promote stem growth, chlorophyll production, and flowering and fruit production. Therefore, the LED’s in the plant growth chambers use LED, emitting light at a wavelength between 640 nm and 680 nm.

The growth chambers are in the form of vertical farms. Vertical farms are chosen over the common farms due to several reasons. Vertical farms are more efficient, requiring 10 times less land to obtain the same yield of crops as compared to normal farms.69 The process of growth of crops is also completely controlled, as opposed to normal methods of farming, thereby allowing for greater modifications in the environment where the crops are grown. It is estimated that one vertical farm, which is 30 m in height and has a cross-sectional area of 7 square meters can produce around 80 tons of food per year, or 220 kg per day.70 It is estimated that the average human eats around 1.2 kg of plant-based food per day.71 For a population of 30,000, the plant-based food required is around 36,000 kg per day. Therefore, it is estimated that around 164 square meters of area is required to grow food. For normal farming methods, around 1125 square meters of area would be required, or an increase in area by almost 7 times.

One square meter of a vertical farm requires around 3500 kWh per year, mainly for artificial lighting.72 For an area of 164 square meters, the energy required is around 574 MWh, requiring power of 65.5 kW.

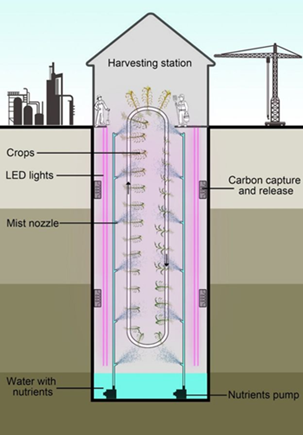


Figure 4: An example of a vertical farm

## 3.2.2 Meat

Meat on Gaia is produced by a form of in vitro cell culture. This is the only method of obtaining meat on Gaia, as it would be impossible to transport meat or animals from Earth to Gaia in large quantities. Therefore, tissue engineering is used to artificially produce meat. In this technique, only the starter cells will have to be transported from Earth to Gaia.

Meat is required by the settlers, as meat provides humans with large amounts of energy and protein, much required by settlers of all ages.

The following meat products are produced on Gaia:

1. Cornish Chicken

2. Hampshire Pig

|  |  |
| --- | --- |
| **Nutrient** | **Amount found** |
| Fat | 14 g |
| Protein | 27 g |
| Sodium | 82 mg |
| Cholesterol | 88 mg |
| Potassium | 223 mg |
| Vitamin B6 | 0.4 mg |

Major nutrients’ content in Cornish Chicken(100 g)

|  |  |
| --- | --- |
| **Nutrient** | **Amount found** |
| Fat | 8 g |
| Cholesterol | 46 mg |
| Sodium | 53.9 mg |
| Potassium | 368 mg |
| Vitamin B6­ | 739 mg |
| Vitamin D | 398 mg |
| Vitamin B12 | 370 mg |

Major nutrients’ content in Hampshire Pig(100 g)

Artificial meat contains nutrients which have more variety, with the nutrients being present in larger quantities, than conventional meat. This is mainly due to the supplementation of several nutrients, mainly vitamin B12 and iron, by means of the growth medium. For example, iron can be provided in a biological form, by using proteins like transferrin, with ferric ions bound to them.74 Thus, artificial meat is not only quicker to produce, it also provides more nutrients.

**Artificial Meat production**

There are generally 3 steps in artificial meat production, obtaining the starter cells, inducing the cells to grow and proliferate, and the processing of the final product.

The starter cells taken are those cells of the animal which have a high cell reproduction rate. Cells generally taken are multipotent, induced pluripotent, totipotent or embryonic stem cells. However, Gaia uses embryonic stem cells are used for artificial meat production. There are mainly 2 reasons for choosing these cells. Embryonic stem cells can differentiate into most of the tissues of an animal, along with having potentially limitless replications. Therefore, embryonic stem cells are the best option among the different types of cells which can be used.

The first step almost entirely takes place on Earth. The obtaining of the muscle sample and the separation of the myosatellite cells(which are unnecessary) from the stem cells takes place in factories on Earth. The transport takes place once every 2 years, with a transport of around 25 tons of stem cells every transport. 10 tons is sufficient for at least 1 year, for a population of around 30,000.73

The second step involves inducing the cells to grow and proliferate in a growth medium. The starter cells are placed in the growth medium, which promotes tissue growth. The medium must also provide nutrients which could supplement the nutrients of the artificial meat. The media generally used are sera from adult or newborn animals, such as fetal bovine serum. These sera could not be produced on board Gaia, which would result in them having to be transported from Earth to Gaia. Therefore, a different medium is used for artificial meat production on Gaia. DMEM (Dulbecco’s modified medium) is the medium used for artificial meat production on Gaia. It can be produced in large quantities on Gaia, mainly due to the fact that the nutrients required for the production of the medium can easily be produced on Gaia or are present in the artificial meat produced.

Another important aspect of this step is the scaffolding required for the growth medium. Several types of scaffolding can be used. Gaia uses a scaffolding made of collagen-porous bead meshwork, with electrically conductive fibers comprising the bed. This type of a scaffolding is useful as the collagen beads are edible, while also providing a means to supplement the meat with more nutrients, whereas a bed comprising of electrically conductive fibers result in faster growth and differentiation rates, along with resulting in the formation of cell fibers of greater length, resulting in the production of a larger size of artificial meat, as compared to using a collagen fiber bed.74

|  |  |
| --- | --- |
| **Nutrient** | **Quantity required (per liter)** |
| Glucose | 4500 mg |
| Glutamine | 320 mg |
| Sodium pyruvate | 110 mg |
| Penicillin | 100,000 U |
| Streptomycin | 100 mg |

The third and final step is the removal and processing of the final product to obtain edible artificial meat. The “sheets” of artificial meat are not removed mechanically to prevent damage them. Instead, they are removed using the thermal liftoff method. Thermo responsive coatings are used to separate the sheets from the scaffolding, therefore preventing damage to the artificial meat.

## 3.2.3 Daily food supply

A combination of artificial meat and crop-based food is provided on Gaia. While, the meat products produced are limited to the two products mentioned in 3.2.2, the crops may slightly vary, based on whether some settlers are willing to pay more to obtain a different crop. However, the diet mentioned here is for the average settler, based solely on the food consisting of primary crops and meat.

It is estimated that the average person eats around 1900 grams of food per day, or 2870 calories per day. The composition of the 1900 grams of food per day is given:75

1. Produce: 750 g
2. Grain: 400 g
3. Sugar and fat: 130 g
4. Meat: 175 g
5. Other: 350 g

The “other” food consists mainly of dairy and eggs, whose nutrition contents are made up for by the different crops and meat.

The diet of the average settler would consist of:

1. 300 g of Amaranth grain
2. 200 g of Emmer wheat
3. 325 g of Savoy spinach
4. 200 g of Romanesco broccoli
5. 200 g of sweet potato
6. 80 g of Hampshire pig
7. 90 g of Cornish chicken

# 3.3 Water

Water is the most essential resource required by Gaia. It is required by the settlers, industry and the food-making process. Therefore, it is vital that water production must be a semi-perennial process. The location of Gaia, at a proximity to the north pole of Mars, provides it with an easier way to obtain water from the Martian north pole, where the ice caps contain millions of tons of water. While Mars may contain lots of water, there are several hurdles in the process of obtaining water, the main one among them being the presence of several harmful substances in the water and the required processing of the water.

There are 2 main sources of water on Mars, the soil, which contains water that is bound to the substances in the soil, and the second being the water present in the polar ice caps. However, water from the soil is not used, due to the high levels of contaminants, low concentrations in the Martian soil and high energy requirements to extract the water. Water from the ice caps is present in a higher concentration in the north pole. Therefore, all the water extraction operations are located above the 30°N latitude.

**Extraction**

The Martian north pole contains water till around 1.5 to 2 km, according to the Mars Reconnaissance Orbiter. It is estimated that the north pole ice cap of Mara has around 1.2 million cubic kilometers of water ice. However, acting as an overburden for the water ice layer is a thick layer of dry ice, with a thickness of around 1 meter in the north pole ice cap.

Water is extracted from bases such as the Korolev crater and the Chasma Boreale. The Korolev crater is surrounded by several small ice sheets with thousands of cubic kilometers of water, while the crater itself has around 2,200 cubic kilometers of water. The second base is the Chasma Boreale, which is one of the largest canyons in the solar system. The area around the Chasma Boreale has around 900,000 cubic kilometers of water, with a depth at places of around 3 km.

Water extraction is carried out by using a mechanical drill and a cryobot combination to extract the water from the water ice below the dry ice. It is estimated that the thickness of the dry ice layer above the water ice layer is about 1 meter. In the later stages of the extraction process though, an electrothermal drill will be used.

In the first stage, during the initial few years of operations, the mechanical drill will be used to drill through the dry ice layer at different points on the ice sheet. The mechanical drill will bore a hole through the dry ice layer, while using a melt tank as part of a coaxial configuration to ensure the sublimation of the dry ice, which is then pumped upwards using a vacuum pump which passes it on to a condenser, which freeze dries the carbon dioxide. The condenser is in effect a shell and tube heat exchanger, where the latent heat of the carbon dioxide is exchanged with the heat exchanger. They work based on the same principle as the heat exchangers used in the IFR onboard Gaia.

After a hole has been drilled, with a radius of around 50-100 meters, the cryobots and condenser system are regularly dropped along a pipe down the hole. The cryobots provide sufficient heat to vaporize the water, following which, the water vapor is then condensed and stored for use. The amount of heat required for vaporizing the water can be calculated easily, using the first law of thermodynamics:

where Q is the heat energy required, m is the mass of water, c is the specific heat of water and ΔT is the change in temperature. Assuming that 1 kg of water has to be melted, the cryobot would have to be supplied with 56.66 kWh. However, as some of the heat released during the condensation of the carbon dioxide and the water vapor is re-used, the energy costs get cut down to around 12-15 kWh per kg of ice. Therefore, 30,000 people, along with industry associated with them, would require around 9800 kg of water per day. This would require around 40,000 MWh of energy per year, which would require a power source of 3 MW.

However, after a few years, when a large hole with a high depth has been dug, it would be difficult to extract the water using a mechanical drill. This is because mechanical drills could undergo severe damage due to the refreezing of melted ice, which might damage the internal parts of the drill. Therefore, after the hole has been dug to a depth of around 500 meters, electrothermal drills are used in place of mechanical drills. Electrothermal drills also consume small amounts of power for heating(around 6 kW), while having a high drill rate of around 6-8 meters per hour in some cases.

The cryobots are double walled metallic structures, with 5 high-energy laser beams. They use multiple lasers to melt water in all directions around them, due to which, less time would be required for extracting the water. A useful characteristic of the cryobots is their small size of generally 3-10 meters. A team of 20 cryobots, operating all the time, with periodic maintenance would be able to provide Gaia with a continuous supply of water.

**Processing**

The main advantage of using this water, as compared to water obtained from the atmosphere, or water obtained from the Martian regolith is the relative lack of contaminants. Only 30 ppm of the water ice are contaminants. However, 10 ppm of the water ice are perchlorate ions(ClO4-). Perchlorate ions are extremely harmful to the human body, as it leads to hypothyroidism, in lower concentrations(24.5 ppb), and causing lung toxicity, aplastic anemia and lymphocyte proliferations, in higher concentrations(70 ppm).76 Perchlorate ions are also harmful to plants, as they are responsible for inhibiting root growth and have been associated with a decrease in chlorophyll content. Therefore, processing the water to reduce the levels of the perchlorates is necessary to ensure that the water can be used by the settlers on Gaia, as well as by the plants.

While perchlorate ions may be harmful for the human body, they have several uses as well. When ammonia is passed through perchloric acid(which can be formed by the reaction between an alkali perchlorate and HCl), ammonium perchlorate is produced. Ammonium perchlorate is a strong oxidizer with a lot of use in rockets. It has the capability to operate at pressures below atmospheric pressure as well, making it a useful oxidizer in rockets. Ammonium perchlorate can be used in rockets transporting cargo from Mars to Gaia.

Another use of perchlorate ions is in the production of small amounts of oxygen. Perchlorate ions can be reduced to oxygen by using the catalyst chlorite dismutase, while producing chlorine ions by-products. Chlorite dismutase has a specific activity of 1928 µmol per mg of protein per minute.77 This shows the capability of the chlorite dismutase to act any substance in the presence of a specific substrate. The product of the molecular weight of the enzyme and the specific activity can be used to calculate the amount of product produced per unit time. For perchlorate ions, 100 g of the dismutase could produce 500 liters of oxygen in about one hour, which is the amount of oxygen required by a human per day.77

The above mentioned system can be implemented in the form of small processing sites near the water extraction sites. The organics production site on Gaia produces the chlorite dismutase and the protein substrate, which is then shipped to the surface of Mars. As 500 settlers are expected to live on Mars at any point, 250,000 liters of oxygen must be produced per day. This would require around 50 kg of dismutase per day to be transported to Mars. Thus, transports of around 1000 kg are expected to take place every 20 days. The perchlorates can be obtained from the water, or from the soil in the event of a shortage.

# 3.4 Residential sectors

Gaia is situated millions of kilometers from Earth. To prevent a sense of longing for Earth and discomfort for the settlers, the residential sectors of Gaia have to be as earth-like as possible. The homes of the settlers should also be customizable, allowing settlers to modify their surroundings as they wish to. However, while modifications in houses and simulation of earth-like are a comfort which should be added, this must be in moderation, using moderate quantities of material which can be obtained in large quantities from Mars.

The residential sectors are located in Torus 3, or the habitation torus. The living quarters are located in the outermost torus mainly due to artificial gravity consideration. Torus 3 has a major radius of 575 meters. This results in a centripetal acceleration at the habitation torus of around 9.81 m/s2, equal to the gravitational acceleration present on Earth. This is necessary for several reasons, including, but not limited to, bone and muscle development, along with several psychological factors. As artificial gravity on the other tori is significantly lower, they have not been chosen as the location for the residential sectors.

The houses are located on the walls of the tori. Each house has a built-up area of around 250 square meters and a height of 4-5 meters. This provides a total volume of around 675 cubic meters, above the 650 cubic meters which is the minimum required in terms of psychological well-being. As each house is expected to have around 3 people(while allowing for even 8 people comfortably), around 10,000 homes are expected to be built, taking up a total area of 2.5 million square meters. This leaves around 370,000 square meters for public spaces, hospitals, governmental buildings and other structures.

When considering the material to be chosen for the construction of the homes, the factors to be considered are the strength of the material, the corrosion of the material and its thermal conductivity. While the strength of the material must be high, the thermal conductivity must be low, with the material not corroding in the presence of oxygen. The material being used on Gaia as steel with 11% chromium and small amounts of tungsten. This particular alloy has a very low rate of corrosion, has a very low thermal conductivity of 45 W/k.m. It also has a specific modulus of around 25.5 m2/s2, thus having a high enough strength but a relatively low density, therefore providing more strength, while using less material. The walls have a thickness of around 3 cm.

The lighting system of the interior of the house uses a wall mounted light fixture. The color and intensity of the light are varied according to the standard time of Gaia. For example, as night approaches, the colors may change from yellow to light blue or so on, while changing in illuminance from 1000 lux to 50-100 lux. The LED’s used can be controlled by the homeowner remotely, while also having the option to allow it to run on its own, allowing it to alter its settings according to the time of the day.

The electricity supply to homes is by a HVDC convertor located in the center of Torus 3. Electricity usage is by means of a 50 Hz, 220 V three-phase distribution. Three-phase distribution is chosen over single-phase mainly due to the efficiency of the three-phase system, where a three-phase distribution system provides more power per cable as compared to single-phase distribution system.

#### Section 4

ISRU

ISRU’s or In-Situ Resource Utilization are the cornerstone for the foundation of any space settlement. To ensure that a space settlement is completely independent of Earth, and meets its objectives, including Gaia’s purpose that it must act as a “backup” world, complete independence from Earth is required. Therefore, to prevent Gaia from relying on Earth for resources, it must have the ability to obtain all the resources it requires on its own from the closest astronomical bodies, in this case, Mars and its moons. Therefore, several ISRU units will be present on Mars and its moons to obtain resources like metals and organic compounds. Another function of the ISRU’s will be to obtain resources like opals and deuterium, which have a high economic value and have the capability to make Gaia a profitable venture.

Gaia’s support structures on Mars are also responsible for several operations like water extraction or fuel preparation, but these have already been detailed in previous sections, due to which they aren’t mentioned here. These support structures are vital in several operations, such as rocket launches, for instance.

# 4.1 ISRU Units

Any structure on Mars would have to be able to withstand several harsh conditions, such as radiation, lack of an atmosphere having sufficient pressure, while having to deal with toxic Martian soil. While providing protection against these adverse conditions to the humans and equipment inside, it must also be strong enough to withstand regular winds of 32 kilometers per hour, while also being able to withstand strong dust storms, which have speeds of 113 kilometers per hour.

**Construction material**

One of the materials which can be used to construct is the local Martian regolith. Martian regolith has large amounts of iron oxides, aluminum oxides and titanium oxides. These compounds lend a high strength to the regolith, while nanoparticle iron oxides might act as a bonding material, as can be seen in the composite metal foams, where the iron nanoparticles are used as a bonding material.

This characteristic of Fe2O3, along with the property of Martian regolith to form a high tensile strength material upon compaction under pressures of 360 MPa, can be used to form a building material which fits all the above mentioned criteria.78

The material is formed following these steps. First, the perchlorates from the soil are removed by treating the soil with chlorite dismutase in a protein substrate. A direct treatment will be sufficient as it is can remove almost all of the perchlorate ions. Following this, it is dried at high temperatures of around 500-600°C, for 10 hours to reduce the water content by up to 95%.

Following this, the nanoparticle iron oxides are treated with acetic acid to separate any form of rust fines from the nanoparticles, following which it is silted and made to undergo the process again, following which it is oven-dried at 350°C. However, FeO can be used directly, without processing. After the addition of the nanoparticle iron oxides, a hydraulic press is used for compressing the Martian regolith, applying a pressure of 360 MPa.

It is estimated that the tensile strength would be around 50 MPa. While the Martian regolith composite’s tensile strength may be lower than steel, this is a better alternative to steel, mainly because it has sufficient strength and can be produced at lower costs, while not using material which is required on board Gaia. It also has the ability to protect from radiation, including galactic cosmic rays and so on. An addition of hydrogen-rich polymers, such as polycaprolactone, can increase the protection capability of the walls of the ISRU’s.

**Location and internal layout**

The units are preferably located at the bases of the mountains, to minimize radiation and temperature differences as compared to the plains. They could be constructed in a partially underground, wide, multistoried design, to increase the stability of the structure, especially during earthquakes, and enable a vertical growth, which would occupy less space and provide more stability and a larger area to establish factories and other operational units.

The wall will be double layered, and there will be 2 entrance sections. After a settler has ventured on the surface and returns, the settler enters the section, where he is subjected to baths to clean off any external regolith. This is undertaken mainly to remove the perchlorate ions, which are highly toxic, and also to remove the Martian regolith. Martian regolith on its own is not harmful, but the constituents of the regolith, such as olivine, pyroxene and feldspar, react with even small amounts of water, and produce compounds which are known to cause lung disease, and in some cases, cancer, which has been seen in quartz miners.

The internal section consists of living quarters for up to 100 people per unit. 800,000 liters of oxygen is always stored in backup, along with 2,000,000 liters of argon, which would last for approximately a month. The internal section has a common cafeteria, along with a separate section where the ISRU activities and other auxiliary activities take place. The entire ISRU unit has LED’s similar to the ones onboard Gaia for providing lighting, following the day-night schedule of Mars. Along with this, the bottom most sections have 20 square meters and a 7 meter high area earmarked as a vertical farm for food growth. The vertical farms are completely self-sufficient, providing 100±25 people with food for an indefinite amount of time. However, this area is not used as the primary food source for the workers in the ISRU’s. Food obtained from Gaia is the primary source. Although this is slightly more expensive, it prevents interference with the backup food source, and it would also provide a secure base for the workers in the event of an accident on the ground level units.

**Power**

It would be useless to base an entire nuclear reactor near the ISRU’s, as an ISRU would not consume energy on the scale of a nuclear reactor. Therefore, a source of power has to be used which does not provide large amounts of energy. Solar panels are a good choice, but the irradiance on the Martian surface, combined with the frequent dust storms, which will block off sunlight, will not provide sufficient power for the ISRU’s and would require a lot of maintenance.

However, RTG’s are a good choice, as they require less maintenance, can operate at any time, and provide sufficient power of around 30 kW. The RTG’S use plutonium-238 as a fuel. Plutonium has a high decay rate, producing 0.56 W/g, and a half life of around 87.7 years, enabling it to be used over longer durations.

An RTG uses the heat produced by the radioactive decay of the fuels. The thermocouple is connected to a heat sink and the container of the radioactive material. The average radioactive decay of the RTG’s throughout a time period of 5 years is around 130,000 curies, which rounds up to around 3 curies per hour. This amount of radioactivity is highly lethal, capable of killing a lot of the workers, though it is not as dangerous as a nuclear reactor. The container of the radioactive material is made of lead, which would prevent radioactive fallout from leaking into the atmosphere. However, the one disadvantage of using lead is that it has a relatively low thermal conductivity of 40 W/m.K, as compared to the thermal conductivity of steel, which is 53 W/m.K. The thermocouple utilizes the heat difference between the heat sink and the container to convert the thermal energy to electricity.

The thermocouples are made of cobalt arsenide which has a high Seebeck coefficient(740 µV/K), enabling it to generate more electricity. The amount of electromotive force generated can be easily calculated using the equation,

where E is the electromotive force, S is the Seebeck coefficient and ΔT is the temperature gradient. For a temperature gradient of 600-900°C, there is an emf of around 0.8 volts.

The RTG operates at an efficiency of around 42%, as it is has a temperature gradient similar to that of the SRG.

It is estimated to produce around 30 kW of power and a mass of around 200-300 kilograms. It is expected that the RTG uses around 10 kg of fuel per month, thereby greatly reducing costs, as compared to the costs associated with maintaining a solar panel as an electricity source.

It should be noted that all ISRU units, excluding the metal processing units use RTG’s for power. Metal processing units use a smaller version of the IFR reactor(5 MW)

# 4.2 Metals extraction

Several metals and metalloids required by Gaia, such as magnesium, aluminum, silicon, titanium and iron are present in large quantities on Mars. The oxides of these substances are found naturally in the Martian regolith, on the order of several weight percent. One example is aluminum, which makes up almost 10% of the Martian regolith. These metals have a variety of uses in the production of machinery, construction of structures, repair work on Gaia and so on.

The regions of Mars where the ISRU units for the extraction of metals are located are the Hellas Planitia area and the Tharsis Plateau region. These areas are expected to have high amounts of nickel, titanium, iron, aluminum, platinum and palladium. These regions are also located close to the equator and thus, it would be possible to conduct rocket launches at much lower costs and transport the extracted material from Mars to Gaia easily.

The power source for the metal extraction units is the IFR reactor detailed in 1.2, except it is a smaller version, producing about 5 MW of power. The power will be consumed mostly by the regolith extraction machinery and in the electrolysis of the molten regolith.

For obtaining metals and their oxides from the regolith, the regolith has to be separated from the resources we want to extract. To extract the metals and their oxides, the regolith is converted to its molten state, by heating it to temperatures of around 900°C and melting it, using a variant of selective laser melting. An ytterbium fiber laser of strength between 250-300 watts can be sufficient to melt around 5 cubic meters of the regolith. The entire process of melting is conducted in an environment of argon, an inert gas, which is present at low pressures of around 0.1 psi.

The molten regolith is then electrolyzed, with the molten regolith being the electrolyte. Platinum, which is found in abundant quantities on Mars is the anode, while the cathode is platinum dioxide. Platinum and its oxide are chosen as the anode and the cathode respectively because they don’t react with oxygen or any other metals which would be deposited on them.

The temperature at which the electrolysis is conducted is 900°C. Although the electrolysis of the regolith can be conducted at higher temperatures of 1600°C, the extraction of the metals which require temperatures this high for electrolysis would require much more power. Therefore, these metal oxides, like aluminum oxide or titanium dioxide, are extracted in their oxide form and refined on board Gaia using other techniques. The current which is passed through the regolith is around 100 kA, with a reasonable efficiency of 92.5%.

During the electrolysis, oxygen is released at the anode, while the iron, silicon, nickel, zinc, magnesium and chromium are released at the cathode. It is expected that the production capacity is around 25 kg per hour for a single electrolysis unit. It is estimated that there would be around 10 electrolysis units, therefore resulting in a production capacity of 250 kg per hour for one ISRU unit.

It should be noted that the metals which have been obtained in the pure form are in the liquid form, due to which, the iron production facilities are on Mars, whereas the silicon is just solidified and transported to Gaia via the GTV. The liquid iron is either passed through molds, or is just solidified and transported to Gaia when required. As most of the iron is used for the upgrading of the ISRU’s or for rocket construction, the bulk of the iron produced needn’t be transported to Gaia, except for the occasional repairs or for the construction of new machinery.

The oxides of metals which haven’t melted can easily be filtered out by means of magnets or by using the difference in the physical states of the oxides and the regolith to carry out a simple filtration process. The oxides are then shipped to Gaia on a GTV.

The oxygen produced, which is around 20 kg per day or 140,000 liters, is the main source of oxygen. 140,000 liters is the amount of oxygen consumed by around 250 people per day. Therefore, there would be around 25,000 liters of oxygen in excess. While some of the oxygen will be utilized in industrial processes on Mars, the remaining small fraction of the oxygen is used in the food production centers present underground in each ISRU unit. Thus, it can be seen that the ISRU units are entirely self sufficient in terms of food, water(Section 3.3) and air.

# 4.3 Opal mining

Opals are one of the most economically valuable resources of Mars. Opals are a hydrated form of silica, having a water content between 3-21%. They are highly valuable on Earth, having a price of up to 360 USD per gram.

Gaia requires a source of income, to maintain itself as a profitable venture, generating some revenue, which will be required for the construction of various structures, expansion of activities, and to provide a means of livelihood to the settlers. Therefore, Gaia has two main sources of income, one of which is opal.

Opals have been found in Martian meteorites, like the Nakhla meteorite. It has also been detected in Martian craters in significant quantities. Craters like the Baldet crater are believed to have large amounts of opals, while opal layers have been seen in outcrops of Martian landforms such as the Valles Marineris. The Valles Marineris region has a particular advantage, as it has a 5 meter thick bed of opal and gypsum, spread out over an area of around 150 square kilometers.79 These sites have an advantage, as they are located in the eastern part of the Tharsis Plateau, where the primary metal extraction sites for Gaia are located. Therefore, 2 opal mining units are located in the eastern part of the Tharsis plateau region.

While the mining and refining of opal may be an easy process, it should be noted that most of the opal in the opal-rich regions is present below a moderately thick layer of gypsum. Therefore, the removal of the overburden, which has a depth anywhere between 5-150 meters is the main step. Drill rigs, such as electromechanical, thermally-heated drill rigs are used. At any one time, the diameter of the shaft dug would be around 1.5-2 meters, for which, a large amount of power would be required, perhaps on the order of 150-200 A, while consuming 850 W of power.

After the shaft has been dug, the rough opals, still covered with dirt, regolith and other unnecessary substances, is brought to the surface. Here, it is put into an industrial agitator, which would have a radius of around 1 meter. The type of agitator used is a mechanical, rotating-tank agitator, so as to hasten the process of separation. While the opal and its associated unnecessary substances are introduced into the agitator, water is pumped through the agitator to remove the unnecessary finer material. There are two outlets, one for the water, which would have finer regolith particles, and the opal in its rough form. The finer particles can be filtered out from the water and the water can be re-used at least 200 times. Following this, the opals are cut and polished, using the dopstick method to refine the opals. Following this, the opals are transported to Earth for sale, bypassing Gaia.

It can be estimated, conservatively, that around 4000 kg of opal is extracted per year. This number may seem high compared to the mining of opals on Earth. For example, the weight of the opals mined in Ethiopia in 2012 was around 7000 kg, with 45+ mines, going up to depths of even 3000 meters at places.80 While, the 2 opal mining units go up to depths of 150 meters, the amount of opal found is concentrated in small areas, primarily volcanic craters, where the lava, which is rich in silica, aided in the formation of opal. An area of 150 square kilometers has an opal “field” of approximate thickness of 1.5-5 meters. Thus, the amount of opal found on Mars is large. Along with this, the deeper shafts might aid in the mining of opals from lower depths. The advantage of the opals at lower depths is that the concentration of precious opals, the most valuable variety of opals, is much higher than on the surface.

If 4000 kg of opal is extracted each year, the net revenue for Gaia would be around 1.44 billion USD per year. This would be the primary source of revenue for Gaia, providing it with enough cash reserves to continually expand its mining operations, and in the distant future, be able to expand its operations beyond Mars.

# 4.4 Launch vehicle fuel production

Launch vehicle fuel production is one of the core activities of the ISRU operations, second only to the water extraction process. The fuel is necessary for transport between Gaia and Earth, or Gaia and Mars. As all of Gaia’s resource supply chains and revenue chains are dependent on the availability of resources from Mars, the frequency of missions between Mars and Gaia would be high. Water and air, the most important resources required for the survival of the settlers, is solely dependent on whether the resources obtained from Mars can be transported to Gaia or not. Therefore, rocket fuel production is one of the most important ISRU processes.

The GTV’s, the launch vehicles used by Gaia for almost all of its transportation purposes, use a liquid CH4/LOX mixture. These substances can easily be obtained on Mars via the Sabatier reaction. The Sabatier reaction requires CO2 and H2­ as reactants, which produce CH4 and H2O. The Martian atmosphere is composed of 95.32% carbon dioxide, while having H2 in trace quantities. Thus, while the carbon dioxide gas can easily be obtained during the liquefaction of air(see Section 3.1.1), the hydrogen has to be obtained by other means. The hydrogen can be obtained by the electrolysis of water, which would produce oxygen as a by-product, which is then liquefied to be used as the oxidizer in the launch vehicles.

The amount of fuel required, if we estimate 30 missions between Mars and Gaia, and 10 missions between Earth and Mars per year, would be around 2800±200 tons of CH4 required per year, or approximately 300 kg per hour. One ISRU unit can handle, at best 50 kg per hour. Thus, 6 ISRU units are used, located at the base of the Olympus Mons mountain of Mars. It is also accompanied by 2 rocket launch ports, at a height of about 12 km above the base. Olympus Mons has been chosen as the primary rocket launch site for mainly 3 reasons:

1. It is located very close to the equator, due to which, the launch of rockets will consume less fuel.
2. Although the atmospheric pressure of Mars may be significantly less, as compared to Earth, a lower pressure on the rocket would reduce the fuel consumed, perhaps on the order of 10-12%. Olympus Mons is a mountain having a height of around 22 km, and as the height increases, the atmospheric pressure decreases to around 72 pascals.
3. Olympus Mons is located very close to the different ISRU units of Gaia on Mars, such as the Tharsis Plateau, where the metal extraction sites are located.

The Sabatier reaction involves the reaction of carbon dioxide and hydrogen, at elevated temperatures of around 400°C, in the presence of nickel as a catalyst and under pressures of 5-6 atm. Although ruthenium or rhodium help accelerate the reaction much more than nickel, they are present in trace quantities on Mars, due to which, nickel, which comprises almost 5%(by weight) of the Martian soil, is used in place of ruthenium or rhodium.

The chemical reaction for the Sabatier reaction is:

According to the reaction, the ratio between the molecular weights of the carbon dioxide(44 a.m.u) and hydrogen(8 a.m.u), is 5.5. This reaction will produce around 16 a.m.u of methane, for the above mentioned amounts of CO2 and H2. As seen above, the ISRU units would have to produce 50 kg of liquid methane per hour. Thus, the amount of carbon dioxide required by one ISRU unit per hour would be 137.5 kg and the amount of hydrogen required would be 25 kg. The pressure maintained inside the unit is around 5.5 atm.

The type of reactor used in the ISRU propellant unit is a packed bed reactor. Although a plug flow reactor model would provide for more efficiency, the addition of reagents at different points in the reactor, which would be required in a plug flow reactor to increase the efficiency, is highly uneconomical on Mars, as the amount of CO2 and the hydrogen obtained would far outweigh the amount actually required. Another advantage of a packed bed reactor is that the catalyst can easily be replaced. The catalyst, nickel, is placed on the bed of the reactor, near the reaction site. The gases react near the site where the catalyst is placed.

A condenser is also placed together with the reactor to remove the heat from the system and to liquefy the methane and water produced. The coolant used is water. The amount of heat produced is around 165 kJ/mol of CH4 produced. This would amount to around 515,000 kJ or 140 kWh. Adding the heat required to liquefy the methane and the water, the heat to be rejected comes to around 200 kWh. The reactor operates at around 375°C as mentioned above. To maximize the amount of heat rejected by the condenser, the temperature difference has to be maximum, due to which, the condenser is maintained at a temperature of 10°C.

The amount of heat rejected by the condenser can be calculated by using Newton’s law of cooling:

where q is the average heat flux, h is the heat transfer coefficient(water has a heat transfer coefficient of 8 kW/m2.K) and ΔT is the difference in temperature between the coolant and the object which has to be cooled(which is around 365°C). Thus, the average amount of heat given out is around 2920 kW/m2. As the amount of heat which has to be rejected is 200 kWh, the area required for the heat condenser will be around 0.07 square meters.

Another thing to be considered is the configuration of the reactors and the thermal management system. The configuration used in the reactor are 3 isothermal reactors, with a condenser. Isothermal reactors are used as they have the highest rate of CO2 conversion of almost 98%.81 However, the drawback is in the thermal management system. While the isothermal reactor may have no difference in temperature at a particular point, there are temperature differences of up to 300°C along the channel or between the reactor and the condenser. The temperature difference will result in the reactor requiring a thermal management system, different from the condenser. Here, the thermal management system would have to maintain a uniform temperature between the different parts of the reactor, to ensure that there is no overheating. However, the main function of the thermal management system will be to remove heat at the site of reaction. This is the main reason why the amount of heat removed at the condenser will be much less as compared to the heat removed in an adiabatic reactor.

At the end of the process, the liquefied methane is stored for operation, while the water produced is electrolyzed for the production of hydrogen and oxygen. The amount of water produced can be estimated to be around 112.5 kg, when 50 kg of methane is produced. The reaction for the electrolysis of water is:

If 112.5 kg of water is dissociated, then 100 kg of oxygen is produced, along with 12.5 kg of hydrogen. As mentioned above, 25 kg of hydrogen is required per hour. As the hydrogen production rate is at 12.5 kg, the remaining 12.5 kg is obtained from the atmosphere.

Another important thing to consider is the amount of oxygen produced. The oxygen is used for two different purposes:- the oxygen for the humans in the ISRU units, and as the oxidizer for the launch vehicles. As there are 6 ISRU units, around 600 kg of oxygen is produced every hour. Assuming 40 people operate one ISRU unit, there would be around 240 people in the ISRU units. One human being would require 35 g of oxygen per hour.82 Therefore, 8.4 kg of oxygen would be required per hour, which is barely a fraction of the oxygen produced.

Around 179.15 kg of oxygen must be produced every hour to fulfill the amount of oxygen required by the launch vehicles. Out of the 600 kg, 179.15 kg of oxygen can be obtained easily. The remaining oxygen is supplied to the other ISRU’s for use in their industrial processes and for the workers in the other ISRU’s. However, it is expected that even after the supply of the remaining oxygen, some oxygen will be left behind. This oxygen could be used for the growth of food in the ISRU units. Therefore, it can be seen that the ISRU units are almost completely self-sufficient, being able to produce oxygen, water and food on their own.

# 4.5 Deuterium production

Deuterium is a hydrogen isotope which has its main applications in nuclear fusion. When nuclear fusion is perfected, the demand for deuterium would rise. Mars has a significant concentration of deuterium, having more deuterium than Earth. This high concentration of deuterium is mainly due to the high amounts of radiation on Mars. The amount of deuterium on Mars is almost 5 times as much the amount of deuterium on Earth, having a concentration of 1 deuterium atom for every 1284 hydrogen atoms.83 Therefore, Mars can provide a major portion of the deuterium required, resulting in its importance, both as a nuclear fuel for Gaia in the future, and as an economically valuable resource.

Deuterium’s importance in nuclear fusion is in the equation:

The triple product for this reaction is easily attainable, mainly due to the low plasma density, lower confinement time(2.1014 nanoseconds) and relatively lower temperatures. This is present due to the energy being released by the reaction through a neutron, which is easy to capture if a thick blanket of lithium or lead is used. This makes the reaction sustainable and easy to conduct.

**Location**

Deuterium can be obtained by mainly 2 sources on Mars, the frozen water or the atmosphere. However, it is rather hard to obtain the deuterium from Mars, as obtaining a significant amount of deuterium would require the liquefaction of a large amount of air, which would be economically unfeasible. Instead, an easier way of deuterium production is from the water of Mars. Mars’ frozen ice has around 1 deuterium molecule to every 400 hydrogen molecules, as compared to 1 deuterium atom every 3200 hydrogen atoms in the water on Earth.84

ISRU sites for the extraction of deuterium can be constructed near the Gale crater on Mars and near the Korolev crater, where the water has a higher deuterium concentration than the other sources of water on Mars.84 There are 3 ISRU units with 5 deuterium production lines each.

**Girdler sulfide process and the extraction of deuterium**

The Girdler sulfide process involves the separation of heavy water, or deuterium oxide from water. After the heavy water is obtained, it can be electrolyzed to obtain deuterium and oxygen as the products.

The Girdler sulfide process uses 2 towers, a cold and hot tower, having water at different temperatures of around 30°C and 127°C. The equation upon which the chemical exchange of deuterium oxide depends on is:

The equilibrium constant at the cold tower is 2.33, while the equilibrium constant at the hot tower is 1.82. Due to the difference in these equilibrium constants, the rate of HDO exchange from the H2S to the cold water is initially high, and it then passes through the hot tower, where the deuterium-rich water passes, and the deuterium exchange between the water and the hydrogen sulphide takes place, thereby enriching the hot water with deuterium. As this water loops several times, the deuterium from the hot water is transferred to the cold water as well by means of the hydrogen sulphide loop.

After a few “loops” of the gas, the deuterium-rich water undergoes fractional distillation. Light water, or H2O, boils at 100°C, while deuterium oxide boils at 101.5°C. The extraction of the heavy water is relatively easy. After the heavy water has been obtained, it is electrolyzed to obtain deuterium.

It is estimated that the production of one kg of deuterium would require around 430 kg of Martian water, while taking around 30 minutes to produce it.85 The entire process would consume around 700 kWh of electricity.85 Therefore, the second IFR unit on Mars is placed for the use of the deuterium production units.

As there are 15 deuterium production lines in total, 30 kg of deuterium is produced in one hour. Thus, around 270,000 kg of deuterium is produced every year. One kg of deuterium costs around $1400. Thus, 270,000 kg of deuterium costs around 380 million USD. As one GEV has a payload capacity of 100 tons, 3 missions, each costing around $1.5 million, are required to transport the deuterium from Mars to Earth. Along with the mission costs, the electricity costs, which can be estimated to be around $3 million/year, must also be factored in. Therefore, Gaia can expect a profit of around $372.5 million US dollars per year from the sale of deuterium.

#### Section 5

Industry

The industrial activities of Gaia primarily consist of metal refining, plastic production, organic chemicals synthesis and electronics production. These industrial activities are one of the most important activities on Gaia because the products of these processes cannot be imported from Earth and have to be produced locally. These are resources upon which Gaia depends heavily and thus, requires in large quantities. Thus, they cannot be imported from Earth. Another reason they have to be produced locally is to ensure that the settlement is completely independent of Earth and has the capability to be self-sustainable.

Gaia’s industry is of 3 different types: artificial-g industry, zero-g industry and Mars-based industry. The artificial-g industry, mainly comprising metal refining, is located in Torus 1. Here, the artificial gravity of Gaia is required in the processes involved. For example, during metal refining, the impure material must be separated from the pure metal. The most cost effective method of doing this is by separating the substances by the action of gravity. However, this would be impossible in zero-g and dozens of centrifuges would be required in zero-g. Therefore, certain industries cannot be based in zero-g. However, certain industrial activities like organic substances synthesis does not require gravity and would work better in zero-g, due to which, they are based in the zero-g section of Gaia. Some processes are based on Mars. This is mainly due to the immense cost involved in transporting the entire impure substance to Earth. This can be seen in the iron and silicon refining industries, where it would be easier to refine them on Mars and transport them to Gaia, instead of transport the entire regolith to Gaia.

It should also be noted that all industries solely use Martian resources. This is to eliminate dependency on Earth. Travel time between Earth and Gaia is around 3 months, and one mission can only accommodate 100 tons of material. However, several missions can be flown between Mars and Gaia, carrying 100 tons each time. This results in Gaia having more resource access from Mars than from Earth. Another harmful effect of relying on critical imports from Earth is that in the event that there is an emergency need for material, the amount of time which will be required to obtain the material will be months, whereas it will be possible to obtain material from Mars at any time. Therefore, all of Gaia’s industries are self reliant.

# 5.1 Metal refining

The metal refining industry on Gaia mainly consists of the refining of aluminum, titanium and copper. The metals are required for several purposes. Aluminum is used on Gaia for a variety of purposes, including for the construction of the PRT vehicles, walls of different structures in Gaia and so on. Titanium is used as the construction material for the walls of Gaia, while copper is required for the electrical wiring inside Gaia.

There are different methods of refining metals. Aluminum requires the Hall-Heroult process, while titanium requires the Kroll process. However, these processes require a lot of energy in the form of electricity. Almost 15.37 kWh of electricity is required for the production of one kg of Al, while around 8 kWh of electricity is required for the production of titanium. This is a comparatively high amount of electricity consumption, due to which different processes are used in the extraction of these metals.

On the other hand, metals like iron and silicon are refined and processed on Mars. The Martian regolith, which contains the different metals or their oxides, cannot be transported to Earth as a whole. This is mainly because of waste disposal, and cargo limits on launch vehicles. In the event that the Martian regolith is brought up to Gaia, it would be very difficult to dispose off the waste parts of the regolith, which would be around 100+ tons. However, if the metals, or their oxides are separated from the regolith on Mars, it would be easier to transport some of the metallic oxides to Gaia for refining, while some metals, such as iron and silicon, can be refined on Mars, and then transported to Earth. The Martian regolith left behind can be used as the construction material for the ISRU units.

The metal refining process is the most important process on Gaia. In the event of a rupture in the external wall of Gaia, the requirement of new ISRU units, etc., the obtaining of the material must be immediate. However, if the process of refining is dependent on Earth’s resources or technologies, an example being centrifuges for metal refining in the zero-g sector, there might be supply chain issues and the entire settlement might be jeopardized. Therefore, the entire process must be self-reliant, without the use of Earth’s resources or technologies.

## 5.1.1 Aluminum

Aluminum is used mainly in the construction of the different structures inside Gaia and for the PRT’s. When alloyed(generally with copper or zinc), the tensile strength of the metal increase by around 5%.86 It’s durability and low density makes it the perfect material for use in the production of different vehicles. It’s light weight and corrosion resistance is a useful feature, which is generally used during the construction of buildings. It has a density of 2.7 g/cc, and a tensile strength of 90 MPa.

Aluminum is obtained on Mars in the form of alumina(Al2O3). The common process used to process alumina and form aluminum is the Hall-Heroult process. This is a form of molten salt electrolysis, where the alumina is dissolved in molten cryolite and electrolyzed in the molten salt bath. Alumina has a high melting point of 2072°C, which is very high for electrolysis to proceed. To lower the melting point and ensure that electrolysis takes place at a higher speed, cryolite is added, which results in the melting point dropping to 1010°C. While this is still rather high, electrolysis can take place at this temperature. However, it consumes a lot of electricity as mentioned above. It would be impractical to divert such a large amount of Gaia’s electric power to the extraction of aluminum. The Hall-Heroult process also has the disadvantage of producing carbon monoxide in large quantities(around 1 kg for every 1 kg of aluminum produced). It would be impossible to dispose of such large quantities of waste.

An alternative to the Hall-Heroult process is carbothermic reduction. Less electricity is consumed by this process, while the by-products are either completely reused in the process or are products required by the settlers on Gaia.

Carbothermic reduction of aluminum involves the reduction of alumina using a carbon-based compound, generally methane. The alumina is reduced to aluminum at high temperatures(around 2000°C) and forms carbon monoxide and hydrogen as a byproduct. The carbon monoxide then reacts with hydrogen to form methane and water. The methane is again reused, while the water is electrolyzed. The hydrogen is used in the reaction with carbon monoxide, while the oxygen is used for the life support systems of Gaia.

The entire process takes place in large low pressure chambers. The environment used is generally argon, which is inert and has a low density. The pressure is around 0.01 kPa. The alumina is heated using 20-30 kW laser pulses, heating it to temperatures of 1500-2000°C. It should be noted that the temperature required has decreased because of the low pressure. Upon heating, the alumina reacts with methane according to the following equation:

The alumina is reduced to aluminum, while hydrogen and carbon monoxide are formed as by-products.

The Gibbs free energy for this reaction is -180 J.87 As the temperature is constant, the enthalpy change, which is dependent on the change in temperature, would be zero. Therefore, the total amount of Gibbs free energy change would be equal to the negative product of the temperature and the entropy change. This shows that the reaction is exergonic or exothermic, releasing 180 J or 43 calories of heat.

It has been estimated that the amount of electricity required to operate the laser is 9.5 kWh per kg of aluminum produced.87 Thus, the electricity consumption is almost halved, as compared to the Hall-Heroult process.

The carbon monoxide is reduced by hydrogen to form methane and water. The water can be electrolyzed to produce hydrogen and oxygen, where the hydrogen is reused for the reduction process, while the oxygen is used for the life support systems on Gaia. The methane is liquefied and stored to be used as fuel for the launch vehicles.

It is estimated that for every 1 kg of aluminum produced, 1.5 kg of carbon monoxide is also produced. Along with this, 1.5 kg of carbon monoxide can also produce 2.625 kg of methane and 2.325 kg of water, while using 0.33 kg of hydrogen. Upon electrolysis, 0.26 kg of hydrogen is produced, along with 2.06 kg of oxygen. Therefore, the aluminum plant has the capability to provide oxygen for breathing on Gaia. However, 0.07 kg of hydrogen is required for the reduction of carbon monoxide, as the amount of hydrogen produced by the electrolysis of the water falls short. Assuming an average reaction time of 10 minutes, around 306.6 kg of hydrogen will be required to be obtained from Mars every month.

## 5.1.2 Titanium and zirconium

Titanium is the most important metal used by Gaia. The entire external metal wall of Gaia is constructed using titanium. It is also used in the construction of several high strength structures on Gaia. It has a low density of 4.5 g/cc. It also has a high tensile strength of around 434 MPa, while the titanium alloys have even higher tensile strengths. Due to this, it can be used for construction of large, high strength requiring structures. It is generally preferred over aluminum because it is almost twice the strength of the strongest aluminum alloys. However, the main disadvantage of titanium is the high cost. While it may have several useful characteristics, the costs associated with its refining is extremely high. Another important and high-cost factor is the conversion of the porous titanium in the initial steps to metallic ingots of titanium, where around 30% of the energy is consumed.88

Titanium is generally obtained in the form of titanium dioxide on Mars. Generally, the titanium refining processes, like the Kroll process or the Hunter process, refine titanium tetrachloride, and not TiO2. Therefore, if titanium has to be obtained, the titanium dioxide will have to be converted to titanium chloride. While there are other alternatives like carbothermic reduction of titanium dioxide, the costs associated are extremely high. Titanium dioxide would have to be heated to temperatures around 2500°C, which would increase the costs by almost two times, as compared to the Kroll process. The carbothermic reduction also has the disadvantage of converting a significant portion of the titanium(around 30%) to titanium carbide, which is extremely brittle and has essentially no use on Gaia. An advantage of using the Kroll process is the low temperatures and the useful byproducts(magnesium and chlorine).

Zirconium is a metal which is used on Gaia for the IFR nuclear reactor fuel, where it is used to raise the melting point of the fuel. Increasing the melting point of the nuclear fuel is necessary, as a higher melting point would result in the chance of a nuclear fuel meltdown decreasing. Zirconium is used for this purpose because it has a melting point of 1855°C. Another use of zirconium is in the nuclear fuel rods’ cladding. It is used for the cladding because it absorbs very few neutrons required in the nuclear fission reactions, while preventing the meltdown and leakage of the nuclear fuel due to its high melting point.

Zirconium is mainly found in the form of zirconia on Mars(ZrO2). Its uses revolved around its high melting point. The Kroll process is used to extract zirconia as well. Carbothermic reduction cannot be used for the refining of Zirconium because it converts a large portion of it to zirconium carbide which would require sintering at 2000°C to be useful in any manner. It should be noted that zirconium carbide is useful, as it has a low neutron absorption cross-section, but it is not used due to the expense associated with it.

The Kroll process involves the conversion of the oxides to the chlorides by chlorination in a carbon monoxide environment, followed by the Kroll process. Carbon monoxide is relatively abundant on Mars, having sufficient quantities required for the extraction processes. Another alternative source of carbon monoxide would be the carbon monoxide obtained from the carbothermic reduction of alumina. Some amounts of carbon monoxide could be reduced by hydrogen, while the remaining part is used for the chlorination of the titanium and zirconium oxides.

The chlorine is obtained from the thermal decomposition of the perchlorate ions, which takes place during the refining of the water and during the process of obtaining the different metals or their oxides from the Martian regolith. As the concentration of the perchlorates is rather high in the Martian regolith(around 400 ppm), the amount of chlorine produced can be expected to be sufficient.

Titania reacts with the carbon monoxide atmosphere and chlorine gas according to this reaction:

The reaction takes place at a constant temperature of 1800°C. The titania is heated using a similar laser as that used in the refining of aluminum, a 25 kW laser pulse, which would take around 50 seconds to heat 1 kg of titania to the required temperature. However, the reaction takes place during the heating and thus, the amount of time can be estimated to be around 40 seconds. The carbon dioxide is utilized in the food growth chambers, where it is required for photosynthesis. Around 500 g of carbon dioxide is produced for every kilogram of titania chlorinated. This amounts to around 130,000 kg of carbon dioxide produced per month, which is sufficient for food growth.

Following the production of titanium tetrachloride, it is made to react with the magnesium. A semibatch reactor is used for the Kroll process. A semibatch reactor is used to maximize the output for the shortest time possible. It has a continuous inflow of material, due to which the amount of time required would decrease.

The titanium tetrachloride is heated to temperatures of 800°C. Due to a constant temperature, the Gibbs free energy has a negative value of 60 J. The reactor is clad with molybdenum, which would act as a catalyst.

After the titanium has been produced, it is made to undergo vacuum distillation at temperatures of 180°C to remove the lower titanium chlorides which may be present. After it has undergone vacuum distillation, it is melted at a temperature of 500°C. The temperature for the melting is low because the metal is not yet pure and has impurities, like TiCl2, which reduce its melting point. Following this, it is passed through a vacuum arc furnace, where it undergoes vacuum induction melting under extremely low pressures of around 5 pascals. After its re-melting process, the different pores and others are removed, therefore purifying the metal. It is estimated that around 67,000 kg of titanium is produced per month.

The magnesium chloride is heated to temperatures of 300°C and made to undergo hydrolysis and form magnesium and chlorine. The magnesium is utilized again for the Kroll process, whereas the chlorine gas can be used to make PVC and other synthetic plastics.

# 5.2 Plastic production

Plastics are used on Gaia for purposes like plumbing, construction of PRT’s, production of electrical components, and for the production of several other objects. It is used primarily due to its malleability and as it can be molded into several different shapes according to the use. The main types of plastics used on Gaia are thermoplastics, such as polyethylene, polyvinyl chloride(PVC) and polystyrene. Thermosetting plastics, such as epoxy, silicone, etc., are produced in a lower quantity, since their use is rather limited.

Polyvinyl chloride, commonly called PVC, is used in plumbing and in electronics production. It has a low weight and low cost, while having a strength of 62 MPa, which is sufficient for plumbing and construction purposes. It is also a polar compound, due to the presence of chlorine and carbon in a bond. Therefore, it has a high dielectric constant as well, due to which, it has a high volume resistivity and therefore, is an insulator. This property of PVC can be used in electrical wiring insulators.

Polyethylene is generally of two types, low-density polyethylene(LDPE) and high-density polyethylene(HDPE), which differ in density, strength and melting points. LDPE has a melting point of 105°C, compared to HDPE’s 135°C. HDPE is also much stronger the LDPE, having a much higher tensile strength and durability. However, HDPE has a higher cost than LDPE due to the high energy consumption in the production process. LDPE also has a larger requirement than HDPE, generally in electronics production and home goods. Therefore, the amount of LDPE produced is significantly more than HDPE.

Plastics are used for a variety of processes, including for the production of a part of the radiation shields, products critical to the digital infrastructure of Gaia, as well as several home goods. Therefore, its importance in the operations of Gaia makes its necessary to produce it using Martian materials entirely. Generally, plastics such as polyethylene are produced using oil and natural gas on Earth. However, due to the inability of the launch vehicles to transport dozens of tons of oil to Mars, substances like carbon dioxide and water are used to produce synfuel, which is then used to produce the plastics.

## 5.2.1 Polyethylene

One of the most common methods used to produce ethene, the monomer of polyethylene, is the reaction of carbon monoxide and hydrogen to produce ethanol, which is then decomposed to produce ethene. However, the process is highly energy consuming, requiring almost 11.3 kWh of energy to produce 1 kg of polyethylene. It consumes power in the electrolysis of water and in the heating of the reactants. There are around 6 reactions involved in the production of ethene. Therefore, an alternative process, oxidative coupling of methane, is used to produce ethene.

The reaction takes place under temperatures of around 800°C and under pressures of 250 kPa. The type of reactor is a semibatch reactor, which is chosen to enhance the speed of the reaction, while ensuring a large inflow of the reactants.

The reaction is exothermic, releasing 177 kJ of heat per mole of ethene produced. The heat exchanger used is a helical coil heat exchanger which is used in the IFR reactors. The reactor used is a packed-bed reactor. This has been chosen to enable the catalyst placement, while allowing more inflow of reactant gases, thereby producing more products in a shorter time.

After the formation of the ethene, it is passed through two different reactors which produce LDPE and HDPE.

LDPE is produced by a high pressure process through free radical polymerization. The reactor producing LDPE uses an atmosphere having an oxygen content of around 10 ppm, under pressures of 100 MPa and temperatures of 100°C. The process is simple, but the main consideration is with regards to the high pressure required. The thickness of the wall of the reactor can be calculated by the equation:

where P is the pressure being exerted, r is the radius of the reactor, t is the thickness of the wall and σ is the tensile strength of the material used for the reactor. This equation is used as the reactor is in the form of a cylinder. Assuming steel is used as the material for the reactor, the thickness of the wall would have to be 14 cm.

The reactor producing HDPE uses a packed bed reactor. This is because packed bed reactors provide a way to use catalysts easily for the reactions, while also allowing for a higher input of reactants. There is a high conversion rate for catalytic reactions, like the polymerization of ethene to HDPE. Therefore, a packed bed reactor is used.

During the reaction, ethylene is passed over a Ziegler-Natta catalyst. They are chosen mainly to prevent branching of the polyethylene into LDPE during polymerization. Some heterogenous catalysts, like titanium tetrachloride, with magnesium chloride as a promoter are highly effective, enabling low pressure and low temperature production of HDPE, without which, the cost would rise exponentially(almost 250%).89

The process generally involves passing the ethylene over the Ziegler-Natta catalyst at temperatures of around 200°C and pressures of 10 atm. The process takes around 20 minutes, during which, it is subjected to rather high temperatures, due to which it undergoes “cracking”. The different ethene molecules combine to form a polymer of having the same substance(ethene) as the unit, or monomer.

Following the production of the LDPE and the HDPE, both products are passed through molds, where they are subjected to cooling below temperatures of 100°C. This is done to ensure that the polyethylene formed is granulated, which is the form in which polyethylene is generally used. The granules can be melted at temperatures of 110°C and molded into the shape required.

Around 33.6 kg of polyethylene was per capita(on average) in 2015.90 As there are around 30,000 people on board Gaia at any time, yearly consumption of plastic can be estimated to be around 1 million kg. Factoring in recycling of plastic, a realistic consumption would be around 760,000 kg. As one production line can be expected to produce around 2-3 kg of polyethylene per hour, the total amount of plastic produced by one line per year would be around 22,000 kg per year. Therefore around 34 production lines would be required to produce the required amounts of polyethylene.

## 5.2.2 Polyvinyl chloride

Polyvinyl chloride, also known as PVC, is a plastic generally used in plumbing, electric cable insulation and in synthetic leather. It is a polymer composed of the monomer vinyl chloride. The primary substances involved in the formation of polyvinyl chloride are ethane and chlorine gas.

Ethane, the primary component of vinyl chloride, is generally obtained via natural gas, forming almost 15% of natural gas. However, due to unavailability of natural gas on Mars, it is obtained by the hydrogenation of ethene. Following the production of ethane, it is made to react with chlorine gas. The chlorine gas is obtained on Gaia from the Martian perchlorate ions decomposition. Chlorine obtained from the perchlorates is generally used for both the Kroll process and the vinyl chloride production.

The hydrogenation of ethene is a catalytic reaction, under temperatures of around 150°C. Ethene is an unsaturated alkene, which is converted to a saturated alkane, ethane(C2H6). Ethene reacts with hydrogen, at temperatures of 150°C, in the presence of the catalyst nickel. It is relatively easy to obtain nickel from the Martian soil. It is present in the elemental form in Martian soil and constitutes around 5% by weight of Martian regolith.91

Upon production of ethane, it is made to undergo high-temperature oxidative chlorination, in which the ethane is made to react with oxygen and chlorine to produce vinyl chloride and water. Compared to chlorination or oxychlorination reactions, this is the most suitable process due to its high rate of ethane conversions of around 96%.

The temperature of the reaction is around 300°C, under pressures of 1.02 atm. The reaction uses a CuCl2/KCl mixture as a catalyst. It has been estimated that this reaction will produce 1 kg of vinyl chloride every 2 minutes. The reaction is highly exothermic, releasing around 239 kJ of heat/mol.92

The reaction for the production of vinyl chloride from ethane is as follows:

The water is produced is electrolyzed to obtain oxygen and hydrogen. The oxygen can be reused in the vinyl chloride and ethene production processes, while the hydrogen is used in the production of methane via the Sabatier reaction, which is then used in the aluminum refining.

The type of reactor used is a plug flow reactor, as they can efficiently pack catalysts like copper chloride and potassium chloride, while the pipe structure allows fluids like gases to flow easily. It also enables a heat exchanger to be connected to the pipe, which is necessary in this reaction as the large amounts of heat produced will have to be removed.

The final process involves the polymerization of the vinyl chloride. The technique used here is the suspension polymerization technique, which produces PVC having molecular weights of 45,000. Following the production of the PVC, it follows the end processes similar to polyethylene, where it undergoes “pelletization”, where it is cooled and dried, following which, it is converted into granules, which can be melted and molded into any shape required.

Vinyl chloride is polymerized by conducting free radical polymerization, by suspending the vinyl chloride in water. It is heated to temperatures of around 52°C, converting it into the gaseous phase, where it is pressurized to 1.2 MPa. Polymerization reactions require initiators, which are in effect catalysts for the production of the polymers. In the case of PVC, the type of initiator used is generally an organic peroxide, derived from alcohols. However, due to the lack of alcohols on Mars, mercuric chloride can instead be used as an initiator for the production of PVC.

Following the production of PVC, it precipitates out of the liquid due to its insolubility in water. Upon precipitation, it is cooled and dried, following which, it is passed through a pelletizer, where it is converted into pellets and stored. It can be melted and molded into any shape desired.

It is estimated that around 16 kg of PVC is consumed per person(on average) in one year. For a population of 30,000, this would translate to around 480,000 kg of PVC consumed per year. After considering recycling, around 350,000 kg of PVC must be produced every year. As one production line produces 1 kg of PVC every 2 minutes, 240,000 kg of PVC is produced by one line every year, assuming around 80% efficiency. Therefore, 2 production lines are used, with one of them operating at a 50% efficiency rate.

Recycling and disposal of plastics is also an important aspect of the production of plastics. It should be noted that after 5 years of operation, Gaia will eliminate all plastic production, with chemical recycling of the plastics. 100% of the plastics used by the settlers are recycled. The production of plastics is primarily for industrial and operational processes. However, production of plastics for them too can be stopped after 5 years, as the expansion of industrial processes would probably not involve the use of plastics. Another process which can be considered is thermal depolymerization, where the polymers are thermally decomposed and the constituents are safely disposed of on Mars, or reused for other processes.

The primary method of plastic recycling is the melting of the plastics. Plastics like HDPE and LDPE, which have low melting points between 110-130°C, are melted and extruded, following which, they can be easily molded into any shape required. This makes the recycling of the plastics extremely easy.

#### Section 6

Society

Gaia’s functioning as a society defines its economic activities and the overall mental health of the settlers. Another important aspect is to maintain an efficient administration, which has the capacity to manage the day-to-day operations of Gaia and maintain order on board Gaia. It is also necessary to maintain a democratic administration and prevent authoritarian forces from rising. Demographics are also slightly modified during the nascent stages of the settlement of Gaia. This is done to ensure that there is a diversity among the people of Gaia.

An ambient environment, with adequate recreational facilities are required to maintain the mental health of settlers, and prevent them from feeling like they are living in a metal structure, millions of kilometers from Earth. The effects of living without recreational facilities in space, like it is on board the ISS, have been well documented by Kanas and Boyd(2007). Therefore, the presence of recreational facilities in space is absolutely necessary to ensure that settlers feel at home on Gaia and are able to work at maximum productivity.

The economy of Gaia is primarily dependent on the sale of substances like deuterium and opals. Maintaining profitability is necessary for Gaia. In the event that Gaia doesn’t have a profitable economy, it would have to rely on money from Earth, which would be detrimental to Gaia’s ultimate goal of complete self-dependence. Money is also required to pay for workers and for contracts to produce goods required by Gaia.

The administration of Gaia practices a form of direct democracy. While the executive branch of the government is appointed by the people, the function of the administration is to execute and enforce the law, there is no legislature, which is a characteristic feature of representative democracies. There will be a judiciary, which is completely separated from the executive, even in matters of appointment, while the law enforcement officers and officials are appointed by the executive.

Recreation generally consists of theme parks and entertainment centers. Several kinds of sports, including zero-g sports are present.

# 6.1 Administration

Gaia’s administration has three primary functions, to execute and enforce laws, to ensure that Gaia’s operations take place efficiently and in co-ordination with each other and decide Gaia’s policy and pass laws. The administration generally consists of the executive, legislative and judiciary. However, Gaia’s administration consists of only the executive and the judiciary, with the broader public acting as the legislative. This has been done to prevent the concentration of power into the hands of an elite few. However, to prevent uninformed decisions from interfering with the policy formulation, law making in certain sections, such as taxation, finance and science, are entrusted in the hands of those who hold academic degrees in these realms.

Direct democracy is practiced on Gaia, instead of a representative democracy. This has been done for several reasons, including for the prevention of power concentration and to ensure that the settlers have a say in Gaia’s affairs. Laws can be proposed and are discussed by the General Council, the body consisting all of Gaia’s settlers. It should be noted that this type of democracy is practiced in very few places on Earth due to the obvious difficulty stemming from the large population on Earth. However, due to Gaia’s small population, this system is highly efficient in allowing the settlers to decide upon Gaia’s laws and policy.

The executive consists of a 10-member body, which appoints law enforcement officers and other important government officials. They ensure that laws are enforced and executed. They ensure that the operations of Gaia take place smoothly. They are directly responsible to the General Council. The executive has a term of 2 years. The term is short to ensure that they are accountable to the people, by preventing them from taking action which is detrimental to the freedom of the people or which, in a broader sense, is not good for the societal harmony of Gaia.

The judiciary consists of 1000 judges. This number ensures that the judge to population ratio would be maintained at an optimal ratio of 3:100. It should be noted that instead of a jury or a single judge deciding the judgement of a case, a Judicial Council of 5 judges is formed, which decides upon the judgement of a case. There is a Chief Judge per Council, who will act as the chairperson for the Council, ensuring that decorum is maintained during the case proceedings.

## 6.1.1 Legislature

The legislature is the law making body of any government. As direct democracy is practiced on Gaia, there are no representatives who will draft laws and therefore, no elections for electing law makers is required. Direct democracy is practiced on Gaia to prevent power from accumulating in the hands of a few people and to allow all settlers to have a say in policy and law making. The broad body of all settlers on Gaia constitutes a form of “legislature” on Gaia and is called as the General Council.

There are generally 3 sections of direct democracy, optional, popular and mandatory.93 Optional referendums are generally concerned with modifying existing laws or policy. In the event that a particular law or policy has to be modified, an optional proposal must be presented with at least 1000 signatures within a span of 90 days. After the required signatures have been obtained, the proposal is presented to all the settlers via a government app, where the settlers can agree or disagree with the proposal. The time for the response will be 14 days, during which, an amendment to the proposal can be proposed, if 100 signatures are collected for the amendment. All referendums require a simple majority.

Popular referendums are referendums in which a new law is proposed. This requires 500 signatures in 100 days. It should be noted that there are two different portfolios of subjects, with subjects like taxation, finance and scientific activities being a part of the Academic Portfolio, where laws or amendments can be proposed only by settlers having an academic degree in these subjects, while the Public Portfolio consists of subjects like citizenship, law enforcement and infrastructure construction.

Popular referendums are subject to the same amendment rules as optional referendums. The executive of Gaia has the power to return the proposal passed by a popular referendum, with a suggestion for any amendment in the proposal. However, in the event that the proposal is passed another time, the proposal becomes law. This system has been enforced so as to obtain the opinion of the politically experienced executive and to pass the best possible version of a proposal.

Mandatory referendums are generally concerned with holding a referendum during the formation of the Constitution of Gaia. While the other referendums may have people not voting, mandatory referendums involve a compulsory vote. This has been done to ensure that all settlers take part in the process of formation of a constitution. Mandatory referendums are mainly held for introducing laws in the first 4 months of Gaia’s formation. During this time period, in the event that a law is proposed in the Public Portfolio, a mandatory referendum is held. In the event that a law belonging to a subject of the Public Portfolio is proposed, a simple majority is required, while a law belonging to a subject of the Academic Portfolio requires a two-thirds majority.

However, as in any other administration, the function of the legislature is not limited to only passage of laws. Other powers such as approval of Gaia’s annual budget and oversight over the executive are a vital part of the General Council’s powers. It should also be noted that the executive is directly elected by the General Council.

Gaia’s annual budget is prepared by the Executive Council, the executive body of Gaia. The budget is available to the public for 14 days before it is brought to a vote. During the 14 days, settlers holding an academic degree in academics can pass amendments, after securing 500 signatures. After the 14 days term is completed, the Budget is presented in a public meeting of all settlers. Each section of the Budget, along with the associated amendments are discussed, following which, a vote takes place. It should be noted that the vote is not mandatory and requires a simple majority.

The appointment of the executive takes place every 2 years. The Executive Council consists of 10 members. Gaia follows a system of election similar to the Upper House of the Indian Parliament. 5 members of the Council are elected every 2 years, with 5 being elected the next year. This is to prevent the members of the Executive Council from founding coalitions, ensuring that the source of the power of the Executive Council rests in the hands of the General Council. It should be noted that during the first term of the Executive Council immediately after the founding of Gaia, 5 members of the Executive Council are granted a one-year extension in their term to ensure that the above mentioned system is implemented.

The executive council is elected by an optional referendum, where candidates can apply for election after they have received 800 signatures of support 60 days prior to the election. The election takes place through the single transferrable vote system.94 According to this system, each settler casts a vote, choosing the different candidates based on their own order of preference. For example, in the event that there are 4 candidates running for election, the settler votes by marking each of the 4 candidates in his/her order of preference. Following the voting, the candidate who would have obtained the least votes is eliminated, and his/her name is struck off on the settlers voting preferences. This process is followed again, until the candidates who figure among the top ten are obtained. This system is followed as it tends to be more efficient and would prevent several elections from taking place to elect a group of 10. It should be noted that candidates have the freedom to organize political campaigns, but the spread of false news is regulated by a committee of settlers who form the Election Commission and are chosen by the Chief Judges of the Judiciary.

## 6.1.2 Executive

The executive of Gaia is responsible for the execution and enforcement of Gaia’s laws. Gaia’s executive consists of a 10 member council called the Executive Council which forms the executive council of Gaia. Its election process has been described in Section 6.1.1.

The Executive Council consists of a Prime Minister, who acts as the Chairperson of the Council. The responsibility of the Prime Minister is to convene meetings of the Council, set the agenda and maintain decorum during the meetings of the Council. After the election of the Council, the Prime Minister picks one member of the Council as the deputy Prime Minister. The other 9 members of the Council have oversight over the 10 departments of finance, infrastructure, interior, justice, science, communication, trade, ISRU affairs, education and operations. One of the primary requirements for the elections is that the candidates running to be the minister for these departments must have an academic degree in the primary subject of the department. For example, the minister of finance must have a degree in economics, while the minister of communication must have a degree in communications. It should be noted that a candidate running for Prime Minister would also be running for Minister of a particular department. Each of these ministers and their position’s details are described below. It should be noted that the Executive Council has a system of collective responsibility. This is mainly because the decisions of the Executive Council are collectively taken and are taken only upon a vote of the members.

The Executive Council has several officials under each department to make governance easier. The officials of the departments and the law enforcement officials appointed by the Hiring Committee appointed by the Council.

The responsibilities of the 10 ministers are:

1. Finance Minister- Prepares the Budget, oversees expenses and taxation, monitoring Gaia’s currency and its production, regulating banks
2. Infrastructure Minister- Enabling the construction of public structures and transport infrastructure on Gaia, ensuring that construction material is produced efficiently, giving permits to settlers to construct buildings on Gaia
3. Interior Minister- Overseeing the law enforcement officials of Gaia, providing visas to temporary visitors from Earth, enforcing immigration policies, preventing human rights violations
4. Justice Minister- Appointing judges to the courts of Gaia, ensuring that proposals of settlers for amendments in laws or the introduction of laws complies with the Constitution of Gaia and its fundamental principles, returning the proposals of settlers and suggesting amendments to them, advising the Executive Council on legal affairs
5. Science Minister- Ensuring that the industrial processes are taking place efficiently, overseeing research facilities and their activities, establishing medical care centers and appointing doctors
6. Communication Minister- Establishing communication equipment, ensuring that the communication equipment is functioning, ensuring that internal and external communication equipment are maintained and operated, maintaining communication satellites, overseeing communications with Earth, Mars and any space-based human settlements
7. Trade Minister- Handling intellectual property and trade with Earth, overseeing imports and exports between Earth and Gaia, regulation of internal trade, establishment of public markets for trade
8. Minister of ISRU affairs- Oversight on ISRU units and activities, finalizing plans for expansion of ISRU units, appointment of ISRU unit workers, identifying spots which are rich in resources and deciding upon how to expand to those spots
9. Education Minister- Ensuring the smooth operation and construction of schools, playing a key role in deciding education policy
10. Minister of Operations- Overseeing all of Gaia’s day-to-day operations, excluding those handled by other ministers, hiring Gaia’s government workers,

ensuring coordination between different departments and operational units

The term limit for any minister is 3 terms. This has been done to ensure the ministers are always accountable and do not attempt to gain too much power. This has also been done to ensure to prevent corruption. It should be noted that term limits and the number of years constituting a term cannot be modified under any situation. This restriction has been placed to prevent authoritarian figures from gaining dictatorial powers. Several such instances have been seen where a leader or head of state changes term limits to ensure that they remain in power for longer terms, by appointing or influencing the judiciary. Therefore, this particular tenet of Gaia’s constitution cannot be modified under any condition.

## 6.1.3 Judiciary

The judiciary is the most important branch of Gaia’s administration, as it is responsible for administering justice and upholding Gaia’s law. The judiciary must have an optimal judge-to-case ratio to prevent a backlog of cases and to ensure that the judiciary gives the best possible judgement to each case, without hurrying through with a case out of time concerns. An optimal judge-to-case ratio would be around 1:20, providing a judge with ample time to handle cases, while ensuring that there is no backlog of cases. Around 40 million cases are handled by the judicial system of the United States. Therefore, a population of 30,000 can be estimated to have around 4000 cases per year. This would result in Gaia requiring 200 judges to handle the cases and ensure the smooth operation of the judicial system.

Gaia’s judges are chosen by the Justice Minister. It is required that every judge must have had 8 years of experience in the legal system, while holding, at least, a master’s degree in law. Each judge has a term of 2 years, but there are no term limits to prevent a judge from running for the position of a judge again. There is no requirement for a term limit as there can be no concentration of power, which is the main reason a term limit is imposed on other elected officials.

There are 2 different levels in the judicial system, the Primary Courts and the Supreme Court. There are 10 courts on Gaia, each having 20 judges. Out of the 10 courts, 9 are Primary Courts, where all cases, except for cases involving a constitutional violation, are heard. Following the judgement of the Primary Courts, the case may be taken to the Supreme Court, whose decision will be final and binding. Another important thing to be noted is that all cases involving a violation of the constitution are directly heard by the Supreme Court.

Supreme Court judges must also have, apart from the criteria mentioned above, 12 years of experience as an attorney or a judge, and must have had a term in the Primary Courts. The Supreme Court is the highest judicial authority on Gaia. Its main functions consist of hearing cases which have received a judgement by the Primary Courts and have been appealed in the Supreme Court and handling cases involving a constitutional error. In the event that a proposal, which has been passed to become law, is unlawful and violates the Constitution of Gaia, the Supreme Court has the power to strike it down. Striking down a law would require a two-thirds majority vote by the 20 judges of the Supreme Court. Therefore, in the event that 14 judges agree to scrap a law, the law would officially be struck down. However, a law can only be struck down within 14 days of the proposal becoming law. After this time period, any settler of Gaia must obtain 1000 signatures to present the law before the Supreme Court and allow them to strike it off or continue with it. In the event that 1000 signatures are collected, the law is presented to the Supreme Court who then decide on whether to strike down the law or continue with it.

Primary Courts and Supreme Courts are directly under the Justice Minister. After one term of the judges has been completed, the Justice Minister appoints the judges of the Courts. Although he appoints the judges, they aren’t bound to follow his orders. A Judge cannot be removed halfway through his/her term except through impeachment. The impeachment vote is a mandatory referendum requiring a simple majority.

If a simple majority is obtained, the Judge must resign from his post or he must be removed by the Justice Minister. Following the removal of the judge, the Justice Minister must appoint a new judge within 7 days.

**Functions**

It should be noted that minor legal issues, such as traffic violations or minor thefts, are handled by the law enforcement themselves by imposing a fine, and in the case of a theft, returning the stolen items to the aggrieved party. The fines imposed are according to a fixed standard which shall be decided by the Supreme Court. It should be noted that the death sentence is not awarded to any criminal. Although it has been argued that the death sentence deters criminals from committing a crime, no credible evidence of this exists. Bigger crimes or lawsuits are brought before the Courts, where a council of 4 judges hear a case. If 3 judges agree with a particular verdict, that verdict is given by the Court, where if 2 judges agree with a particular verdict, while 2 don’t, the seniority of judges is used for the verdict. If the cumulative age of 2 judges in favor of a particular verdict is more than the cumulative age of the other 2 judges favoring another verdict, the first verdict would be the verdict of the court.

Severe cases are awarded life sentences, to prevent the same crime from being repeated again. The criminal law code of Gaia is the only legal binding document not decided upon by Gaia’s settlers directly. The First Supreme Court, i.e. the Supreme Court which has the first term on Gaia, frames the Criminal Code of Gaia, which can be amended only by a proposal by a judge of the Primary or Supreme Courts. A judge of the Primary Court requires the approval of 50 other judges of the Judicial System, while a Supreme Court judge requires the approval of 30 other judges of the Judicial System, following which, the proposal is discussed by all 200 judges of Gaia and is then put to vote. All votes require a simple majority. Another method for amending the Criminal Code of Gaia is by the request of at least 2000 settlers, following which, it is discussed by the judges of Gaia.

The Supreme Court also advises the Executive Council on legal matters of the state.

# 6.2 Currency

A currency is required on Gaia for payment purposes. If a settler purchases a good, or a worker works for the government or any company, the payment for these will be through a currency. However, traditional currencies are highly regulated by governments and banks. In the event that a person places their money in a bank, the interest rates would be low, as compared to inflation rates, which would cause inflation rates to decrease the value of the money of any settler. However, cryptocurrency would prevent that, as there is no inflation in a cryptocurrency. The amount of cryptocurrency would be limited. For example, Bitcoin has only 21 million BTC, which can ever be mined. In the initial stages of “mining”, there will be high volatility in the market value and inflation will be high due to a current inflow of money through mining. However, the amount of time for which this volatility persists is inversely proportional to the population using it. This is primarily due to the large cash inflow during the initial stages of mining. However, the system of mining, where cryptocurrency is rewarded in exchange for validation of transfers, doesn’t exist in Gaia’s currency. Instead, all validations of transfers are done by the Executive Council’s finance ministry. Thus, there is no inflation at any point and no necessity for settlers to keep money in banks, due to which, the traditional system of banking, which involves bank accounts and interest rates on bank accounts doesn’t exist on Gaia. This is the primary reason for cryptocurrency being chosen.

Cryptocurrency on Gaia, also known as Gaian Dollars(GND), is a decentralized currency used as the primary method of money transfer, with a limited circulation of 10 million GND. The control over validations of transfers is with all settlers of Gaia, but the Executive Council’s Finance Ministry is the authority which has the legal obligation to perform these validations.

The system maintains its value and prevents volatility due to its high demand and usage on Gaia. GND is used as the primary method of money transfer between Earth and Gaia so as to increase the number of potential users of GND and increase its demand.

There are exchange centers on Gaia run by the Executive Council, where settlers can exchange GND for any other currency they wish to.

A blockchain generally relies on a series of blocks, each having a hash number and a timestamp, along with transaction data. However, if the transaction data of a single block is altered, the cash transfer might take place to the unintended recipient. In this manner, there might be attacks on the blockchain by hackers to steal large amounts of cash. However, as each transaction’s data is present in the next block, a potential hacker would need to alter all the blocks of the blockchain. This can, however, be done only with the agreement of a majority of users. Generally, a blockchain is attacked by a 51% attack, where a hacker creates an alternate blockchain, forking from the original blockchain. In the alternate blockchain, the hacker could have complete control over the blockchain and “award” himself with coins by mining the alternate blockchain and creating a chain which is longer than the original chain. As the hacker is the only user present in the alternate blockchain, or controlling more than 51% of the alternate block chain, the overwriting of blocks to award himself with any amount of money is possible. Following the forking, the hacker broadcasts to the original blockchain that the alternate blockchain is the original chain. The consensus protocol will agree to this, since the alternate chain is longer than the original chain. This will result in the alternate chain being considered as the original blockchain, where the hacker has added large amounts of money to his own account. However, there is a way to prevent such attacks.95 The number of blocks between the latest block mined and the block where the hacker tries to fork the blockchain is counted at the time when any user broadcasts about the status of the blockchain. If the number of blocks between is 5 or more, the blockchain can inform the users about the cryptocurrency account of the hacker, which is then used by law enforcement to trace and arrest him.

However, there will be an increase in the inflow of currency on Gaia which might lead to an increase in the number of GND. Two solutions are present to solve this. In the event of transactions, it might be made compulsory to use Earth’s currencies on Earth only. This would lead to a constant number of GND being in circulation. Another possible method is to increase the number of credits directly in proportion to the amount of GND which needs to be added to the blockchain. This would involve a 51% attack conducted by the Government, where the number of blocks is extended, without any mining taking place. Following this, the Earth-based currencies are converted to GND and added to the blockchain, while the amount of GND which has been lost by the individual members of Gaia is added to the individual accounts by the Governments. This is used only rarely, only when a large amount of Earth-based currencies(above 200 million USD), is to be converted to GND. This particular action takes place under the supervision of the Supreme Court and the Finance Minister to prevent anyone from tampering with the blockchain.

# 6.3 Recreation

Recreation on Gaia is vital for maintaining the mental health of the settlers. Maintaining the mental health of settlers also increases their productivity. Recreation in Torus 3 is generally of the same variant as on Earth. It includes theme parks, sports fields and parks. However, the primary recreation centers are the zero-g recreation centers, which are located in the Central Core.

The recreation facilities are generally maintained by the Executive Council and its lower, local bodies. However, it is possible for enterprises to set up recreation centers. Zero-g facilities are, on the other hand, maintained only by the Executive Council to prevent accidents of any kind.

Several sports fields are present. Sports such as football, rugby, cricket, basketball, and other games which are highly popular have specialized fields, while less popular sports have generalized stadiums, which use mobile equipment to temporarily convert the sports field to a field for that particular sport.

Zero-g recreation involves several activities like gymnastics and zero-g football. Zero-g provides an environment unlike anything on Earth, due to which the different games and their zero-g versions would be hard to predict. However, the zero-g facilities are maintained directly by the Executive Council to prevent mishaps from occurring in zero-g. Gymnastics in particular is expected to undergo large scale changes. Apart from providing recreation for settlers, zero-g recreation is expected to be a major tourist attraction of Gaia.

Apart from sports, several gyms and yoga centers are also present on Gaia. Some gyms are operated by the Executive Council, while there are specialized gyms present on Mars to ensure that all workers work out for at least 1-2 hours every day to prevent bone density and muscle mass.96 Several recreation centers are also present on Mars for the workers. Although enterprises can establish recreation centers on Mars, the economic unfeasibility makes it unlikely. Therefore, the construction of recreation centers and gyms is handled by the Executive Council to ensure that the centers present on Mars are sufficient without any extra construction by enterprises.

Digital content on Gaia is also available, mostly in the OTT form. Most Earth-based content would be transferred to Gaia initially to prevent the hassle of having to download films on Gaia from Earth. This would be highly problematic as the downlink time would be a lot, extending to 20 minutes at times. However, Gaia’s official broadcasters or other enterprises would be expected to download digital content from Earth regularly and distribute to the settlers. This would be more useful, instead of thousands of settlers attempting to download the same movie. A Film Broadcasting and Shooting Council would also be created to promote the production of films on Gaia. Several Earth-based directors and production houses could be invited to shoot movies on Gaia.

Artificial beaches are also a concept which can be developed as a method of recreation. If sufficient light is produced(around 100,000 lux), the sunlight of beaches can be mimicked, along with the use of large wave pools and the use of a zero-depth entry pool, where the depth of the pool increases gradually inwards. Sand could also be imported from Earth to make it more realistic, but care must be taken to prevent it from being contaminated.

# 6.4 Demographics

The demographics of Gaia are not controlled by the administration on Gaia. Initially, the population chosen is intended to represent Earth’s different ethnicities in the same proportion as on Earth. As this is an entirely new world in space, it is expected that Earth’s conflicts wouldn’t play a role in separating communities on Gaia.

The population for Gaia during the initial years is chosen in such a way that no one ethnicity does not have a majority. This would prevent any form of majoritarianism and would ensure that all communities would co-exist peacefully. Another thing to be noted is the population control. Gaia does not have the capability to have a population larger than 40,000. Therefore, a restriction on the number of children a couple can have is necessary to prevent a population explosion. A good example of this is China’s One-Child policy. According to this system, parents with a single child are rewarded financially, while parents with 2 or more kids have hefty fines imposed on them.97 Generally, the fine could be a substantial fraction of the family’s total fine. The reward system can be based on a ‘certificate’, which allows lower cost for use of certain family-themed governmental activities or the lowering of entry costs for theme parks, recreation centers, etc. It should be noted that these policies are implemented when the population exceeds a limit of 35,000. As the average fertility rate can be expected to be around 1.6, which is the average for the OECD.98 Assuming an average death rate of 7.7 per 1000 people, which is equal to the global average death rate, and an average birth rate of 18.5 per 1000 people, which is equal to the global average birth rate, the net birth rate is around 10.8 births per 1000 people per year. Therefore, Gaia, which has a population of 30,000 population initially, can be expected to grow at a rate of around 324 people per year, while the rate will increase by 11 more births once every 3 years. Therefore, Gaia could reach a population of 35,000 in 9 years. However, to ensure that the population decreases, or at the very least plateaus, the One-Child policy after the population reaches 35,000. However, if the population drops to 30,000, the One-Child policy can be removed.

After the One-Child policy has been implemented, however, the birth rate can be expected to drop to 1.1, based on numbers from the Chinese One-Child policy.97 The death rate, however, would remain constant. Therefore, the average birth rate can be estimated to be around -6.6 per 1000 people per year. For Gaia’s population of 30,000, the average population decrease per year can be estimated to be around 200 people. Therefore, the population would take around 25 years to reach 30,000. Therefore, an alternate cycle of 9 years and 25 years is expected to effectively maintain Gaia’s population, to prevent a population explosion, while also preventing the population from dropping to low numbers.

All settlers are allowed to practice their religion freely. The Executive Council could also construct public places of worship for all religions. However, while all religions have the freedom to practice their religion, public displays of religion, which might cause disturbance, is not allowed. Public calls to prayer in Islam would not be allowed, while an alternate system, where the time for prayer is notified to every Muslim through an app on their phone would be encouraged. All attempts at proselytization is banned. Therefore, Gaia allows the freedom for settlers to practice their religion, but actions which might cause public disturbances aren’t allowed.

The demographics of any particular ethnicity will not be controlled by the Executive Council in any manner. In the event that a population reduction is required, the One-Child policy is implemented in such a manner that all ethnicities are equally affected by it. While preventing a particular ethnicity or religion from increasing in population to become a majority is unethical and will not be done, the active implementation of measures to reduce a particular ethnicity’s population is also unethical and unlawful on Gaia.

#### Section 7

Construction

Construction of Gaia will take place in several phases, with each phase forming the basis for the next phase of construction. The establishment of the life support systems is one of the most important phases which is done only after the complete construction of Gaia’s external structures and some vital internal structures has taken place.

The establishment of a small colony on Mars is also necessary. It would be infeasible to transport titanium, the construction material to Martian orbit, which is millions of kilometers away. Therefore, it is imperative that the procurement of titanium must be from local Martian sources. Apart from this, the construction of launch vehicles and fuel production are also the primary activities in the initial stages of construction. As titanium procurement, launch vehicle manufacturing and fuel production are all based on Mars even after the construction of Gaia, it would be economical to establish the Mars colony at the future ISRU sites. Therefore, the Martian colony is located in the Tharsis plateau region, where more ISRU units for metal extraction, opal mining and launch vehicle fuel production are constructed in the future.

After the Martian colony has been constructed, the actual construction process of Gaia would begin. The different sections of Gaia will be completed in the outward manner, where the Central Core is constructed first, following which, Torus 1, Torus 2 and Torus 3 are constructed in that order. The vital parts of the interior, such as the flooring, lighting, and communication infrastructure, are constructed, following which, the Life Support Systems are installed. After the installation of the Life Support Systems, a few humans, mainly construction workers and a few government officials settle Gaia, with the workers constructing the finer parts of Gaia, such as the residential sectors, restaurants, etc. Upon the completion of the interior, Gaia can be steadily populated.

Several launch vehicle missions would be required to construct Gaia. If non-reusable launch vehicles are used, several rockets would have to be constructed, increasing the construction time for Gaia significantly, while also wasting several resources. For this purpose, reusable launch vehicles are used, which significantly reduce cost and time.

# 7.1 Phase One

The construction of the Martian colony takes place during Phase One. This is a stage where Gaia is almost entirely dependent on Earth. During this stage, material from Earth is transported to Mars, where it is used for the construction of the Life Support Systems and the vital ISRU units. The location of this Martian colony is near the Tharsis Plateau region, which contains adequate amounts of water and metals.

The Mars colony would be constructed out of the local Martian regolith. However, robots on Mars for the construction, machines for the different ISRU processes and some materials for the assembling of RTG’s are some items which have to be imported from Earth. As these items would be required for construction processes, while the construction material is obtained from the Martian regolith, the import of these items would have to take place only once. Therefore, it can be estimated that around 3+2 launch vehicles would be required, with 3 launch vehicles, having a cumulative cargo mass of 450 tons and 2 launch vehicle which would carry around 200 humans. There will also be follow-up missions bringing in around 1000 humans once the Central Core has been established.

The fuel depots launch sites and ISRU’s are constructed using Martian regolith. Though it can be argued that the use of 3D printers for the construction of the ISRU’s or any other structures would make the task easier, the best 3D printers in the world use either concrete or plastic, while being incapable of handling material like steel or Martian regolith. Therefore, the Martian regolith is first modified into several flat blocks of ISRU walls. Following the formation of the required amount of blocks, friction stir welding is used to weld these different blocks together. The basics of friction stir welding are as follows: the two blocks are clamped together, following which, rotating cylindrical tools, which could be made of tool steels such as the L6 type of steel. The rotating cylindrical tool generates heat due to friction and other

sources, which heats up the material to soften it, which then fuses together, both due to their soft state and the mechanical pressure of drill.

Following the formation of the blocks, they are assembled by a team of robots and humans. The robots can be utilized for carrying a heavy load of the blocks, while humans could assemble the blocks.

The design of the first few ISRU’s are to be similar to the ISRU’s mentioned in Section 4.4. The main resources required in Phase I would be rocket fuel/oxidizer, oxygen, carbon dioxide , water, titanium and food crops. The ISRU’s producing launch vehicle fuel, provide all the resources mentioned above, excluding titanium and food crops. However, the seeds of the food crops are provided during the launch vehicle missions, while the water, oxygen and carbon dioxide are procured from the Sabatier reaction or are obtained from the atmosphere. It is estimated that around 10 ISRU units are required, which would collectively produce around 80 kg of fuel per hour(Section 4.4). It can be estimated that Gaia would require around 30 missions to be constructed, while the launch vehicles would be launched over a period of 8 years. Therefore, around 6000 tons of methane would be required, which would be produced easily by the ISRU units.

7 metal extraction sites are to be constructed near the Tharsis Plateau Region, which is rich in metals like Titanium. Based on the surface area and thickness calculations in Section 1.1.3, the amount of titanium required would be around 120,000 tons of titanium, which is equivalent to the amount of titanium China produces in 2 years.99 Each of the ISRU units can process around 250 kg of 99.7% pure titanium per year.100 The titanium required for the construction of Gaia would be produced within 7.5-8 years.

Phase I will also involve the construction of the Central Core of Gaia. The titanium plates are to be welded together using the friction stir welding method on Mars.

The titanium plates are then to be transferred to the Mars-Sun L2 point, where robots are to assemble the different parts of Gaia. After the core has been established, the different life support systems are to be established, including the food and water reserve, for around 500 workers.

The core is small in size, along with being incapable of launching any missions towards Earth or Mars. Gaia’s artificial gravity is generated by the rotation of the structure. Gaia is set into rotation by the mission launches, but due to the lack of capability of launching a mission, there would be no artificial gravity on the Central Core. One of the methods to prevent any health-based negative effects is to establish gyms in the Central Core. However, due to the present size and the lack of space, it is not possible to establish gyms. It is estimated that the loss in bone mass is around 1.5% per month, with the safe limit being 2%.101 Therefore, astronauts can go on missions to Gaia for around 1.5 months without any serious side effects.

Following the establishment of the Central Core, the on-board titanium refining units are to be set up, which will, after the complete construction of Gaia, be converted into metal refining units, including titanium among other metals. The atmosphere of the Central Core at this point is 80% nitrogen and 20% oxygen, as the Central Core will be the primary base of operations in space for Gaia.

After the Central Core and all its internal industrial units have been set up, some amounts of titanium can be brought up to the Central Core, where it is converted into metal plates and used for the establishment of further structures such as the tori, along with the industrial and life support systems.

The radiation shielding is also a necessary hazard to be considered at this point. Therefore, to prevent the workers on the Central Core from being affected by radiation, the graphite and steel required also have to be produced. The graphite is produced using the excess carbon dioxide present in the ISRU’s atmosphere, while the iron is easily available as it is obtained directly during the Martian regolith’s electrolysis.

# 7.2 Phase Two

Following the construction of the Central Core, the metal refining and extraction ISRU’s along with the fuel production units, and an established system for conducting missions from Mars to the Mars-Sun L2 point, the next logical step would be the construction of the inner tori(Torus 1 and 2), along with the expansion of ISRU units on Mars.

The construction followed in this Phase is similar to the construction process followed in Phase I, but the facilities for the production of the titanium plates are expanded. Two more habitats are constructed on Mars for around 2000 workers to temporarily settle on Mars.

The ISRU units constructed on Gaia are now diversified into producing several different products, along with being placed at different locations. ISRU units are established near Valles Marineris and the Korolev Crater. The first few ISRU units for opal and deuterium production are established, with the production capacity of water being increased, with the establishment of more water extraction sites near the North Pole.

The number of water extraction sites are increased by almost 2 times, with an improvement in the infrastructure for transporting the water from the extraction sites to the other ISRU units. Water transport between the different ISRU units can be simplified by the establishment of large pipeline systems. A good example of this system is the Great Man-Made River of Libya.102 A cluster of 15 pipes, each of diameter 70 cm, can be semi-buried in Martian soil, and used to transport water. The pipelines could be made of material like carbon steel, which would reduce weight and abrasion. The pipelines are semi-buried to provide protection for the pipeline, while also not having to dig Martian soil for kilometers on an end. The water from the pipelines is regularly diverted to a reservoir of sorts. The pipeline also has water volume sensors throughout its surface. This is done to monitor and cut off water supply in the event of a leak or damage to the pipeline. If it is detected that the pipeline is leaking water at any point, the sensor can notify the reservoir, which cuts off water supply, and stores incoming water while the leak is repaired.

The launch vehicle fuel production units are also constructed at the base of Olympus Mons, along with the establishment of launch vehicle ports at a height of around 12 kms(Section 4.4). The reason launch vehicle ports are established at Olympus Mons is primarily due to the rarer air, which would result in the amount of pressure acting on launch vehicles reducing significantly. The pressure at an altitude of 12 km reduces the pressure to around 72 pascals, thereby reducing the amount of fuel consumed by the launch vehicles.

The metal extraction and refining plants on Mars are increased in number, producing more titanium, while also enabling the production of other metals as well. It is expected that till this point, silicon and other materials would have to be imported from Earth for the production of electronics, or other consumer products using materials like silicon would have to be imported from Earth. However, the production of metals like silicon on Mars, at this stage, would make Gaia self-reliant in the production of different machines, electronics and various other products.

At this stage, special graphite and steel production units are also established. Phase 2 and Phase 3, which together involve the construction of Torus 1,2 and 3, require large amounts of graphite and steel for the production of the radiation shields. The graphite used is an artificial form of graphite, synthesized from soft, graphitic carbons. These carbons or their carbides are heated at high temperatures of 2500 K, which would then form graphite in large quantities, while also reducing costs.103 Steel, on the other hand, is produced easily, by alloying the iron obtained during the electrolysis of Martian regolith.

The tori will be constructed using the same titanium plates mentioned in Section 7.1. The titanium plates are welded together using friction stir welding on Mars, while they are welded using the stick welding or other such techniques. However, the primary construction problem faced during this construction technique is the construction of the tori. Tori can withstand a larger pressure gradient between the internal and external areas, primarily due to them having no fixed corners. However, it is hard to construct a torus, because reinforcement would be required at several points throughout the torus. However, instead of adding reinforcement structures, the plates being used in the construction of the torus will be slightly overlapping, in a structure similar to a lap joint.

Torus 1 is not constructed in its entirety all at once, but is instead constructed in a modular method, with the torus being divided into several different modules. Each module would contain nothing but a construction area near the exterior, and a storage area near the interior of the module. The storage area would contain all the materials required to build the next module, therefore freeing up space in the Central Core. It should be noted that during the construction of the modules, only 4 different modules are under construction at any point. The 4 modules can be considered to be two pairs, with each pair being diametrically opposite. This is done to prevent the center of mass of the entire structure of Gaia from shifting. In the event the center of mass shifts, the force exerted during the reception of different missions from Mars may cause Gaia to have stability problems. After the construction of all the modules, the walls separating the different modules are removed, therefore completing the construction of a torus. Torus 2 is constructed in a similar manner.

After the construction of Torus 1 and Torus 2, all life support systems will be installed, along with the establishment of lighting and other basic structures. Food growth is to begin on Torus 2, along with the production of metal refining sites and plastic production units.

However, the biggest addition to Gaia at this Phase is the Integral Fast Reactor. The structure is to be constructed initially. After the entire system has been constructed, the liquid sodium is to be transported to Gaia. Around 200 liters of liquid sodium is required. 200 liters of liquid sodium weighs 185.4 kg. This amount of liquid sodium can be easily carried by a GMV, with around 95% of the cargo mass being used for other purposes. However, liquid sodium is highly flammable, making its transportation a high-risk mission. Therefore, the mission upon which the liquid sodium is transported transfers material which is easily reproducible or of lower importance. A failsafe is installed, to ensure that the rocket blows up in the event that the liquid sodium begins leaking, therefore preventing the rocket from blowing up in vicinity of Gaia. The liquid sodium is stored in 200 1-liter steel containers, at temperatures below 20°C.

Another addition to Gaia is the installation of the Liquid Droplet Radiators(LDR’s), on the external surface of Gaia, which will be responsible for the radiation of almost 72% of Gaia’s unused heat(Section 2.4). The installations of these radiators will be hard, primarily due to the EVA missions which would be required, while regular refilling of the liquid storing tanks would be required. However, the use of robot crawlers, such as NASA’s Robonaut, can be useful in performing these missions. Robots can easily be developed to perform the installations and refills.

# 7.3 Phase Three

Phase Three is the last phase in the construction of Gaia. It mainly involves the establishment of several ISRU’s, the construction of Torus 3 and the expansion in the facilities on board Gaia. This is the phase where settlers would begin settling Gaia, permanently and in large numbers.

The opal mining units are to be increased in number, while only 2 deuterium production units are to be established on Gaia. The opal mining units are increased, so that larger amounts of opal are sold. However, lower amounts of deuterium are produced at this point, mainly due to the lack of a high demand for it. Instead of building more deuterium units, Gaia must perfect the process of deuterium production, while slowly increasing the number of deuterium units. This will enable the sale of high-quality of deuterium at lower rates to Earth, helping Gaia increase the amount of deuterium purchased.

The Torus 3 is constructed in the same modular method used for Torus 1 and 2. However, the mass of the modules would be significantly decreased, allowing the center of mass to be changed in an insignificant manner during construction. This allows the construction of several modules at once. If the same method as mentioned in Section 7.2 was followed, the construction of Torus 3 would take several years. The titanium plate production, along with their welding is done locally on Gaia, thereby reducing the number of missions between Gaia and Mars. Along with this, aluminum refining units are also setup on Gaia. Therefore, several internal structures, such as houses and factories are also built quickly and, in some instances, parallelly with the construction of Torus 3.

The Integral Fast Reactor is operating at maximum capacity at this point(200 MWe), but the amount of energy to be used for the settlers and other such uses is extremely low, mainly due to the low number of settlers and workers present on Gaia. Thus, this large, permanent energy source allows for a larger spending of energy on the processes which are directly responsible for the construction of Gaia, like titanium and aluminum refining, plate production, etc.

After the construction of Gaia, the entire structure needs to be rotated to produce the artificial gravity. It has been estimated in Section 1.1.3 that a tangential velocity of 75 m/s is required for Gaia to have Earth standard gravity of 9.8 m/s2.

Assuming that each of the GTV’s exert a force of 3000 kN, on a mass of around 1.5 million tons, the amount of acceleration produced is around 0.002 m/s2. This figure can be easily calculated using Newton’s Second Law of Motion’s equation. To obtain a velocity of 75 m/s, the force would have to act for 37,500 seconds. As the GTV’s have a burn time of around 800 seconds, around 47 missions would be required to obtain the required artificial gravity, consuming over 11,280 tons of liquid methane.

The life support systems have to be installed in Torus 3 before settlement. In this phase, the air present in the Central Core is transferred to Torus 2, while the emergency chambers are being established. The liquid components of the air are converted to the gaseous form and introduced into Torus 2 and 3, while the carbon dioxide regulators are also installed. The water supply routes through the “spokes” of the tori are setup, along with the communication lines.

Most of the work to ever take place on the Central Core and the tori have already been finished. However, several structures like theme parks, fields, etc. aren’t constructed yet in Torus 3, while the artificial meat production lines aren’t sufficient to feed a population of 30,000. However, these will be constructed in due course of time.

Finally, the settlers are transported from Earth to Gaia. Assuming that each mission carries around 50 humans, around 600 total missions are required for transporting the 30,000 people who will form Gaia’s initial population. However, the launch vehicles are completely reusable, while the number of missions launched at any one point are around 15. Considering that missions are launched every 15 days, the entire population can be transferred to Gaia within 1 year and 8 months.

#### Section 8

Finances

The finances and the annual budget of Gaia are usually handled by the Finance Ministry. There are several costs incurred by Gaia, including launch vehicle missions, ISRU unit’s construction, etc. However, these are costs which are paid only once during Gaia’s lifetime. Most of Gaia’s cost is incurred during its construction, with a majority of the cost being incurred due to the import of material and machines during Phase One of construction. However, after the construction of Gaia’s main structure and the ISRU units, the costs are significantly decreased, with the main costs being incurred due to the import of some materials and from the missions between Gaia and Earth. Some costs would also be incurred due to the welfare programs for settlers.

The main sources of income for Gaia are the export of deuterium and opals. However, deuterium is not a product which is required in large quantities right now, mainly because nuclear fusion hasn’t been developed sufficiently to operate on a commercial scale right now. Therefore, deuterium production units are few in number initially, working on perfecting the production technique and lowering production costs. The opal units, on the other hand, are built in large numbers in different regions such as the Tharsis Plateau region, which is also the site of the metal extraction units, and the base of the first, temporary Martian colony.

# 8.1 Construction costs

The construction costs are relatively low. During Phase One, most of the construction material for the Mars colony and the few ISRU units is imported from Earth, because it isn’t possible to possible to produce such high amounts of material during the early stages. Therefore, materials like aluminum would have to be imported. Steel and plastic are also required.

Assuming 2 dome-shaped habitats of radius 20 m are built for the workers in Phases One and Two, the amount of aluminum required would have a mass of 6.7 million kg. However, instead of exporting all this aluminum, which would be infeasible and require around 40 missions. Instead, this aluminum is used to establish a small habitat for a few workers, while some aluminum is used in the construction of an aluminum refining plant. This would require a much lower amount of aluminum, which can eb estimated to be around 600 tons, or 4 GTV missions worth of cargo mass. Assuming standard rate of aluminum on Earth, the aluminum would cost 1.2 million USD. Assuming the ISRU’s are of a similar size, Phase One would require around 11.2 million USD, while Phase Two would require 6 million USD. It should be noted that the amount of material, including aluminum, used in Phase Two is more than the amount used in Phase One, but the amount imported is decreased because most of the aluminum imported during Phase One is used in the construction of aluminum, steel and titanium refining plants.

Next would be the polyethylene imports. Polyethylene is imported for the construction of the radiation shielding of the worker settlements on Mars. Though other materials like graphite and steel are used on Gaia, polyethylene is sufficient for Martian radiation. The polyethylene would have a thickness of around 10 cm. Therefore, around 285 tons of polyethylene are required for the Martian colony. This would cost around 300,000 USD. Adding up the costs for the ISRU’s, the cost of polyethylene imported adds up to around 4.3 million USD.

Though aluminum and polyethylene form the bulk of the construction material imported from Earth, some materials like steel and titanium are also imported by Gaia, mainly for the repairing of different machines. However, this is for barely a few months, and the amount imported is negligible as compared to the other imports, due to which, it isn’t mentioned.

Therefore, total construction costs are mainly for Phase One and Phase Two.

# 8.2 Launch Vehicle costs

The primary cost for space settlement of any kind is the cost associated with launch vehicles and their fuel. However, the GTV, modelled on the SpaceX Starship, is extremely cheap. Using the GTV results in 1 kg of cargo mass costing 20 USD, while using rockets like the Atlas V results in 1 kg of cargo mass costing 12,220 USD. Therefore, the prices of Gaia’s launch system are so radically low, that the total costs are decreased by almost a third.

The different substances which have to be imported to Gaia are the construction materials, machines of different kinds, certain consumer products, while also transporting the settlers of Gaia. The construction materials have been described in Section 8.1. The machinery used can be expected to weigh around 500 tons in total.

The consumer products required by Gaia are not an immediate import, and will take place on a larger scale upon the construction and permanent settlement of Gaia. However, 3 missions per month, carrying over 450 tons of cargo, is expected to be sufficient.

The settlers consume a significant amount of the launch vehicle costs. Around 30,000 settlers are transported during the first stages of settlement. However, each GEV has the capacity for transporting only 50 humans. Escaping Earth’s gravity well would cost a lot for normal rockets. However, the GEV can easily transport 50 humans for a very low cost. Around 600 total missions would be required to transport 30,000 people to Gaia, which would add up to around 1.2 billion USD in costs. Though the cost is generally calculated by multiplying the cost-per-kg with the actual mass of the cargo, or in this case, the settlers, the cost cannot be calculated in that manner, primarily because of the large amounts of space which would remain unused during a human settlement mission. Therefore, transporting 150 tons of cargo, would cost the same as transporting humans whose total cumulative weight would be around 3.25 tons. Another cost multiplier would be the several protection standards on board, along with the slightly higher energy consumption. Any mission would be exposed to large amounts of radiation, but the exposure of humans to radiation would be extremely harmful. Several protective measures, such as the construction of special radiation protection chambers, use of some amounts of polyethylene on board and so on would significantly increase the cost of human missions from Earth to Gaia.

Another cost increasing factor for human missions is the different path followed. Human missions to and from Gaia are a conjunction-class mission(Section 2.1.2). This method reduces time, therefore reducing radiation and preventing any long-term mental health effects on the settlers, but the cost of the mission slightly increases, due to the higher amount of fuel used. The amount of fuel used increases by around 43.6 tons of liquid CH4 per mission. However, each kg of liquid methane costs around 1.35 USD, therefore increasing the total cost of the mission by 60,000 USD.

The total cost of transferring 30,000 humans to Mars is around 1.38 billion USD, factoring in the increased fuel costs, the protection methods, and the cost of the launch vehicle itself.

Supply missions are also a major cost, though they cost much less than settler missions. The main factor, responsible for the lower cost of supply missions, is the cost-per-kg. Human missions provide for the transport of 3.25 tons for a cost which would be slightly more than 2 million USD, while the supply missions would transport 150 tons for a cost of 2 million USD. However, the cost of supply missions increases due to the large number of those missions. As the GTV’s are completely re-usable, the main cost would be the fuel, liquid methane. The cost of liquid methane is low, costing 1.35 USD per kg. It is estimated that around 240 tons of liquid methane is required per mission, costing 324,000 USD of rocket fuel per mission. Gaia would need 30 missions to be constructed. Therefore, Gaia has a fleet of 30 launch vehicles. Each would require 2 million USD to be constructed, with the cost of fuel for each mission being 324,000 USD. 30 missions in all would cost 70 million USD.

Assuming that 3 missions are required each month for the resupply of Gaia, the total cost per month would be around 1 million USD.

Therefore, the total launch vehicle cost for Gaia during the initial stages would be 70 million USD. Following the construction, the cost of the mission per month would be around 1 million USD.

# 8.3 Imports

Gaia’s imports from Earth are one of the major yearly costs. However, it would be very hard to predict the imports of material. Therefore, all of Gaia’s residents have the ability to purchase goods from Earth, but they are shipped by Gaia’s administration from Earth. In order to pay for the transportation of those goods, a tax is imposed on the settlers, which could be anywhere between 5-15% of the annual income.

Gaia’s imports, which refers to the imports required by Gaia for public works such as ISRU units, growth of food, etc., are generally fixed. The imports on themselves wouldn’t be costly, as compared to the cost of other operations, but their transportation would be a problem. An instance of this is seen in the imports of plant seeds and animal cells. These imports are required in a high quantity, but they require adequate protection. Therefore, Gaia also needs to impose a tax for the imports of items like these, while the launch vehicles are paid for by the profits Gaia earns, from the sale of deuterium and opal, and from the prices paid by the settlers for different utilities like electricity.

# 8.4 Exports

The primary exports of Gaia are opal and deuterium. The sale of these items is expected to be the main source of income for Gaia. Opal is a material which can be sold easily on Earth, due to the high demand and low supply, but deuterium cannot be sold right now on Earth in large quantities. Deuterium’s primary sales are expected to be to the nuclear fusion industry. However, at present, nuclear fusion isn’t a viable energy source. Therefore, deuterium is initially sold for other purposes, like for the medicine industry and for scientific purposes. However, upon the development of nuclear fusion as a viable energy source, deuterium is expected to be a major revenue maker for Gaia.

It is estimated that around 4000 kg of opal is refined every year on Mars. One kg of opal costs around 360,000 USD. Therefore, 4000 kg of opal brings a revenue of around 1.44 billion to Gaia every year. The main points of sale on Earth would be in Western European countries, the US, China, Japan and India. However, as more opal mining sites are constructed, the production of opals would increase. It is expected that by the end of the first decade of Gaia’s construction, the opal refined in one year would be around 7000 kg. Mars is rich in opals, with several locations having several tons of opal. Several examples, like the Tharsis Plateau and the Valles Marineris canyon. The cost of transportation of the opals is minor, compared to the profits earned from their sale. However, instead of sending several missions to Earth, the opals are transported to Earth in a single mission, probably at the end of one Earth year. Another possible option for the transport of opals is the sale of small amounts of opal throughout the year, with transport of some amount of opal, along with other exports to Earth. The second method is preferred, as the first method might be conceived as a form of economic dumping, along with creating a relatively higher supply of opals.

There are around 15 deuterium production lines, producing 30 kg of deuterium per hour. Therefore, the total capacity for deuterium production is around 270,000 kg of deuterium per year. The 15 deuterium production lines are expected to be completely built within 5 years from the start of Phase Two. However, after the development of nuclear fusion as a viable energy source, the number of production lines are expected to increase to 25. Gaia will also be expected to invest heavily in the development of the deuterium production process, to maximize the amount of deuterium produced, along with increasing its purity. It is expected that within 10 years of Gaia’s establishment, its deuterium production capacity would have increased to 100 kg of deuterium produced per hour, therefore producing around 876,000 of deuterium every year. Initially, the sales of deuterium are expected to bring a net revenue of 372.5 million USD.[[3]](#footnote-3) However, after the expansion of the deuterium production facilities and an improvement in technology, the net revenue is expected to be around 1.2 billion USD.

Therefore, opal and deuterium together are expected to bring in a revenue of 2.6 billion per year, within the first 5 years of Gaia’s construction. However, there could be another source of income for Gaia, which though abstract in nature, has been proven several times in history to be a major source of revenue. As stated by Robert Zubrin in “The Promise of Mars”, the labor shortages, the difficult conditions on Mars, the society which would be harmonious in nature(as compared to Earth), along with the adventurous and intelligent population might result in Gaia developing several new technologies, in fields like biology, energy, transport and communication. It would be obvious that scientific development would aid Gaia, as the new technology would help in reducing the effects of the harsh conditions of Mars. The development of such technology would also be useful on Earth. The licensing of this intellectual property, or the establishment of factories on Gaia to sell these products could be a large source of revenue for Gaia.

# 8.5 Net Cost of Gaia

The net cost of Gaia consists of the difference between the cost of construction of Gaia and the profits earned from the sale of deuterium and opals. Several other costs, such as the costs incurred by the several launch vehicle missions must also be factored in.

The total cost of Gaia during Phase One is expected to be around 500 million USD, with the expansion of the ISRU units costing around 3 billion USD more. The basic cost of the Mars base and the launch vehicles is low, but the construction and expansion of ISRU units, along with the cost of importing technology and machines from Earth. The costs have been detailed in Sections 8.1 and 8.2. Therefore, the total initial cost of Gaia is around 4 billion USD, including the launch vehicle missions and fuel.

Assuming 3 supply missions take place every month, the total cost would be around 6 million USD per month, with an annual cost of 72 million USD, or 216 million USD in 3 years. However, several other factors such as imports from Earth and so on, add the cost up to at least 10 billion USD.

The total cost of Gaia after 5 years is estimated to be around 15 billion USD, though it can be assumed to be 20 billion USD to account for other expenses, such as the construction of factories and different facilities on Gaia, which haven’t been included. Gaia makes a profit of 1.7 billion USD per annum. Therefore, the base cost is recouped within 9 years, with Gaia making a profit of 1.5 billion USD per year.

#### Section 9

Conclusion

Gaia is meant to be the future home of humanity, but its population capacity is too low to ensure that humanity repopulates within a time frame of, say 100 years. Therefore, Gaia will be the first step in a long series of space settlements, built all over the solar system. Several other large structures, like a skyhook system, could also be constructed to ensure that transport times between Earth and Gaia, initially, and Earth and the Outer solar system decrease by several months. The construction of such structures would help in reducing the time and cost of building new space settlements by several years and billions of dollars. It can be guessed that skyhooks would be a necessity for the construction of space settlements, mainly due to the fact that the GTV’s used by Gaia would unable to transport significant payloads to the Outer solar system.

However, new space settlements aren’t expected to be the only new structures constructed. In the not too distant future, perhaps within 10-15 years, special structures, like a skyhook might be constructed, which would reduce the travel time between Earth and Mars by several months. One interesting proposal would be the use of Phobos as a counter-weight, primarily due to its small size, but sufficient weight. A system of skyhooks between Earth and Mars, could also be used for transportation with the inner and outer Solar System. Mars, and Gaia, could act as a major transit point for any missions to the outer space settlement. The construction of any space settlement in the outer solar system would need to use Mars, mainly for its resources and as a stopover to planets like Neptune and Saturn.

The new space settlements could be located in locations like Titan, which has a large amount of water on its surface, or Ceres in the asteroid belt, where there are millions of tons of valuable resources, like gold and iron, and water. The titanium, iron and aluminum resources of Mars could be used for the construction of the base colony on these planets, along with the construction of ISRU units. Mars could also be a transit point, with shipments from Earth landing on Mars, and then using the already built Martian launch infrastructure to send exports to the asteroid belt.

# 9.1 Future space settlements

Space settlements of the future would be constructed in locations like Ceres and Titan. Section 1.0.3 contains a comparison of different locations for Gaia. As the launch infrastructure would have been developed significantly on Mars, it would be easily possible to send several missions to the asteroid belt or Saturn’s moons. Olympus Mons, the primary launch site for Gaia is expected to have the capacity to launch 10 GTV’s per day. The liquid methane production sites located at the base of Olympus Mons would be a reliable source of fuel to the GTV’s. Olympus Mons has several advantages, due to which, it is chosen as the primary launch site. It’s high altitude results in low atmospheric pressure, therefore reducing fuel consumption. It is also located very close to the Tharsis Plateau, where most metal refining and deuterium production sites are located.

It is estimated that around 13,400 tons of titanium is produced per month. The amount of aluminum produced is around 20,000 tons per month. Gaia weighs around 1.62 million tons. The amount of aluminum and steel produced is sufficient for the construction of a second Gaia as well. However, the amount of titanium required for the construction of a second Gaia would be massive. It is estimated that a second Gaia can be constructed within 10 years.

It can be safely assumed that the second space settlement would be similar to Gaia with regards to the layout. The cost would be around the same as the cost of building Gaia, as the distance and the orbits followed, which would be the Hohmann transfer orbit, while using the ballistic capture method, would be the same followed during the Gaia.

However, the main difference would be the location. Ceres, for example, is located in the asteroid belt between Mars and Jupiter. It contains millions of tons of water and several other valuable resources, like iron and titanium. Titan on the other hand, contains large amounts of water, methane and hydrogen, all materials required for human survival. Therefore, Titan and Ceres seem like suitable options, but the presence of a large amount of resources, such as iron, gold, titanium and water make Ceres a more favorable option than Titan, which has very few iron reserves. Therefore, it is believed that the second space settlement after Gaia could be constructed on Ceres. Ceres is also useful, mainly as it provides the large amounts of titanium and iron required to undertake large scale projects like the construction of skyhook. It could also serve as a refueling station for long-term missions to the Outer Solar system. Ceres is also closer to Gaia, located at a distance of 122 million km, which would be around 1.5 times the distance between Earth and Gaia. Ceres could be highly profitable by selling large amounts of gold and similar valuable minerals to Gaia or Earth, or acting as a manufacturer of rocket fuel for launch missions from Earth, which would have to refuel near Ceres. Asteroid mining near Ceres would fetch hundreds of tons of minerals like gold and iron.

It should be noted that the Moon and Venus haven’t been mentioned. It would be very difficult to establish a colony near Venus, due to the extremely high temperatures of Venus, which would make it impossible to establish ISRU units on Venus.

Instead of establishing a space settlement near Lunar orbit, or any one of the Earth-Moon Lagrange points, it would be better to exploit the Moon’s vast resources, mainly resources such as Helium-3 and several rare earths. These resources would be worth a lot. Helium-3 is scarce on Earth and would be used in large amounts in nuclear fusion reactors, whereas rare earth metals are required for the production of a wide variety of electronics. However, China has a near-monopoly on the rare-earth trade, controlling 90% of global rare earth production.104 Countries would prefer at this stage to prevent any one country, like China, from holding a monopoly over the production of a very important resource, due to which, the rare-earth metals production of the Moon would have a large market on Earth. However, the Moon has the problem of having low amounts of certain substances which are required for human survival, which would increase dependency on Earth. The Moon is also very hard to terraform, which would perhaps be a perfected method sometime in the distant future. Therefore, it would be much more profitable to have the Moon as a large-scale mine of resources. Mercury is also a viable future option, having large amounts of metals, primarily iron. It also has a low average temperature, as compared to Venus, of around 125°C, though the large variation in temperature might be a problem. Mercury also has the advantage of having a large solar constant(6.5 times that of Earth).

# 9.2 Skyhook

A skyhook system between Earth and Mars would reduce the time to travel between Earth and Mars by a third.105 One skyhook in LEO, and another skyhook near Mars would reduce travel time, reduce dependency on rockets and increase the payload capacity for a lower cost.

The skyhook system would be highly advantageous for Gaia. A skyhook system, with one located near Earth and the other near Mars, would help in easier transit between Earth and Mars. The skyhook system could also be expanded to help in transit between Mars and the planets of the Outer Solar System, like Jupiter and Saturn. If a skyhook, having a length of around 7000 meters is constructed near Gaia, it would reduce the time taken to travel to Ceres, a potential location for the second space settlement after Gaia, by several months. It would help in transporting the abundant minerals of the asteroid belt to Earth very easily.

However, the technological hurdles associated with it, which are mentioned below, result in the construction of such a structure being extremely difficult right now. It is expected that most of these technological hurdles can be easily overcome within 10-15 years.

**Hurdles**

Skyhooks work on a principle which is easy to implement, but there are several technological hurdles. Most of the technology required for the construction of a skyhook is already present, but certain aspects have not yet been sufficiently developed. There are also engineering hurdles, primarily in the mass of the counterweight and so on. However, it is expected that these problems are solved within 15-20 years.

A skyhook consists of a tether and a counterweight. However, the payload capacity of the skyhook is limited by the counterweight. A counterweight which has a lower mass would be unstable, with even a small unbalanced force affecting the orbit, which would result in the skyhook becoming unstable, and crashing into Mars or Earth. A larger mass would have a higher inertia, and therefore, the amount of force required to affect its orbit would be higher. Therefore, it would have the capacity to transfer a larger payload. The ratio between the maximum payload mass and the mass of the counterweight varies. However, the general ratio is around 1:50.106 Therefore, a skyhook having a mass of, say, 50,000 kg, would be able to transport a payload of 1000 kg. While this would be difficult to implement for Earth, there is a rather interesting solution for Mars.

Phobos, the Martian moon, has a mass of 1016 kg. Its dimensions are also very small, with the radius of Phobos being 11 km. It also has a very low gravitational attraction of 0.0057 m/s2. Phobos is also located very close to Mars, with a distance of around 6000 km between them. Therefore, Phobos has all the requisite conditions to act as a counterweight for the skyhook. It would have a payload capacity of around 2.1014 kg. The only limit to the amount of payload which can be transferred would be the volume of the payload.

Phobos as a counterweight is highly useful, as the distance between the Martian surface and Phobos is around 6000 km. The tether would terminate at a distance of around 60 km above the surface of Mars. This is mainly to prevent heating of the tether due to friction. A system for the launch of the payload would be required to transport a payload from Mars to the lower tip of the skyhook. This would be a difficult maneuver, as the relative velocity between the lower end of the skyhook and Mars would be around 534 m/s. This speed can be achieved easily, but the accuracy and precision required to ensure that the payload comes into contact with the lower tip is important. The window of time within which the payload has to come into contact with the skyhook varies from 2 to 3 minutes.

Another hurdle would be the strength of the material used to make the tether. The cable would have to handle the weight of the payload, due to which, the strength of the material would have to be high. If the skyhook was very large, say above 4000 m, the mass of the cable would also have to be factored in. Therefore, the material must have a high tensile strength. The materials which can be considered for this are M5 fibers, zylon or carbon nanotubes.

Carbon nanotubes have a high tensile strength of 30 GPa, and a density of 1350 kg/m3. Though carbon nanotubes have been produced in sizable quantities, the large-scale production of carbon nanotubes, which would be required for the construction of a skyhook, isn’t possible yet. However, techniques like the liquid electrolysis method and chemical vapor deposition show promise.

M5 fiber, also known as PIPD, has a tensile strength of 5.3 GPa, and a density of around 1700 kg/m3. This fiber has already been produced, but has a complex production process, involving several different compounds such as tetraaminopyridine, which would have to be produced themselves. If the production of the M5 fiber is simplified in the future, it would be one of the best possible materials which can be used.

The final option is Zylon fibers. This is also the best option, as of now. Zylon fibers have a tensile strength of 5.8 GPa, and a low density of 1540 kg/m3. It is also easy to produce, and would already be produced on Mars. Gaia’s external structure consists of a layer of zylon as well. Therefore, a skyhook made of zylon is easily possible and can be constructed with the technology present today.

Therefore, the only problems which remain are the development of strong enough materials, and the establishment of Gaia. It should be noted that the Earth skyhook doesn’t need a high-mass counterweight, mainly because the payload it transports has a low mass.

**Design and working**

The skyhook system consists of 2 parts, called the MaST(Mars Skyhook Transport System) and the EaST(Earth Skyhook Transport System). The MaST and EaST systems are designed to work in conjunction with each other, with MaST transporting goods or people from Mars to Earth, and vice versa. MaST is also used for transportation to the asteroid belt, and the planets Jupiter and Saturn.

This system of 2 skyhook structures, working together, has been established to handle the momentum problem. As one payload is launched by a skyhook, the skyhook has to apply a certain amount of force to push the payload, which would cause the skyhook to lose some momentum. If a skyhook, whose mass is 50,000 kg, loses momentum, and has a momentum below 390 million kg.m/s, the skyhook would crash into Earth. Therefore, its momentum has to be maintained. This isn’t a problem for MaST, as it uses Phobos as a counterweight. The huge mass of Phobos prevents any significant momentum loss, which would make the skyhook unstable. However, a method would be required to maintain the momentum of EaST. Therefore, a transfer of momentum might be the best technique to ensure that the EaST doesn’t lose momentum. Any incoming payloads could be slowed down by the EaST by attaching to its upper tip. The push exerted by the incoming payload could be used to counteract the loss of momentum due to the launch of payloads.107 This is a viable and implementable solution to handle the momentum problem. To ensure that a large enough factor of error is available, the skyhook is initially set to move at around 11.7 km/s, providing a margin of around 1.5. Therefore, a skyhook of mass 50,000 kg, moving at this speed, would need to launch a total payload mass of 195 tons, following which, a momentum recalibration would be required. The amount of mass launched, after which the recalibration takes place, can be calculated by dividing the difference in the initial momentum of the skyhook and 390 million kg.m/s, by 1000 m/s, which is the velocity required by the payload to approach and be captured by the skyhook. Assuming that the average payload transfer between Earth and Mars would have a mass of 50 tons, and would take place once a month, a recalibration would be required once every four months.

MaST itself will have a length of 6000 km long, with the tip of the skyhook moving at a velocity of 0.77 km/s, and a relative velocity of 0.52 km/s. The skyhook would terminate at a height of 60 km above Mars, connected to Phobos at the Stickney Crater. At this velocity, the skyhook would complete 2 revolutions of Mars in a day, which would be the same as that of Phobos. This gives the opportunity to launch 2 missions in a day from the same spot, or more missions if launched from different points on Mars. Any payload launched could have a velocity as low as 1000 m/s, requiring an engine thrust of 15 kN.108 The time window during which the missions would have to contact the tip of the skyhook would be around 2 to 3 minutes. It is expected that the duration of the missions would be around 3-4 months.105

The MaST mission would itself encompass the launch of a mission from possibly Olympus Mons, which is also located extremely close to the Martian equator. The advantage of using a skyhook is the path followed by the payload during its journey. The orbit followed involves the launch of the payload to follow a heliocentric path, where the payload would follow the same heliocentric path as Earth at 1 A.U. Therefore, this orbit can be considered to be a form of ballistic capture mission, but requiring lower time and lower mission costs, primarily due to the usage of a momentum-transfer unit instead of chemical rockets.105

The EaST skyhook is the skyhook system for Earth. The tip of the tether moves at a velocity of 1.88 km/s, with the orbital velocity of the skyhook being around 11.7 km/s. With regards to EaST, the orbital velocity is important primarily because an orbital velocity below 7.8 km/s would result in the skyhook crashing into Earth. The difference of 4 km/s is present to ensure that a momentum recalibration every time a mission is launched. The EaST skyhook’s lower tip is around 150 km above Earth’s surface. This height is higher than that of MaST mainly due to the frictional heat which would severely affect the skyhook at heights lower than this. For an orbital velocity of 11.7 km/s, and this height of the lower tip above the Earth’s surface, the skyhook completes 24 revolutions around Earth in a day. However, the major difference is that the missions being launched would require an initial velocity of around 3.6 km/s to ensure that the payload is transferred within 3 months to Mars.106

EaST is expected to transfer payloads of mass 2-3 tons, as it has a mass of around 100 tons, where the counterweight is mostly made of dead satellites in Earth orbit. This is a very low payload mass, but is sufficient considering that the mass of the payload which must be transferred is around 300 tons. Therefore, 100 launch missions using the EaST skyhook system would be sufficient to satisfy the amount of payload which has to be launched. However, a single launch site can launch 24 missions in a day, though the capacity of a launch port to launch that number of missions in a day is doubted. As 3-4 missions must be launched every day to satisfy the cargo shipping requirements, the missions towards the skyhook can be launched from 3 or 4 different locations every day. The orbit followed by the EaST missions will be the same as the mission orbit followed by the MaST missions, which involves a ballistic capture method.

One of the most important aspects of the construction of a skyhook is the protection of the tether. The tether will be susceptible to damage, primarily from micrometeorites. In the event that a micrometeoroid collides with the tether, the tether might get ruptured and the skyhook would no longer be operational. Therefore, the protection of the tether is required. There have been several solutions suggested, but the idea suggested by Foreward(1992), is one of the most practical and effective methods. The tether would be in the form of a net, with several small strands, attached with each other with the connection points being made of a high strength material like MTM57-M40J epoxy, the strongest adhesive in the world. The strands appear to form a continuous net, with the strands being attached to one other at short lengths with high adhesive strength materials. The strands are kept at a large distance from each other to ensure that the chance that more strands get cut when one does is extremely low. Therefore, a type of redundant system is created, where the tether survives even if one of the strands is cut. This would ensure that the tether would survive for a decade or more. The tether’s damaged parts need to be replaced only when a significant part of a section has been damaged. A section of the tether can be removed in phases, with only one strand being replaced at a time. This is the only method available to repair the tether without losing the other parts of the tether. Though this is a time-consuming process, it would be highly effective, ensuring that the tether would not be damaged again for a long time.

This is the basic design for the skyhook system. However, a third skyhook could be established in the future, near the Mars-Deimos L2 point. This skyhook would enable a zero relative velocity transfer orbit(ZRVTO) between Phobos and Deimos.109 The transfer of payloads between these 2 moons would require zero reaction mass, excluding the insignificant mass required for the attachment of the payload to the lower tip of the skyhooks. This would be useful in transferring payloads at an almost zero cost from Deimos to Gaia, or to Ceres via MaST.

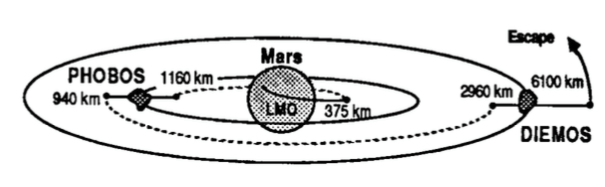


Figure 5: ZRVTO between Phobos and Deimos

Another use of the skyhook system is for the transfer of payloads to Ceres. It has been estimated that the construction of a second space settlement could be completed within 10 years of Gaia’s construction. The skyhook system could be constructed within 15 years of Gaia’s construction. Therefore, transfer of payloads from the asteroid belt to Earth and vice versa would have to take place through the use of chemical rockets from Ceres to Earth via Mars, or vice versa, until the skyhook system is constructed. Following its construction, the chemical rockets transfer would have to take place between Ceres and Gaia, following which, the MaST skyhook system could be used to transfer the payload to Earth. It is also possible to establish a skyhook on Ceres, due to its high mass, low gravity and small dimensions.

Though the skyhook system cannot be established right now, mainly due to logistical hurdles, the technology required for its construction is already present. The development of stronger fibers, and the required infrastructure on Mars, would be all that is sufficient for the construction of MaST, while several missions are launched from Earth to LEO to collect dead satellites at one point and use them for the construction of a counterweight. The counterweight could have a small, temporary habitable area, capable of accommodating around 5 people. The Mir space station had a mass of 130 tons, around 30 tons more than the EaST counterweight. Around 5 people can be expected to live in the temporary habitable structure at any time, which would be developed gradually into the counterweight for EaST.

The skyhook system could potentially make chemical rockets unnecessary for transfer of payloads between Earth and Mars, or for missions to Ceres. It can transfer large payloads between planets, for almost zero reaction mass. However, due to the logistical hurdles, it hasn’t been implemented yet, but upon construction would reduce costs for transportation and construction of rockets by a large factor. It could also enable the dismantling of methane production plants, to a stage where only 3-4 production lines would be required. The methane production plants cannot be entirely removed because the transfer of the payloads to the lower tip of the skyhook would still require a rocket.

# 9.3 Conclusion

Gaia is meant to be a future home for humanity in the stars, but it is by no means the only home. Gaia will be the first in a line of several space settlements throughout the solar system. The resources of Mars, the asteroid belt and the Outer Solar System will be opened up to humanity. Gaia is meant to be a space settlement for 30,000 people, with the capacity for 10,000 more people. It is meant to be a settlement, where people are truly free and have no conflicts with each other. It will be the best possible version of Earth, and a New World.

Gaia will be completely self-reliant, utilizing resources from Mars, and importing only a limited range of objects from Earth, which are not essential for basic living. This self-reliance enables Gaia to act as a “backup” world for humankind. In the event of any extinction event on Earth, be it an asteroid collision, changes due to global warming, or a devastating pandemic, Gaia, which is millions of kilometers away from Earth and is completely self-reliant, would prevent humanity from being wiped out. It would ensure that humans would repopulate Earth, or maybe even continue expanding to other planets.

Gaia will take quite some time and a significant cost to construct. However, the costs of construction are low enough for several countries, and even some of the richest men on Earth to finance. The economic returns from Gaia would be significant, especially from the exports of opal and deuterium. The revenue from Gaia is estimated to be around 1.7 billion USD per year, which would only increase as opal mining units increase in number and nuclear fusion is developed for commercial purposes.

Gaia also opens up the abundant resources of the asteroid belt. The large amount of resources present near the asteroid belt would be easy to access from Mars. The construction of new space settlements, perhaps near Ceres, along with the construction of a skyhook system, would ensure that large amounts of resources would be transferred from the asteroid belt to Earth. Conflicts on Earth for control of resources would probably end, mainly due to there being no need for anyone to try and take control of Earth’s resources, while Ceres provides humans with millions of tons of various resources.

Gaia will be the largest and most difficult project ever undertaken by humanity, but it will be the greatest mission ever undertaken, building an entirely new world, from scratch.

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1. It is to be noted that the number of neutrons is in decimals as it is an average value [↑](#footnote-ref-1)
2. It is to be noted that the amount of energy radiated is calculated for radiation of all wavelengths [↑](#footnote-ref-2)
3. This revenue has been calculated, factoring in launch vehicle, electricity and other overhead costs. For further details, see Section 4.5. [↑](#footnote-ref-3)