Harmonia-Triton

Rotational Habitat for long-term human survival beyond Neptune .Stellars (29.10.25)

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Abstract

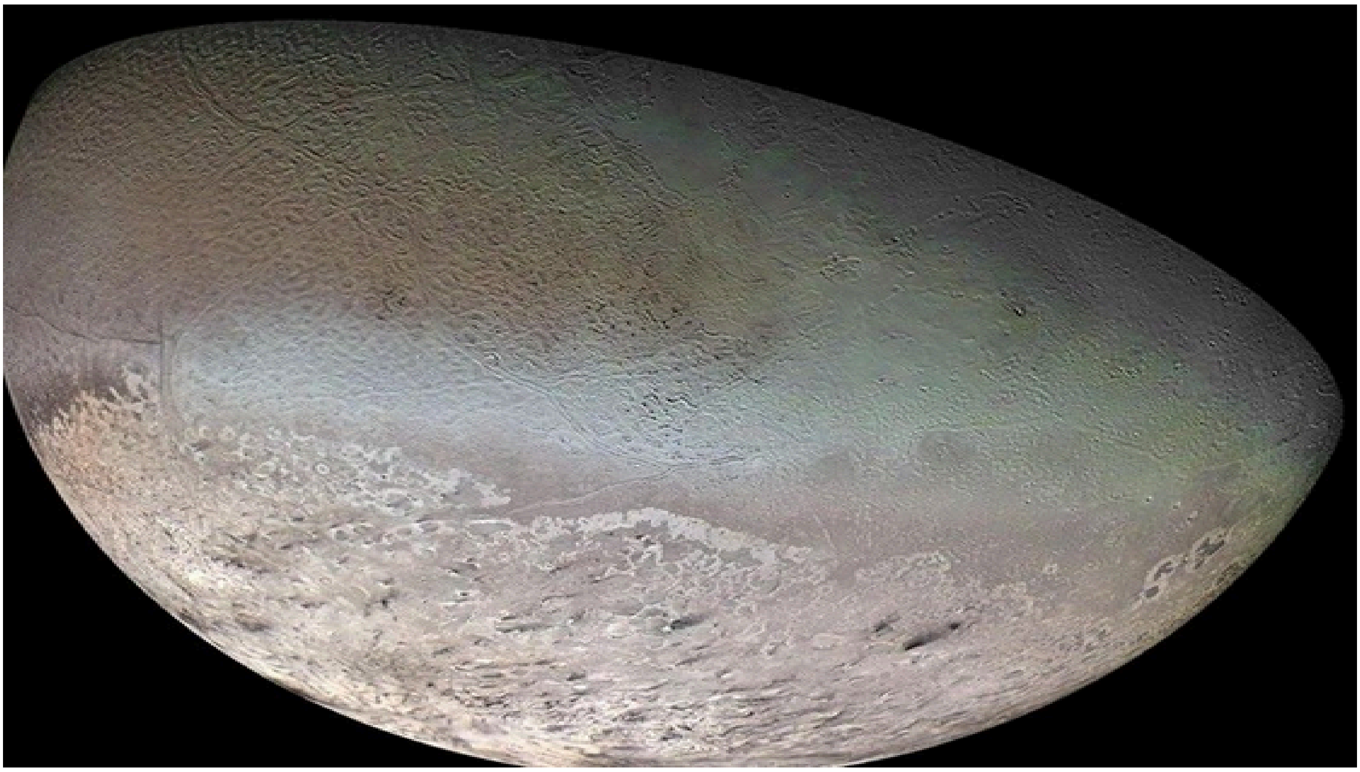
Harmonia is a fully autonomous space colony located in the Kuiper Belt, designed to last for 80 Earth years. The colony is positioned in a low elliptical orbit around Triton, allowing for safe rendezvous for resource extraction while maintaining a safe distance from its surface. Harmonia is designed to support a continuous population of 100,000 to 300,000 people and provides artificial gravity through the rotation of a toroidal (ring-shaped) habitation module.

The settlement includes closed-loop life support systems, a power infrastructure based on controlled thermonuclear fusion, and agricultural biomes containing more than seven plant species to ensure food security and preserve biodiversity.**[1]** The space colony's mission is to ensure the long-term physical and psychological health of its residents and to develop culture and social sustainability by creating an environment optimized for circadian rhythms, education, work, and personal growth. Safety measures, environmental waste reduction, and responsible use of space make Harmonia a cutting-edge technology for expanding humanity's presence beyond the inner solar system.

Introduction

Exploring the distant regions of the Solar System is a key step in creating more sustainable and long-term living conditions for humanity in the future. As populations grow and resource demands increase, the need for new living conditions and expansion beyond Earth and traditional space objects arises. The Kuiper Belt contains numerous icy bodies and is projected as a promising direction for space expansion..

The Harmony Project envisions the creation of the first fully autonomous space colony in the Kuiper Belt. Its location is being selected based on Triton- As the largest moon of Neptune, Triton is the prime place to make a base of operations around the furthest (known) planet[2]. Thought to be a captured Kuiper Belt Object, Triton is the only sizable rocky object in the Neptunian system. As such, Triton is the only place with a colonizable surface in the system. Neptune's largest moon, it contains large reserves of frozen water, nitrogen, methane, and other cryogenic materials. The colony's location in a low, elliptical orbit around Triton allows for regular resource extraction without the need for constant contact on the surface, increasing safety and reducing energy consumption.



1.1 Why Triron

Its diameter is approximately 2,700 km[3] comparable in size to dwarf planets. Triton's unique feature is its retrograde orbit: it orbits Neptune in the opposite direction to the planet's rotation. This fact strongly suggests two remarkable properties of Triton: its retrograde orbit suggests that it was captured from the Kuiper Belt, and Triton has one of the youngest surfaces of any icy moon in the Solar System.[4]

Surface temperatures reach nearly -235°C, making it one of the coldest objects in the solar system [5]. Triton's icy crust is composed of water ice, nitrogen, and methane. Observed cryovolcanism and surface geological variations indicate the existence of internal heat sources and, possibly, a subsurface ocean, which is of great interest to astrobiologists. The orbital parameters (distance from Neptune is about 354 thousand km, orbital period is 5.8 days) create a dynamically stable zone for the placement of an orbital colony.[6]

1.2 Resource potential

Triton contains large reserves of ice and volatiles, which form the basis of a self-sustaining colony. An icy crust of water ice (H_2O) can serve as a source of drinking water, oxygen, and building materials. Nitrogen (N_2) and methane (CH_4) form the basis for the crew's production of breathing atmosphere and fuel components.[7]

Spectroscopic studies of the surface confirm the presence of N_2 and CH_4 ions [7].Geological activity-cryovolcanism and resurfacing-indicate internal heat sources and, possibly, a subsurface ocean, making Triton not only a resource target but also a scientific research site. **[8]**

1.3. Strategic advantages of an orbital colony

Placing an orbital colony around Triton rather than on its surface offers several important advantages: reduced risk of extreme surface conditions, minimal mass lift costs, use of orbital logistics, and protection from geological and climatic threats [3]. A low elliptical orbit allows for periodic rendezvous with Triton to extract resources [3] while remaining at a safe distance from the surface. These conditions ensure sustainable operation of the station without interfering with the surface and its ecosystem.

2.1. Orbital Trajectory and Positioning

The Harmonia colony is envisioned as a long-term settlement in orbit, strategically positioned within the Kuiper Belt, well beyond Neptune's reach. It follows a stable circular trajectory with an eccentricity of less than one, ensuring consistent solar exposure for efficient power generation and effective temperature regulation. This type of orbit is ideal for self-sustaining space habitats, as highlighted in NAASA's seminal work, "Space Settlements: A Design Study" (NASA SP-413) published in 1977. [9]

Located in the resource-rich Kuiper Belt, Harmonia has access to plentiful supplies of water ice, methane, and organic compounds. These materials are essential for producing fuel, oxygen, and food-key components for sustaining life. This concept of utilizing local resources aligns with findings from NASA’s report on Space Resouces and Space Settlements (NASA SP-428) from 1979, which emphasized the necessity for future colonies to depend on materials found in their vicinity to reduce reliance on Earth.[10]

To ensure stability and maintain reliable communication, Harmonia employs a gyro-stabilized orbit and makes periodic adjustments using low-thrust ion propulsion systems. These advanced technologies are inspired by current deep-space satellite stabilization techniques employed by ESA and NASA probes operating in regions beyond Jupiter.[11]

Harmonia orbits in a stable region near the Kuiper Belt, far beyond Neptune’s orbit.This location was chosen for several scientific and practical reasons.First, the region offers relative stability with minimal gravitational interference from nearby celestial bodies. Second, it provides access to abundant frozen resources such as water ice and methane, which can be refined into fuel, oxygen, and drinking water.The colony follows a near-circular trajectory, ensuring constant sunlight for its solar collectors and thermal systems.Harmonia’s rotation around its longitudinal axis generates artificial gravity equivalent to about 0.8 g.[12]

This rotation is essential for maintaining human health, preventing muscle atrophy and bone loss during long-term space habitation.The direction of rotation, shown by arrows in engineering diagrams, creates a continuous downward force that simulates a “floor” along the inner surface of the cylinder.In effect, residents experience normal walking, sleeping, and working conditions, almost identical to those on Earth.[13]

2.2. **Structure and Artificial Gravity**

Harmonia is inspired by the O’Neill cylinder, a groundbreaking habitat design proposed by physicist Gerard K. O’Neill in his influential work, The High Frontier (O'Neill, 1977). This innovative structure generates artificial gravity through rotation, providing an environment that offers approximately 0.8 g-equivalent to 80% of Earth’s gravity. Research conducted by Hall (1999) indicates that this level of gravity is physiologically sustainable for humans.[14]

With a rotation rate oa 1 revolution per minute (rpm), the station creates a gentle centrifugal force along its inner surface. This allows residents to walk naturally and helps mitigate long-term muscle and bone los. The axis of the cylinder and its direction of rotation are clearly indicated with arrows on engineering diagrams, illustrating the synchronized counter-rotation of dual rings. This design is not only efficient but has also been proven to maintain structural balance effectively (NSS, 2024).[15]

2.3. **Habitat Design and Internal Systems**

Bio-Dome Ecosystems

At the heart of our project lie vibrant green zones, encased in transparent glass-ceramic domes, which nurture over seven different species of plants, including cereals, algae, and fruit trees. These unique ecosystems function as self-sustaining systems that recycle air, purify water, and produce food-much like the closed ecological systems explored during NaSA's Biosphere II experiments. Research highlighted in NASA SP-428 reveals that spending time in environments rich with vegetation significantly enhances psychological well-being and alleviates stress.[16]

Rescue and Safety Pods

Strategically placed along the outer hull are autonomous evacuation capsules. Each capsule is equipped with life-support systems, navigation tools, and communication devices, allowing them to detach swiftly in case of an emergency. Their design draws inspiration from NASA's Crew Escape Vehicle studies, ensuring that every resident can evacuate safely within minutes. [17]

Observation Windows

Expansive panoramic windows provide breathtaking views of deep space, including sights of Neptune and Triton. Tis direct connection to the cosmos not only fosters a sense of wonder but also supports mental health by mitigating feelings of isolation. Studies on visual stimulation in confined habitats (Olabisi et al., 2022) further affirm these benefits.[18]

Transportation Network

A magnetic transport line weaves through the interior, functioning much like a subway system that links residential areas with research and cultural sectors. This innovative network minimizes physical strain in partial gravity while enabling quick access between different modules.[19]

Culture and Education Complex

Harmonia boasts a comprehensive culture and education complex featuring theaters, museums, classrooms, and sports facilities. According to NASA's psychological adaptation models (SP-428, 1979), engaging in cultural and educational activities is essential for maintaining long-term morale, fostering cooperation, and igniting creativity within isolated environments.[20]

2.4. **Materials and Energy Systems**

The outer frame of the station is built using titanium-carbon composites, which provide exceptional strength and resistance to radiation. Transparent panels are crafted from aluminosilicate glass and enhanced with nano-coatings. These coatings effectively block harmful UV radiation while still permitting visible sunlight to enter, creating realistic "day-night" cycles that can be managed by the interior lighting system. [21]

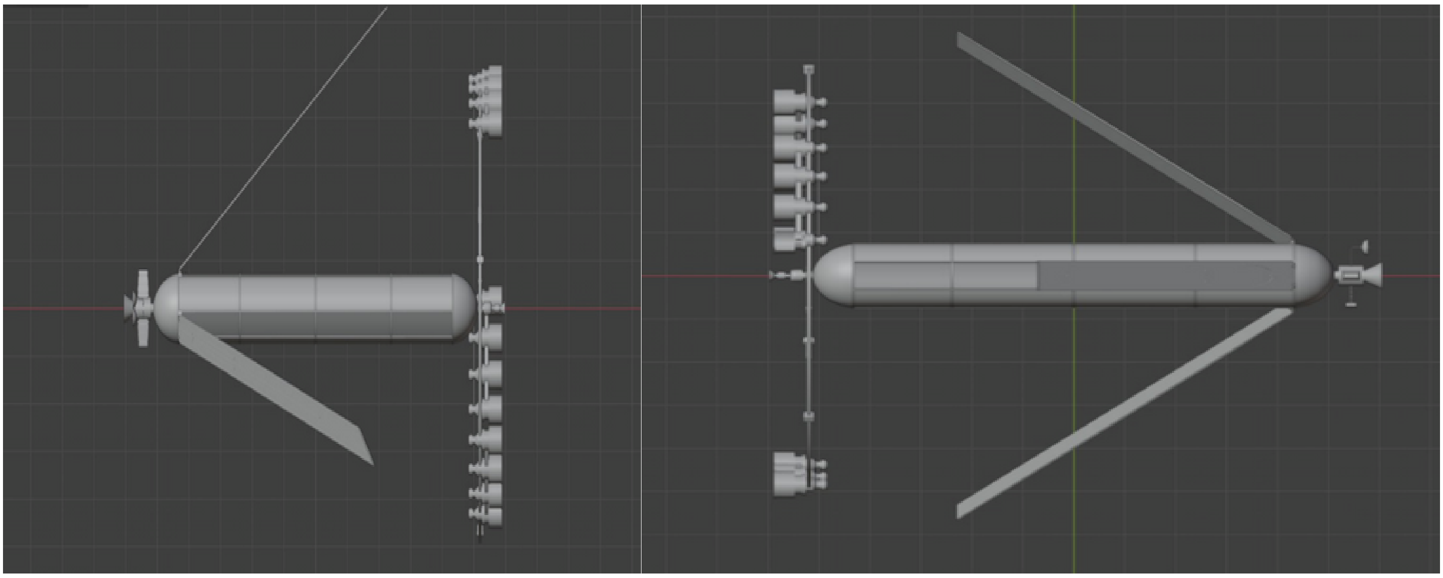
Energy for the station comes from a compact fusion reactor, which is supplemented by solar panels and stored in advanced magnetic torus batteries, as detailed in the ICES Report from 2016.

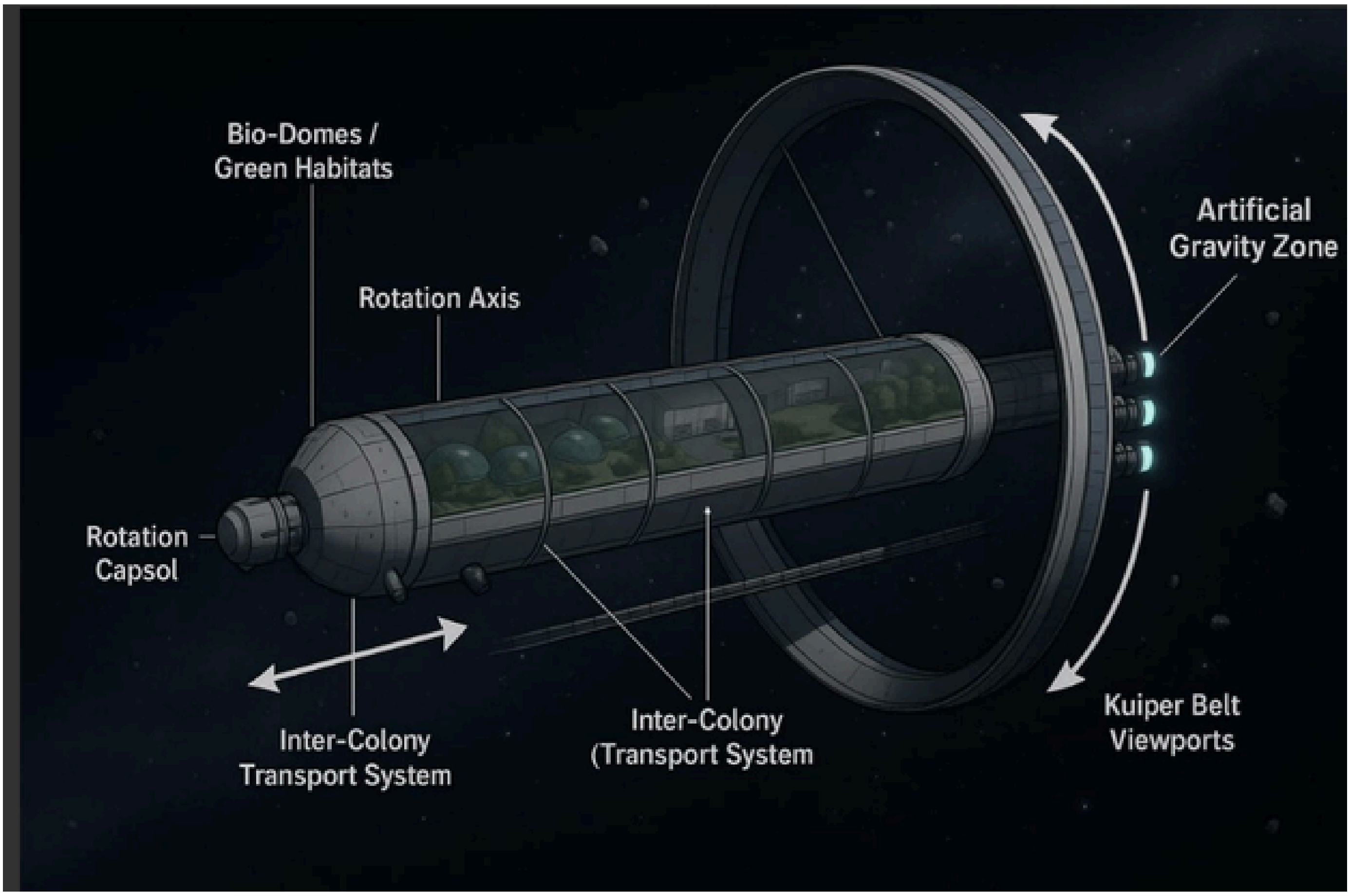
All modules are seamlessly connected through magnetic docking joints. This innovative design allows for easy replacement and expansion without interrupting ongoing operations, drawing inspiration from the modular principles used in the International Space Station (ISS).

2.5. Sustainability and Human Adaptation

The colony functions as a closed-loop ecosystem, efficiently recycling air, water, and organic waste. Local ice mining supplies a consistent source of hydrogen and oxygen, which are refined on-site through the process of electrolysis. Life within Harmonia adheres to a 24-hour light-dark cycle, mirroring Earth's natural rhythm to support circadian stability.

By harmonizing engineering precision with ecological balance, H armonia showcases the potential for humanity to flourish beyond Earth while safeguarding psychological well-being and cutural identity. Its innovative design builds upon the scientific foundation laid by NASA's O'Neill studies and represents a tangible step towards establishing a permanent human presence in the outer Solar System.[22]





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Life support system and biodiversity of the colony

3.1 General concept of life support system

The system's goal is to ensure continuous regeneration of oxygen, water, and food, completely independent of external resources. The system is based on bioregenerative cycles, where plants, microorganisms, and physicochemical modules interact in a single closed circuit.

The CELSS concept was explored in te NASA MELiSSA (Micro-Ecological Life Support System Alternative) and Biosphere-2 projects, which demonstrated that a closed ecosystem could support human respiration and nutrition for decades. [24]

3.2 Gas exchange, oxygen, and air purification

The main source of oxygen is plant photosynthesis:

$$[6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2]$$

1 m² of wheat or soybeans absorbs up to 1.1 kg of CO_2 per day and releases the same amount of oxygen. For complete gas balance, each organism requires about 1 m² of photosynthetic area.Plants provide up to 40% of the oxygen; the rest is replenished by water electrolysis Moreover,inside the station are photobioreactors filled with algae(picture 1) such as Spirulina and Chlorella.They work like trees: they take carbon dioxide (CO_2) that humans exhale,and release oxygen (O_2) under artificial light. According to NASA's ECLSS (Environmental Control and Life Support System), microalgae can recycle up to 90% of CO_2 in a closed habitat, producing breathable oxygen for people. [24] Thus, the colony's atmosphere is autonomous and safe for humans. Moreover,inside the station are photobioreactors filled with algae(picture 1) such as Spirulina and Chlorella.They work like trees: they take carbon dioxide (CO_2) that humans exhale,and release oxygen (O_2) under artificial light. According to NASA's ECLSS (Environmental Control and Life Support System), microalgae can recycle up to 90% of CO_2 in a closed habitat, producing breathable oxygen for people. [25].

3.3 Water cycles and food production

The water cycle is built on the principle of the earth's hydrological cycle:

Moisture evaporates through plant transpiration → condenses on cooled surfaces → is filtered and disinfected with UV light → is returned to the tanks.

Urine and wastewater undergo biooxidation treatment, where microorganisms decompose organic matter into nitrates and phosphates -plant fertilizers. he ISS Water Recovery System recycles up to 98% of water, including atmospheric moisture ["We have now demonstrated that we can reach total water recovery of 98%, thanks to the brine processor. "The BPA takes the brine produced by the UPA and runs it through a special membrane technology, then blows warm, dry air over the brine to evaporate the water]-[26]In emergency situations, organic matter can be converted into CO_2 and water by wet oxidation at 250–300°C.[27] Food production is based on hydroponic systems and bioregenerative cycles:

One person requires 2,500 kcal per day; 10 square meters of mixed crops (wheat, soybeans, rice, potatoes, vegetables) fully meets this requirement. A colony of 100,000 people would require approximately 1 square kilometer of biocultivated area, which is approximately 1% of the inner surface of the ring.[24]

The biomass is completely recycled: leaves → fertilizer, roots → substrate, organic waste → biogas.

• Transparent domes are used to grow vegetables, fruits, and herbs hydroponically, as well as insects (e.g., crickets) for a sustainable protein source [24]

• In cases of shortage of fresh food, 3D printing of synthetic protein is [24]

Additional microalgae, such as Chlorella vulgaris, can produce up to 15 g of oxygen per 1 kg of biomass per day, ensuring self-regulation of the gas environment and nutrient recycling [28]

3.4 Artificial gravity

The colony has a ring-shaped (toroidal) structure with a diameter of 4 km. Artificial gravity is created by centrifugal acceleration.

$$A = \Omega^2 * r$$

A full rotation of the ring occurs in 101 sconds (~0.6 rpm).

Acceleration is 80% of Earth's gravity, which is sufficient to maintain cardiovascular, bone, and muscle health. [29]

3.5 Closed loops and waste recycling

- All organic waste undergoes biochemical composting using aerobic bacteria; thegenerated heat and CO_2 are returned to the system.
- • Inorganic waste is processed using plasma gasification, which allows for the recovery of metals and glass.
- • Waste recycling approaches 100%, reducing the need for external resources by more than 95%. [30]

3.6 System Stability and Adaptation

Biomonitoring using sensors allows for the tracking of CO_2, O_2, humidity, pH, and nutrients

If biological systems fail, a backup physicochemical process, the Sabatier reaction, is activated:

$CO2+4H2 \rightarrow CH4+2H2O$ The system ensures the colony's autonomy for over 80 years, maintaining population stability and internal ecological balance. [31]

№	Plant species	Role in the system	Explanation	Source
1	Wheat	Source of carbohydrates and oxygen	Wheat provides up to 60% of daily calories for colonists and is one of NASA's recommended crops for Advanced Life Support systems.	[35]
2	Soybean	Protein and fats	Soybeans fix nitrogen from the air, enriching the nutrient solution for other plants and reducing the need for synthetic fertilizers.	[36]
3	Rice	Reserve source or starch	Rice complements protein crops like soy and potatoes. Experiments by JAXA showed it performs well in confined, low-gravity farming systems.	[37]
4	Potatoes	Resistant to low light:source of potassium	Potatoes were tested in NASA's CELSS experiments and proved ideal for space farming due to high yield and fast growth in hydroponic setups.	[38]
5	Lettuce	Fast growth cycle-oxygen source	Lettuce was the first crop eaten on the ISS (NASA Veggie Project, 2015).	[39]

			It also serves as an environmental indicator, reacting sensitively to air and water quality.	
6	Tomatoes	Source of vitamins and organic acids	Tomatoes show the efficiency of photosynthesis and help improve crew morale with their color, smell, and taste.	https://www.discovermagazine.com/moon-rice-could-soon-sprout-in-space-adding-a-fresh-ingredient-to-astronauts-diet/
7	Algae(spirullina or chlorella)	Rapid growth:CO_2 absorption and 0_2 production	Used in ESA MELiSSA and NASA OMEGA projects as a biological air and water purifier. Spirulina supports both nutrition and life support cycles.	[40]

4.Energy and Heat source

Since the sunlight barely reaches to Neptune using solar panels would be useless because it wont generate enough energy. Our alternative are **radioisotope power systems**.

New Horizons carries seven scientific instruments and a radioisotope thermoelectric generator. The spacecraft weighs 1,060 pounds.

RPS - short for **radioisotope power systems** -are sometimes referred to as a type of "nuclear battery." RPS attach directly to a spacecraft, much like a power cord being plugged in.

RPS produce electricity and heat for decades under the harsh conditions of deep space without refueling. All RPS systems, flown on more than two dozen NASA missions [32] since the 1960s, have functioned for longer than they were originally designed. NASA's twin Voyager spacecraft -powered by RPS -have operated for a record-setting 47+ years in space.

Two types of Radioisotope Power Systems are currently in use by NASA:

- Radiosotope Thermoelectric Generatos [33] power spacecraft such as New Horizons and Mars rovers Perseverance and Curiosity.

Radioisotope Heater Units [34] provide heat for spacecraft in the cold environment of space

- **4.1 General Purpose Heat Source (GPHS): The Building Block**

The **general purpose heat source module, or GPHS**, is the essential building block for the radioisotope thermoelectric generators used by NASA. These modules contain and protect the plutonium-238 (Pu-238) fuel that gives off heat for producing electricity. The fuel is fabricated into ceramic pellets of plutonium-238 oxide (238PuO2) and encapsulated in a protective casing of iridium, forming a fueled clad. Fueled clads are encased within nested layers of carbon-based material and placed within an aeroshell housing to comprise the complete GPHS.

- Each GPHS is a block about four by four by two inches in size, weighing approximately 3.5 pounds (1.5 kilograms). They are nominally designed to produce thermal power at 250 watts at the beginning of a mission, and can be used individually or stacked together.
- GPHS modules have been subjected to extreme safety testing conditions that significantly exceeded the intensity of a wide range of potential accidents. Such tests have included simulating multiple reentries for a single module through Earth's atmosphere, exposure to high temperature rocket propellant fires, and impacts onto solid ground.
- The enhanced GPHS modules used in the latest generation of radioisotope power systems incorporate additional rugged, safety-tested features that build upon those used in earlier generations. For example, additional material (20 percent greater in thickness) has been added to the graphite aeroshell and to the two largest faces of the block-like module. These modifications provide even more protection to help to contain the fuel in a wide range of accident conditions, further reducing the potential for release of plutonium-238 that might result**.[34]**

4.2 Radioisotope Thermoelectric Generator (RTG): Power to Explore

A model of Voyager's Radioisotope Thermoelectric Generator is placed in a shipping container.

NASA/JPL-Caltech

A **radioisotope heater unit, or RHU**, uses a small, pencil eraser-sized pellet of plutonium oxide to generate heat for spacecraft structures, systems, and instruments, enabling their successful operation in harsh space environments. Some missions use a few RHUs for extra heat, while others have dozens. NASA has also studied the potential for using the same small fuel pellet in a RHU to power a compact system that could provide a few dozen milliwatts of electrical power**.[34]**

Conclusion

The integration of backup physical and chemical processes, including the Sabatier reaction, maintains the atmosphere's chemical balance even when biological cycles are disrupted. Artificial gravity, generated by the rotation of the ring structure, ensures healthy bones, muscles, and cardiovascular systems for the inhabitants.

Organic and inorganic waste recycling systems, coupled with closed water and food cycles, ensure the colony's near-complete autonomy and minimize the need for external resources. Overall, the proposed design demonstrates the feasibility of creating a long-term, safe, and self-sustaining space environment that could serve as a model for future interplanetary settlements..

This project developed a concept for an autonomous space colony orbiting Neptune, equipped with a closed-loop life support system (CELSS) capable of sustaining human life for decades. The use of bioregenerative cycles with plants, microalgae, and hydroponic systems ensures stable oxygen production, carbon dioxide recycling, and food and water production.

[1] Back to the future: Revisiting the perspectives on nuclear fusion and juxtaposition to existing energy sources

[2] The Top Ten Places for Humanity to Colonize in Our Solar System

[3] Triton - NASA Science

[4] Triton's Captured Youth: Tidal Heating Kept Triton Warm and Active for Billions of Years

[5] Triton, Neptune's largest moon

[6] There are 14 known moons of Neptune, but the most prominent of the Neptunian moons is Triton, which is Neptune's largest moon.

[7] Triton: Fascinating Moon, Likely Ocean World, Compelling Destination!

[8] Cryovolcanism

Ideas for station taken from:

[9] Elon Musk's Mars Colonization Project: What We Know So Far

[10] Natural Resources, Geography, and Climate | SpringerLink

[11] How Gyro-Stabilized Systems Delivers Innovative Gimbal Design

[12] Kuiper Belt Facts

[13] Science in Space: May 2024

[14] O'Neill Cylinders And Long-Term Space Colonization

[15] How to Calculate Rotations Per Minute (RPM) - The Tech Edvocate

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[24] ESA - MELiSSA life support project, an innovation network in support to space exploration

[24] Space Crops - NASA Science Biological & Physical Sciences

[25] Crop yields have increased dramatically in recent decades, but crops like maize would have improved more without climate change - Our World in Data

[26] NASA Achieves Water Recovery Milestone on International Space Station - NASA

[27] Detection and Treatment of Emerging Contaminants in Wastewater

[28] The Microalga Chlorella vulgaris as a Natural Bioenergetic System for Effective CO2 Mitigation—New Perspectives against Global Warming

[29] Period and Frequency in Uniform Circular Motion Explained: Definition, Examples, Practice & Video Lessons

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[36] First Soybean Harvest from International Space Station - Innovations Report

[37]A Brief History of Rice in Space | USA Rice Federation

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