Space colonization (SASS)

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Table of Contents

1. Purpose and Environment of the Kuiper Belt

The Kuiper Belt lies far beyond Neptune, between 30 and 50 astronomical units (AU) from the Sun. At this distance, temperature averages around 50 K (–223 °C), creating an extremely cold and hostile environment for any form of life. Sunlight is approximately 1,600 times weaker than on Earth, making solar power generation impractical. The region is constantly exposed to cosmic radiation, solar wind particles, and micrometeoroid impacts, all of which pose continuous threats to human life and equipment.

The purpose of the Kuiper Belt Colony project is to establish a long-term, self-sustaining human settlement beyond the traditional limits of the Solar System. This colony functions both as a scientific outpost for deep-space research and as a prototype for future interstellar habitats.

To ensure survival and comfort for its 150,000 residents, the colony must provide:
Artificial gravity close to Earth's level (≈0.9 g) to maintain bone and muscle health
A sealed and breathable atmosphere at approximately 1 atm pressure. Reliable protection from cosmic radiation and heat loss. Closed-loop life support systems, including air and water recycling and sustainable agriculture. Full energy independence through fusion reactors and advanced thermal regulation systems.

This project explores a sustainable space colony on a dwarf planet in the Kuiper Belt, designed to support a population of 100,000 and a lifespan of 80 Earth years. As stated above, the primary goal is to develop a sustainable system that is viable, provides people with essential resources such as water, air, food, and energy. Moreover,the project analyzes the sources and methods of extracting vital substances from asteroids and icy bodies in the Kuiper Belt, the creation of closed ecosystems, and the design of the colony's spacecraft and living quarters. Particular attention is paid to technological innovations that enable the stable operation of the settlement and to issues of human life in long-term isolation.

2. Artificial Gravity System

Principle:

The colony generates artificial gravity through rotational motion. Each habitation ring rotates around the central axis, creating centripetal acceleration that simulates the sensation of weight on Earth.

Formulas

$a = \omega^2 r$

$\omega = 2\pi \times \text{rpm}/60$

$v = \omega r$

Where:

a — artificial gravity (m/s^2)
ω — angular velocity (rad/s)
r — radius of rotation (m)
v — tangential (linear) velocity (m/s)

Adopted Parameters

Rotation speed: 1.5 rpm → $\omega = 0.157$ rad/s
Target acceleration: 0.9 g = 8.83 m/s^2
Ring radius**:** r = 358 m
Linear velocity at the rim**:** v = 56 m/s

Human Safety and Comfort

A rotation rate of 1.5 rpm is within the comfort threshold for most humans. Medical studies (NASA, ESA) show that motion sickness usually becomes significant only above ~2 rpm. Artificial gravity of 0.9 g ensures normal walking, bone density development in children, and healthy blood circulation, very similar to Earth's conditions.
The colony includes three independent habitation rings, each capable of supporting the full population in case of emergency isolation.
This modular redundancy improves safety, maintenance access, and social stability.

3. Atmosphere and Pressure

The colony maintains an Earth-like atmosphere to ensure human comfort and biological compatibility for plants and animals.Pressure and composition are kept constant through a combination of automated control systems and biological recycling processes.

Pressure: P = 101 kPa (1 atmosphere)
Temperature: T = 293 K (approximately 20 °C)
Composition: 21% oxygen (O_2), 79% nitrogen (N_2)

The atmospheric behavior is described by the ideal gas law: PV = nRT. Each habitation ring of the colony has an effective internal volume of about 1.0×10^8 m^3. With an air density of approximately 1.2 kg/m^3, the total air mass per ring reaches nearly 1.2×10^8 kg.

Air circulation is maintained by large-scale ventilation systems and temperature-controlled ducts to prevent stratification and ensure even distribution of oxygen and carbon dioxide. Oxygen is continuously consumed through human and biological respiration, as well as slow leakage through microfractures in the hull. To replenish oxygen, the Environmental Control and Life Support System (ECLSS) performs electrolysis of water, following the reaction:

$2H_2O \rightarrow 2H_2 + O_2$.

The produced oxygen is returned to the habitat atmosphere, while the hydrogen is stored and later reused in the Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$) to regenerate water and remove excess carbon dioxide. Nitrogen serves primarily as an inert buffer gas that stabilizes pressure and prevents flammable oxygen levels. It is stored in cryogenic reservoirs and automatically released when internal pressure decreases. The atmosphere passes through multilayer filtration and sterilization systems, including HEPA filters, activated carbon, and UV sterilizers, ensuring the removal of dust, microorganisms, and volatile compounds.

In this environment, residents breathe normally without spacesuits, experiencing a natural and comfortable atmosphere almost indistinguishable from that of Earth. The combination of physical, chemical, and biological processes guarantees long-term atmospheric stability for centuries of continuous habitation.

4. Energy and Thermal Balance

At a distance of about 40 astronomical units from the Sun, solar radiation is over 1,600 times weaker than near Earth, making solar energy insufficient for large-scale use. Therefore, the colony relies on compact nuclear fusion reactors as its primary and continuous power source.

Pt — total thermal power of the reactors (GW)

Pe — effective electrical output (GW)

η — efficiency of thermal-to-electric conversion

The relationship between these parameters is given by: $Pe = \eta \times Pt$

For the colony's energy demand, the following design values are adopted:

$\eta = 0.38$

$Pe \geq 0.75$ GW

$\rightarrow Pt = 2.0$ GW

This output ensures a stable supply for all life-support systems, propulsion units, environmental control, and agricultural lighting. Because energy conversion is not 100% efficient, excess thermal energy must be removed into space through radiator panels.
The radiative heat dissipation follows the Stefan–Boltzmann law: $Q = \varepsilon\sigma A(T^4 - Ts^4)$

ε — emissivity coefficient of the radiator material (≈ 0.9)

σ — Stefan–Boltzmann constant (5.67×10^{-8} W/m²·K⁴)

A — total radiator surface area (m²)

T — radiator temperature (K)

Ts — background space temperature (≈ 3 K)

For a total waste heat of 2.0 GW and radiator temperature of 400 K, the required radiator area is approximately 7.7×10^5 m². Part of the recovered heat is recycled to maintain comfortable living and agricultural temperatures within the colony, supporting stable internal conditions and minimizing energy loss. This integrated system keeps the thermal balance of the station constant, preventing both overheating and excessive cooling in the deep-space environment of the Kuiper Belt.

5. Radiation Protection

In deep space, far beyond Earth's magnetosphere, exposure to galactic cosmic rays (GCRs**)** and solar particle events (SPEs) poses a serious long-term threat to human health. High-energy ionizing radiation can damage DNA and increase the risk of cancer, neurological disorders, and cellular mutations. Therefore, reliable radiation shielding is one of the key safety requirements of the Kuiper Belt Colony.
The attenuation of radiation through a shielding material can be described by the exponential relation: $D = D_0 \times \exp(-k \times S)$

where:

D — radiation dose after shielding

D_0 — unshielded dose

k — absorption coefficient (material-dependent)

S — areal density of the shield (g/cm²)

The areal density is given by:

$S = \rho \times t$

where ρ is the density (g/cm³) and t is the thickness (cm).

A water layer of 2 meters is used as the primary radiation barrier:

ρ (water) = 1 g/cm³

t = 200 cm

$S = 200\ g/cm^2$

This layer absorbs a significant portion of ionizing radiation and, in combination with external metallic shielding, provides comprehensive protection. Additional aluminum and lead layers are applied externally to block secondary particle emissions and increase overall attenuation. The total protected surface area of the inhabited section is approximately 16,929 m^2, ensuring uniform coverage of all living modules. The design goal is to reduce the annual effective radiation dose to ≤ 0.05 Sv/year, comparable to long-term occupational exposure limits for radiation workers on Earth. Besides shielding radiation, the water layer also serves as a thermal buffer, stabilizing the internal temperature of the habitat. This dual-purpose concept — a “hull + water” composite — is inspired by advanced spacecraft shielding models that use combined layers of lead, aluminum, and hydrogen-rich materials to achieve optimal protection against solar and cosmic radiation.

6. Water and Air Systems (ECLSS)

ECLSS stands for Environmental Control and Life Support System. Its main function is to maintain a closed loop of water, air, and waste recycling to ensure full autonomy of the colony. Drawing on the experience of the International Space Station (ISS), the system continuously recovers and purifies air and water. Moisture from condensation, wastewater, and even urine are collected, filtered, and reprocessed into clean water suitable for drinking and hydroponic agriculture. For the Kuiper Belt Colony, the water recycling efficiency is designed to exceed 95%.

This is expressed by the relation: $M(\text{recycled}) = \eta \times M(\text{used})$ where $\eta \geq 0.95$

In other words, at least 95% of all used water is recovered and reused after purification. Oxygen is continuously regenerated by electrolysis of water, following the reaction:

$2H_2O \rightarrow 2H_2 + O_2$

The oxygen (O_2) is returned to the atmospheric system, maintaining breathable air. The hydrogen (H_2) is stored as a reserve fuel for propulsion and used as a feedstock for energy systems through the Sabatier process. To support a population of 150,000 residents, the system employs large-scale industrial electrolysis units with a total current capacity of about 100 kA. Any remaining water deficit is replenished by mining ice from nearby Kuiper Belt objects, where deposits rich in H_2O, CO_2, and NH_3 are abundant. The extracted ice is melted, purified, and integrated into the closed-cycle system.

In conclusion, the colony’s ECLSS operates completely independently of Earth, ensuring stable and continuous recycling of essential life-support materials for centuries of operation.

7. Food Production and Agriculture

Crop	Yield (kg/m²/year)	Caloric Value (kcal/kg)	Required Mass (million kg/year)	Area (km², single-layer)
Millet	1.2	3600	20.93	17.45
Potato	4.0	770	35.55	8.90
Soybean	0.8	4460	3.06	3.83
Fig Tree (Ficus carica)	4.5	740	9.24	2.06
Algae + Chlorella	8.0	4000	3.42	0.44
Total	–	–	**72.20**	**32.66**

Effective cultivated area (after vertical stacking):
10 layers → ≈ 3.27 km²
5 layers → ≈ 6.53 km²

Oxygen demand (humans):
0.84 kg/person/day × 150,000 × 365 ≈ 45.99 million kg O_2/year
Oxygen production by biomass:
72.20 million kg biomass × 1.0667 ≈ 77.0 million kg O_2/year
→ about 1.67× more oxygen than required.

Conclusion: Total agricultural surface (single layer): ≈ 32.7 km².
With vertical farms (10 layers): ≈ 3.3 km² actual occupied area.
The biosystem provides more than enough oxygen and food for 150,000 people.
Chlorella photobioreactors serve as rapid O_2 buffers and backup nutrition sources.
It is recommended to maintain 15–30% redundancy in crop area and seed storage for emergencies.

Crop-Specific Conditions:

1. Millet (Panicum miliaceum)

System: nutrient film technique (NFT) hydroponics on vertical shelves.
Growth cycle: 90–110 days.
Lighting: 400–600 $\mu mol \cdot m^{-2} \cdot s^{-1}$; 14–16 h photoperiod.
Notes: high carbohydrate yield; two or three harvests per year are possible under artificial cycles.

2. Potato (Solanum tuberosum)

System: deep-container hydroponics or aeroponic tuber formation.
Cycle: 90–120 days.
Lighting: 400–500 $\mu mol \cdot m^{-2} \cdot s^{-1}$.
Special care: stable root oxygenation; robotic harvesting and replanting.

3. Soybean (Glycine max)

System: hydroponic substrate with perlite; can grow in vertical layers.
Cycle: 100–120 days.
Lighting: 400–600 $\mu mol \cdot m^{-2} \cdot s^{-1}$; controlled photoperiod for flowering.
Feature: nitrogen fixation; contributes to natural nutrient recycling.

4. Fig Tree (Ficus carica)

System: dwarf self-pollinating trees in containerized soil modules.
Cycle: fruits continuously year-round with controlled temperature and photoperiod.
Lighting: 300–500 $\mu mol \cdot m^{-2} \cdot s^{-1}$; 14 h day length.
Role: provides fruit, improves humidity and psychological well-being in park-like sections.

5. Algae and Chlorella vulgaris

System: closed tubular photobioreactors with blue-red LED light (450 nm & 660 nm).
Cycle: continuous growth culture.
Lighting: 100–300 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 24 h/day.
Function: main oxygen generator and CO_2 recycler; also produces protein-rich biomass for human consumption.

Integration with Life Support Systems: CO_2 cycle: human respiration and industrial CO_2 are directed into the agricultural zones and photobioreactors.
O_2 cycle: oxygen generated by plants and Chlorella is filtered, balanced, and returned to living quarters.
Water cycle: condensed humidity and treated wastewater are purified and reused for irrigation.
Waste cycle: organic residues are converted into compost or biogas, which returns nutrients to the hydroponic system.

8. Human Life and Social System of the Colony

One of the most crucial aspects of creating a sustainable system is the need for a fully functioning social structure that will develop the individual. Regardless of gender, origin, age, or profession, everyone has the full right to property, personal space, work, freedom of movement, and cultural development. The goal is to create a closed space, but one that is open to growth and development, where people born in this place can live a full life without

leaving the system and without feeling restricted.

Personal space and housing: Each person will be allocated a separate space of approximately 30-40 square meters (equivalent to Earth standards). Housing will be located in multi-level modules with artificial gravity and a controlled climate.
Right for personal property: The system combines personal digital and material assets such as housing, clothing, equipment, etc., while resources such as water, air, and energy belong to the colony.
Work and self-realization: Residents of this colony will be assigned work that balances physical and mental work. For example, professions such as mining, energy, agriculture, medicine, ecology, science, education, and communications management will be considered. Residents are required to devote at least 20 hours to work for the well-being of their location.
Freedom of movement and cultural life: Despite the fact that the system is closed, people can move quite calmly between residential and natural modules, between stations

Speaking about cultural life, we can safely say that the colony is developing in such areas as holographic theaters or films, laboratories, museums and holidays dedicated to life in space.

9. Construction and Dimensions

Each habitation ring of the colony is designed as a large rotating structure that provides both artificial gravity and living space for the population.

The main parameters of one habitation ring are as follows:
Radius (r): approximately 358 m
Diameter: 716 m
Structural width of the inhabited section: ~50 m
Height: 10 decks (levels)

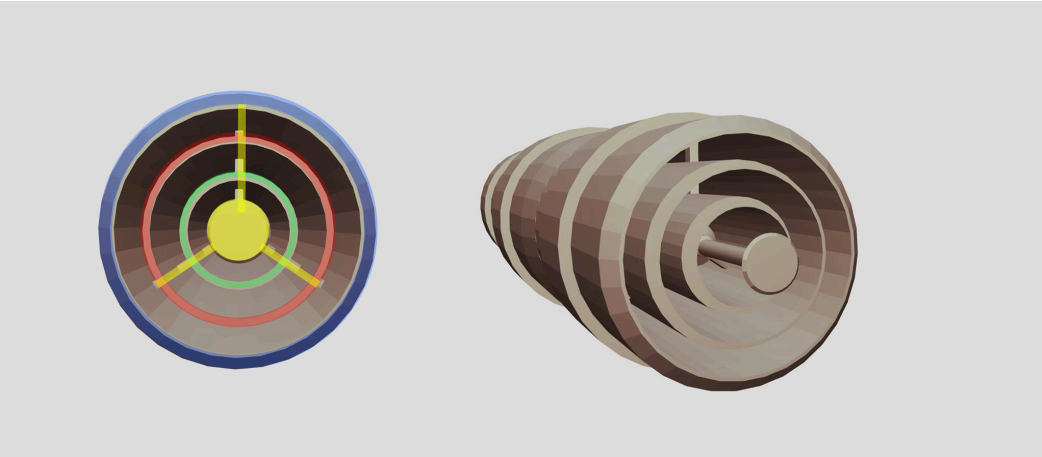
The circumference of a single ring is calculated as: $L = 2 \times \pi \times r = 2{,}248$ m.

The total floor area of one ring is therefore:

$A(ring) = L \times W \times N$

$A(ring) \approx 1.12$ km².

With three identical rings operating simultaneously, the total living and working area equals about 3.37 km². If required, this area can be expanded up to 13.5 km² by increasing the width of each ring to around 200 m and/or adding additional decks.



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3d model:

https://sketchfab.com/3d-models/hackathon-sass-station-4b4eac004e4946169ee8b5e54e418612

The blue colored ring: it acts as the sustainability powerhouse. This ring can hold acres of fertilized land to handle agriculture. This ring allows us to foster and develop enormous food supplies for the colony.

The red colored ring: it acts as the storage (for resources and farmed foods) and housing (apartments and rooms) for the colony, as well as the commodities for the colonizers. E.g. hospitals, places for leisure like canteens, places with greens, etc.

The green colored ring: the mitochondria of the settlement. It holds the nuclear reactors, administration bridge, and such.

The yellow star-like structure: holds the docks together, as well as handling the transportation and movement between the docks using elevators.

Such modular scalability ensures flexibility for future population growth and additional infrastructure.

The overall architecture provides structural balance, redundancy, and easy access between living sectors and the central technical spine, ensuring the colony's long-term stability and safety in the harsh environment of the Kuiper Belt.

10. Materials and Structural Integrity

The colony's hull is constructed as a multilayer composite structure designed to withstand internal pressure, radiation, and micrometeoroid impacts.

It consists of the following layers:
Inner frame: high-strength aluminum alloys and composite materials such as Kevlar and carbon fiber
Intermediate layer: technical-grade water serving both as a radiation shield and a thermal buffer
Outer layer: a combination of lead and aluminum for additional radiation protection and micrometeoroid resistance

The mechanical strength of the habitat is analyzed as a pressurized cylindrical shell, governed by the formula for circumferential (hoop) stress:

$\sigma = (\Delta P \times R) / t$

where:

ΔP — internal overpressure ($\approx 1.0 \times 10^5$ Pa)

R — ring radius (358 m)

t — thickness of the load-bearing hull (0.05 m)

Substituting these values gives: $\sigma \approx 7.16 \times 10^8$ Pa = 716 MPa

The ultimate tensile strength of advanced aluminum–composite materials and Kevlar reaches approximately 800 MPa, providing an adequate safety margin for long-term operation. The outer water layer further absorbs micrometeoroid impacts and dissipates shock energy, preventing structural fatigue over centuries of service.

This multilayer “hull + water + metal” configuration ensures both mechanical stability and radiation shielding efficiency, making the habitat resilient in the harsh environment of the Kuiper Belt.

11. Mass and Energy Balance

The total estimated mass of the colony is calculated based on the main structural and functional components:

Water-based radiation shield: 4.2×10^9 kg
Structural frame and hull: 0.8×10^9 kg
Reactors and power systems: 0.05×10^9 kg
Atmospheric gases: 0.12×10^9 kg
Equipment, farms, transport units, spare parts: 0.1×10^9 kg
Total mass of the station: approximately 5.3×10^9 kg.

This value includes all major systems required for long-term autonomous operation, including shielding, life-support modules, and maintenance reserves. Energy consumption of the colony is determined primarily by life-support, agricultural, and industrial needs. The average electrical power output is Pe = 0.75 GW, supplying energy for lighting, farms, air and water recycling, and ice-processing facilities. The thermal output of the fusion reactors reaches Pt = 2.0 GW, which must be radiated into space using large radiator panels to prevent overheating. This power system enables full operation of heating networks, electrolyzers, industrial workshops, and heavy processing units — all functioning independently of solar energy.

The balance between electrical and thermal energy ensures stable internal temperatures, reliable system performance, and complete self-sufficiency even in the dark, frozen environment of the Kuiper Belt.

12. Key Equations

1. $a = \omega^2 \times r$ — artificial gravity from rotation
2. $\omega = 2\pi \times rpm / 60$ — relation between rotation speed and angular velocity
3. $v = \omega \times r$ — linear velocity at the rim
4. $PV = nRT$ — ideal gas law (atmospheric control)
5. $Pe = \eta \times Pt$ — electrical output of the reactors
6. $Q = \varepsilon \times \sigma \times A \times (T^4 - Ts^4)$ — required radiator surface for heat dissipation
7. $D = D_0 \times \exp(-k \times S)$, $S = \rho \times t$ — radiation shielding attenuation
8. $M(recycled) = \eta \times M(used)$ — closed water cycle
9. $\sigma = (\Delta P \times R) / t$ — structural stress of the pressurized hull
10. $2H_2O \rightarrow 2H_2 + O_2$ — electrolysis for oxygen generation
11. $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$ — photosynthesis for food and oxygen production

13. Final Conclusions

The radius of each habitation ring is approximately 358 m; rotation at 1.5 rpm produces 0.9 g, allowing humans to live in near-Earth gravity conditions.
Atmospheric pressure of 1 atm and a controlled O_2/N_2 mixture provide natural breathing without spacesuits.
A massive shielding layer — 2 meters of water plus metal armor — reduces radiation

exposure to safe human levels.
Fusion reactors provide about 0.75 GW of electrical power and 2.0 GW of thermal energy for all systems.
Agricultural areas of around 7.5 km², combined with closed air and water cycles, fully supply food and oxygen within the colony.
The total habitable floor area of the three rings is about 3.37 km², with modular potential for future expansion.
The total station mass is approximately 5×10^9 kg.
The colony supports 150,000 residents and is designed for autonomous operation exceeding 1,000 years without resupply from Earth.

The engineering principles of closed ecological systems, ECLSS design, functional division of "city zones", and population control were inspired by earlier concepts of large-scale autonomous spacecraft for over 50,000 inhabitants, featuring water recycling and renewable resource loops.

The Kuiper Belt Colony represents a sustainable model of human civilization beyond planetary influence, capable of thriving independently in the depths of the Solar System.

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