AEROO Space Settlement Competition 2025

Project name:

Lumora

Team name: 4Brain

Category: Senior division

Institution: Nazarbayev Intellectual School of Physics and Mathematics in Nauryzbay district, Almaty

Almaty, 2025

Content

Team introduction

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Achievements: KazRobo – Nomination “Best Product Design”

2nd Place – International Competition of Social Projects Launch Zone

Nominated for Best Green Technology Startup of the year in Kazakhstan at the Global Startup Awards

3rd Place – Network Scientific Projects Competition

1st Place – Galymind Research Paper Contest

Awarded $25,000 in Google Cloud Credits and unlimited Nozomio Credits – Investly Startup Battle

Semifinalist – GCIP Acceleration Program

Finalist – Invest Match Acceleration Program

Prize winner – Next Startup Battle

Askerbek Ansar — Biotechnologist, Life support engineer

Achievements: 3rd place – Hacktime by global education

2nd place – 2025 Almaty Physics Battles Qualifying round

Beissenbay Assem — Visual and 3D designer

Achievements: KazRobo – Nomination “Best Product Design”

1st Place – Galymind Research Paper Contest

Awarded $25,000 in Google Cloud Credits and unlimited Nozomio Credits – Investly Startup Battle

Finalist – Technovation Girls

Shortlisted in the Creative IT category at the Steppe Awards

Empowered Excellence Award supported by Synopsys

Prize winner – Next Startup Battle

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Achievements: Silver Honour – 2025 IAAC top 5%

2nd place – 2025 Almaty Physics Battles Qualifying round

3rd place – Hacktime by global education

Abstract

Lumora is a next-generation autonomous orbital colony located within the Kuiper Belt, which is one of the most distant yet resource-rich regions of our Solar System. It is engineered to sustain a stable population of 100,000 - 300,000 people for over 80 Earth years without any external support from Earth or other colonies.

The colony's design consists of four counter-rotating O'Neill cylinders, each 5 km in length and 500 m in radius, interconnected by a central energy and docking hub. Every module generates 0.95 g of artificial gravity through rotation and is protected by a 2-meter-thick water layer acting as both a radiation shield and thermal regulator. This modular configuration allows dynamic rebalancing and adaptive adjustment even during orbital flight, ensuring continuous structural stability and safety.

At the core of the settlement functions Lumora AI - an adaptive artificial intelligence system that regulates every essential life-support process. It collects and analyzes environmental data (temperature, humidity, light intensity, CO_2/O_2 ratios, water cycles, energy demand) and dynamically adjusts the habitat's parameters to maintain ecological balance. Using machine learning, Lumora continuously optimizes lighting schedules, hydroponic nutrient delivery, and air composition, ensuring maximum agricultural efficiency and long-term human health.

The colony's resource independence is achieved through in-situ extraction of Kuiper Belt ices, which are processed into water, oxygen, methane, and ammonia, what is essential for energy production, life support, and material recycling. Its closed ecological loop ensures 98% water recovery and near-total waste reutilization, minimizing environmental impact and maintaining biospheric harmony.

Ultimately, Lumora embodies a fusion of engineering precision, biological sustainability, and artificial intelligence, presenting a realistic, scientifically grounded vision of how humanity can create a self-sustaining civilization in deep space.

Introduction

Problem: Humanity's next frontier lies beyond the inner Solar System.

Yet all existing space colonization concepts, from lunar bases to Martian settlements, remain dependent on Earth for energy, resources, and environmental regulation. True autonomy has never been achieved: communication delays, radiation, and resource scarcity make long-term self-sustaining habitats nearly impossible.

To establish a permanent civilization beyond Earth, a colony must function independently by producing its own food, water, oxygen, and energy, while maintaining ecological balance for multiple generations.

Solution: Lumora proposes a fundamentally new approach: an AI-governed orbital ecosystem capable of self-regulation and long-term adaptation.

Goals:

1. Maintain a stable, self-sufficient population of 100,000–300,000 people for at least 80 Earth years, ensuring artificial gravity and environmental conditions remain within ±20% of Earth norms.
2. Develop a machine-learning ecological regulator (Lumora AI) for predictive environmental control.
3. Achieve closed-loop sustainability in air, water, and biological cycles.

Objectives:

1. Design a stable rotating habitat generating 0.95 g artificial gravity.
2. Develop Lumora AI for autonomous environmental regulation and data-driven learning.
3. Implement closed-loop life-support systems for air, water, and food with ≥98% recycling.
4. Establish radiation and thermal protection, including a 2 m water shield and modular radiator networks.
5. Utilize local Kuiper Belt resources (ISRU) for water, oxygen, and fuel production.
6. Ensure system reliability and sustainability for over 80 Earth years of independent operation.

Uniqueness:

- AI-managed biosphere: Lumora AI learns from every environmental fluctuation, evolving toward optimal life conditions.
- Dynamic architecture: Rotating modules can adjust rpm or reconfigure through the central hub while maintaining stable living conditions.
- Deep-space autonomy: Every aspect of life, such as energy, water, air, food, culture, and reproduction, occurs within the system itself.

Technical realizations
Scientific and engineering foundation

1. Artificial gravity and human physiology

The colony applies the O'Neill cylinder principle, creating gravity through rotation rather than mass [1]. At a radius of 500 meters and a rotation speed of 1.3 rpm, Lumora achieves 0.95 g, which minimizes bone loss, muscle atrophy, and cardiovascular stress. Studies by NASA and ESA confirm that sustained artificial gravity above 0.8 g is sufficient for multi-generational human adaptation in space.

Several artificial gravity configurations were modeled to find an optimal balance between comfort, rotation speed, and structural load. The relationship between angular velocity (ω) and radius (r) is shown in Fig. 1. The results indicate that increasing the radius lowers the required rotation rate, with the most stable design point at r = 500 m (ω = 1.3 rpm), producing approximately 0.95 g is optimal for long-term habitation.

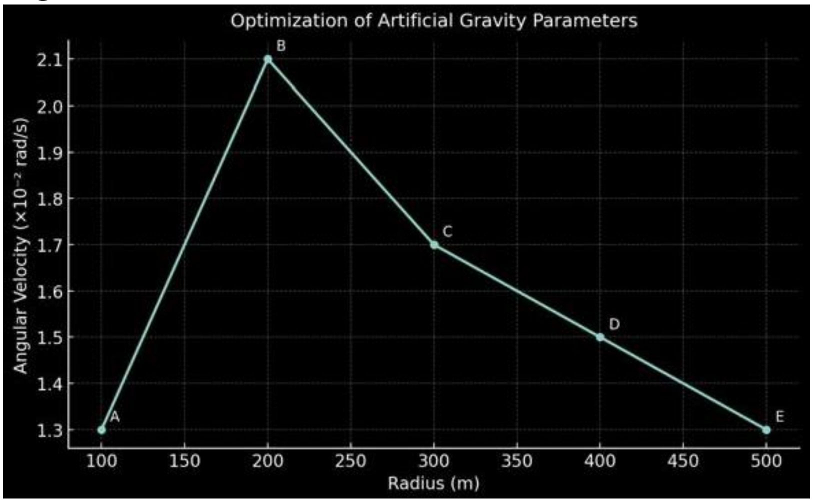

Fig. 1. Angular velocity vs. radius for achieving 0.95 g artificial gravity.

2. Radiation protection

Beyond Earth's magnetic field, exposure to cosmic rays and solar flares is a critical threat.

Lumora's solution is a 2-meter-thick water shield surrounding each cylinder. This layer provides over 200 g/cm² of areal density, which exceeds ICRP recommendations for deep-space habitation, while also serving as a thermal stabilizer and water reservoir [2].

In emergencies, localized "safe zones" offer triple shielding for additional protection.

3. Closed ecological life support systems (CELSS)

The ecological structure is based on ESA's MELiSSA Project and NASA's controlled ecological life support system (CELSS) [3]. Air, water, and food cycles are fully closed:

- Air regeneration: $CO_2 \rightarrow CH_4 + H_2O$ (Sabatier/Bosch) and O_2 is then produced via electrolysis.
- Water recycling: Multi-stage membrane and catalytic filtration with 98% efficiency.
- Food production: Multi-level hydroponic and algal bioreactors supporting ≥12 crop species.

4. Energy systems and thermal regulation

Due to limited solar flux at 44 AU (<0.1% of Earth's), Lumora relies on modular nuclear fission reactors with an output of 4 GW_e total.

Heat is dissipated through liquid-metal radiators, following the Stefan–Boltzmann law: **P=σAT4cap** (P equals sigma cap A cap T to the fourth power).

At 300 K and emissivity 0.9, 10 km² of radiating surface can reject 4 GW_t safely.

Redundant heat loops prevent thermal overload, ensuring stable temperature distribution within each cylinder.

5. Artificial intelligence control (Lumora AI)

Lumora AI serves as the autonomous regulatory core of the colony. Using sensor data and reinforcement learning, it:

- Predicts environmental changes (e.g., CO_2 rise, temperature drift).
- Adjusts lighting, irrigation, and ventilation in real time.
- Optimizes resource flow for maximum energy and biomass efficiency.
- Self-trains continuously to improve precision and resilience [4].

Lumora AI represents a practical evolution of current spacecraft environmental control systems [4].

6. In-Situ resource utilization (ISRU)

Kuiper Belt objects contain abundant frozen H_2O, NH_3, and CH_4, which can be converted into water, oxygen, and fuel [1].

Lumora employs robotic mining units and mass-driver transport, capturing sealed ice payloads via magnetic nets at the central hub. This resource chain eliminates dependency on Earth and closes the colony's material cycle. The estimated extraction volumes and their primary uses are summarized in Table 1 below.

Resource	**Quantity (t/year)**	**Utilization**
H_2O	1.5×10^6	Shielding, biosphere
NH_3	5×10^5	Fertilizers
CH_4	2×10^5	Fuel

Table 1. Estimated annual extraction of primary resources from Kuiper Belt ices and their utilization within Lumora Colony.

7. System integration

The combined implementation of artificial gravity, water-based shielding, CELSS, and AI regulation forms a fully autonomous self-correcting ecosystem.

Every physical, biological, and digital subsystem interacts through feedback loops by making Lumora not just a mechanical habitat, but a cyber-biological organism capable of evolution.

Architecture and design

1. General structure

Lumora consists of four counter-rotating O'Neill cylinders, each 5 km long and 500 meters in radius, arranged symmetrically around a central docking and energy hub.

The central hub is a non-rotating module that functions as: the command, AI control core, energy distribution center, and transportation dock for supply shuttles and resource collectors.

Each cylinder acts as an independent biome, with its own air, water, and energy cycles, while remaining interconnected for stability, transport, and data exchange. The cylinders are connected via magnetic coupling rings that transmit power and data while allowing mechanical flexibility. This layout ensures both rotational balance (through opposite spinning directions) and fault isolation; if one module fails, others continue operation independently [5]. To neutralize gyroscopic torque and preserve structural stability, opposite cylinders rotate in counter directions, as illustrated in Fig. 2. This configuration ensures complete angular momentum balance and minimizes mechanical stress on the central hub. The overall 3D configuration is illustrated in Fig. 3, showing the four counter-rotating O'Neill cylinders symmetrically attached to the central hub. This modular geometry ensures mechanical balance, easy docking access, and efficient energy distribution across the entire colony.

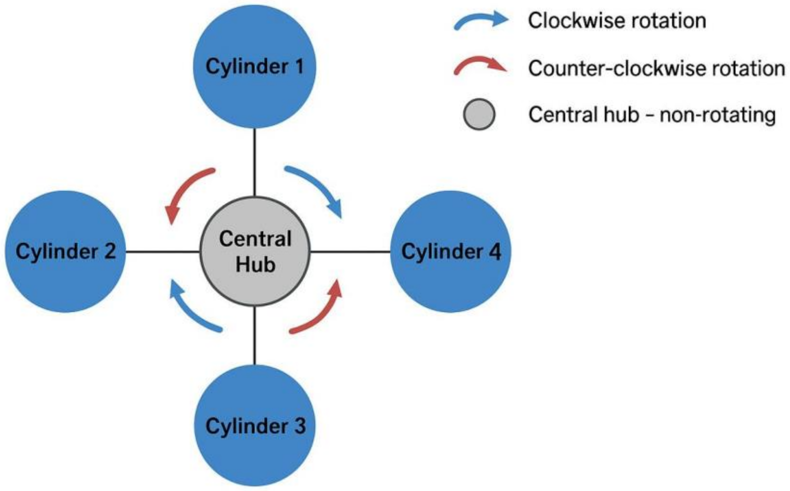

Fig. 2. Cylinder rotation and torque balance around the central hub.

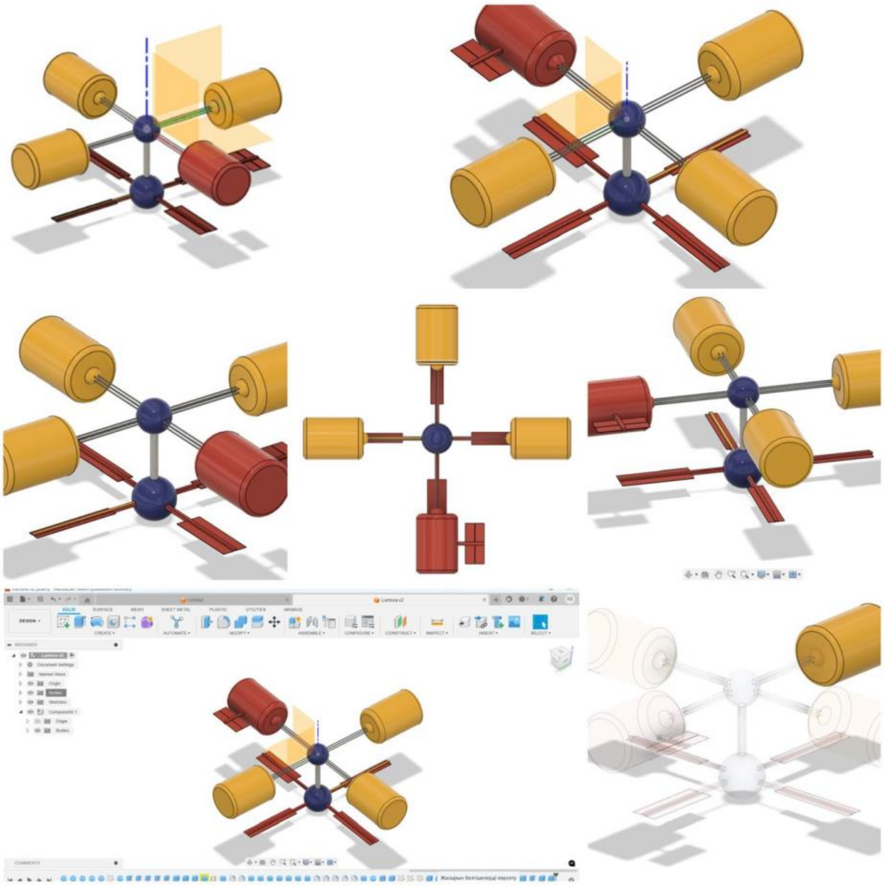

Fig. 3. Overall structural layout of the Lumora orbital colony.

2. Rotation and gravity

Each cylinder rotates to generate 0.95 g of artificial gravity on its inner surface. The rotational speed is calculated by:

$$a = \omega^2 r \Rightarrow \omega = \sqrt{\frac{a}{r}} = \sqrt{\frac{9.3}{500}} = 0.136\,\mathrm{rad/s} \approx 1.3\,\mathrm{rpm}$$

This value ensures:

- full physiological comfort for long-term habitation,
- minimal motion sickness (below NASA's 2 rpm limit),
- stable atmospheric and hydrodynamic behavior.

The counter-rotation of cylinders cancels gyroscopic torque, stabilizing the entire system's orientation.

3. Materials and shielding

The frame is constructed from aluminum-magnesium alloys reinforced with basalt-fiber composites, chosen for:

- high tensile strength (≈800 MPa),
- radiation resistance,
- thermal stability in cryogenic vacuum conditions.

The outer hull includes:

1. 2 m water layer for radiation and thermal control.
2. Micrometeoroid shield - composite polymer panels layered in a Whipple configuration.
3. Thermal insulation shell - multilayer aluminum-coated film to reduce temperature swings.

4. Internal zoning

Each rotating cylinder is divided into three primary zones:

1. Residential zone (35%): housing, recreation, education, health.
2. Agricultural zone (40%): hydroponic farms, algal bioreactors, and water recycling.
3. Industrial and technical zone (25%): power converters, maintenance, material recycling.

Every zone is illuminated through adjustable light mirrors reflecting solar or artificial light via fiber systems. Lumora AI controls photoperiods to simulate day-night cycles and maintain circadian health rhythms.

Dynamic systems and adaptation

1. Adaptive rotation system

Each of the four O'Neill cylinders is equipped with variable-speed magnetic drive rings. These allow Lumora AI to modify the rotation rate of individual modules by ±10% to:

- balance mass distribution as population and agriculture shift;
- reduce structural tension during maintenance or orbit correction;
- synchronize internal gravity levels for biological experiments.

AI Function: When any imbalance or micro-oscillation is detected in gyroscopic sensors, Lumora AI automatically compensates by redistributing angular momentum across modules or through controlled flywheel adjustments in the hub.

2. Modular reconfiguration in flight

Each cylinder can detach and reconnect via electromagnetic docking rings located on the central hub. This allows:

- individual rotation testing,
- repairs or replacements,
- installation of new submodules,

without interrupting the daily life of inhabitants.

The central hub contains autonomous drones and maintenance robots, which carry out external inspections and micro-repair operations under AI supervision.

AI control protocol: During separation, Lumora AI locks atmosphere gates, reroutes energy flow, and stabilizes pressure.

Once reattached, it rebalances rotation and restarts data exchange, all autonomously, within 3 minutes.

3. Environmental adaptation

Lumora's internal atmosphere and lighting dynamically adapt to habitat conditions. When one module enters a shadow phase (due to orientation change), Lumora AI automatically increases internal illumination and adjusts spectral composition to maintain plant photosynthesis. If humidity or CO_2 rises above tolerance, it reroutes air flow to other cylinders, acting as a distributed life-support network. In emergency scenarios (e.g., reactor overload or radiation spike), non-critical modules enter "low metabolic mode", reducing energy consumption by up to 45%. This system ensures bio-environmental resilience; every part of Lumora supports the others, forming a "shared organism" model.

4. Self-learning structural control

Lumora AI uses a feedback-based learning algorithm combining real-time data with long-term performance history. It analyzes:

- internal pressure fluctuations,
- gravity-induced stress,
- vibration frequencies,
- and thermal gradients.

Over time, the AI learns the most stable configurations, creating predictive models that allow preventive maintenance rather than reactive correction.

Example: If a small rotational imbalance appears repeatedly under certain load conditions, Lumora AI preemptively redistributes fluid mass in water tanks to neutralize it without human command.

Life support systems and ecosystem

1. Atmospheric system (Air cycle)

The air regeneration process combines biological oxygen production with chemical CO_2 conversion [3]:

1. CO_2 Capture: from human respiration and agriculture.
2. Chemical Conversion: Sabatier and Bosch reactions reduce CO_2 into CH_4 and H_2O.
3. Electrolysis: Water is split into O_2 (for breathing) and H_2 (reused in reactors).
4. Photosynthetic Balance: Plants and algae consume CO_2 and release O_2, complementing the cycle.

Sensors track O_2, CO_2, and humidity levels across all modules every 10 seconds.

Lumora AI adjusts air flow and temperature gradients automatically to maintain homeostasis (21% O_2, 0.04% CO_2, ±1.5 °C tolerance).

2. Water system

Water is the central medium of Lumora's ecosystem, serving as: radiation shielding, thermal stabilizer, life-support fluid, and biological nutrient carrier.

Recycling process:

- Greywater is filtered through membranes and UV sterilization;
- Organic waste is converted via catalytic bioreactors;
- Condensation recovery from air by 98% efficiency [3].

3. Food and agriculture

The Agricultural zone of each cylinder (≈40% of internal surface area) hosts multi-level hydroponic, aeroponic, and algal systems. Food diversity is essential for nutrient balance and morale. Therefore, Lumora maintains at least 12 species of major crops types to ensure long-term nutritional and ecological stability, as summarized in Table 2 below.

Type	Examples	Function

Cereals	Wheat, rice, maize	Energy & carbohydrates
Legumes	Soy, peas	Protein & nitrogen fixation
Roots	Potatoes	Calorie stability
Leafy plants	Lettuce, spinach	Vitamins, hydration
Fruits	Berries, tomatoes	Antioxidants, morale
Microalgae	Spirulina, chlorella	O_2 production & emergency nutrition

Table 2. Major crop types cultivated within Lumora's agricultural zones and their primary ecological functions.

AI-regulated lighting simulates 24-hour light cycles with blue-rich spectra for growth and warm tones for rest periods.

When environmental stress is detected (e.g., humidity drop or nutrient deficit), Lumora autonomously adjusts pH, nutrient ratios, and irrigation timing.

4. Biodiversity and psychological health

Beyond function, Lumora's ecological design preserves biodiversity for emotional balance.

Small natural environments "biospheres" simulate Earth-like landscapes with vegetation, rivers, and artificial weather. These serve both ecological (O_2 balance, pollination) and psychological roles, reducing isolation and cognitive fatigue among inhabitants. AI monitors population activity and environmental stress indicators (noise, crowding, light levels), then adapts public spaces accordingly. maintaining social equilibrium as part of overall system health.

Energy and power systems

1. Primary power source

Lumora's core energy generation system consists of four lead-cooled fast reactors (LFRs), each rated at 1 GW_e. These reactors are chosen for [6]:

- Long core lifetime (≥30 years);
- Passive safety through natural convection cooling;
- Compact shielding suitable for orbital habitats;
- High efficiency (35–38%) even in low-gravity environments.

The modular configuration ensures redundancy: if one reactor is under maintenance, others sustain the colony. All reactors are housed in the central non-rotating hub, separated by magnetic containment layers to prevent vibration transfer to the living modules.

2. Secondary systems and energy storage

To balance load fluctuations, Lumora integrates secondary power systems:

- Fuel cells for emergency use;
- Superconducting flywheel banks to store rotational energy;
- Biogas generators using waste-derived methane;
- Cryogenic batteries for rapid backup (<5 seconds response time).

3. Thermal regulation and waste heat control

Each reactor produces ~4 GW_t of thermal energy, which must be radiated into space.

Lumora's radiators use liquid-sodium heat loops with emissive carbon-nanotube panels (ε = 0.9) [4].

According to Stefan–Boltzmann law: $P=\sigma \varepsilon A T 4$ (P equals sigma epsilon cap A cap T to the fourth power). At T = 300 K, radiating 4 GW_t requires ≈10 km^2 of surface area.

Panels are arranged on rotatable wings behind the hub to maintain orientation opposite the Sun and Kuiper dust flux. Lumora AI continuously monitors: coolant flow, heat gradient, and emissivity degradation. It adjusts radiator orientation and surface temperature to maintain equilibrium automatically.

4. Power distribution network

All cylinders receive energy through superconducting plasma conduits, reducing transmission losses to <1%.

The AI-driven grid management ensures: fault isolation, energy rerouting in case of circuit failure, and priority balancing between life-support, AI cores, and rotation drives. An emergency sequence automatically powers down non-critical systems while maintaining full biosphere stability for up to 72 hours on stored reserves.

Human habitat and society

- Population: 100,000 - 300,000 people distributed evenly across four cylinders.
- Governance: Decentralized democratic system, where each module elects its representative council.
- Education & culture: Schools, research centers, virtual universities, art and music zones integrated into the residential section.
- Psychological health: AI monitors light exposure, sound, and social density to reduce isolation stress.
- Human development: Children are born, raised, and educated entirely within Lumora, adapting to 0.95 g gravity and artificial sunlight. Generations evolve together with the ecosystem, forming the first deep-space civilization — autonomous, self-sufficient, and creative [1].

Environmental impact and sustainability

The environment inside the colony functions as a controlled artificial biosphere, supporting natural cycles of air, water, and organic matter.

- Waste processing: Everyday waste from residents and agriculture is separated automatically. Organic material is converted into compost and biogas in sealed bioreactors, while plastics and metals are recycled mechanically into new materials using low-energy reprocessing units.
- Atmosphere regulation: The exchange between people, plants, and algae keeps oxygen and carbon dioxide naturally balanced. Additional filters and chemical scrubbers work only when necessary, preventing accumulation of unwanted gases and maintaining air purity.
- Water and energy efficiency: Condensation systems and multi-stage filters return up to 97–98 % of used water to circulation. Heat from reactors and habitats is reused to warm agricultural zones, reducing power demand.
- Ecological stability: All parameters, like temperature, humidity, microbial activity, are monitored by the AI network [3, 4].

Validation and metrics

The performance metrics, target values, and validation methods are summarized in Table 3 below.

Parameter	Target	Validation Method
Artificial gravity	0.95 ± 0.05 g	Rotation simulation
Radiation protection	≥ 200 g/cm²	Shield density test
Water recovery	≥ 98 %	Closed-loop trials
Temperature stability	± 1.5 °C	Thermal monitoring
Power reliability	≥ 99.8 % uptime	System logs
AI prediction accuracy	≥ 92 %	Data feedback cycles

Table 3. Performance targets and validation methods for Lumora's critical environmental and engineering systems.

Validation of AI prediction accuracy (≥92%) and system uptime (≥99.8%) are based on models used in NASA JPL's control systems [4].

Radiation protection verified against ICRP Publication 123 guidelines [2].

Risk management

To ensure the long-term safety and stability of the Lumora colony, all major technical and psychological risks were analyzed, and mitigation strategies were developed for each scenario.

The key risks and their corresponding countermeasures are summarized in Table 4 below.

Risk	Mitigation
Reactor failure	Modular redundancy and passive cooling [6]
AI malfunction	Dual-core system and manual override
Resource delay	Strategic reserves for 6 months
Structural imbalance	Counter-rotation and mass redistribution [6]
Psychological stress	Adaptive lighting and nature simulation

Table 4. Identified operational risks for Lumora colony and corresponding mitigation strategies.

80-Year development roadmap

The long-term evolution of the Lumora colony is divided into four major phases, each representing a distinct stage of technological, ecological, and social advancement.

The timeline and corresponding developmental priorities are summarized in Table 5 below.

Phase	Years	Focus
I. Initialization	0 – 10	Partial activation, AI training, 100 k population
II. Expansion	10 – 30	Four modules operational, full food autonomy
III. Stabilization	30 – 60	ISRU mining network active, energy optimization
IV. Evolution	60 – 80	300k population, advanced osphere, cultural independence

Table 10. Eighty-year phased development plan outlining Lumora's growth from initial activation to full autonomy and cultural maturity.

Conclusion

Space colonization poses major scientific and social challenges.

Lumora offers a realistic response - an autonomous orbital ecosystem capable of sustaining life for more than eighty Earth years without external supply.

During the project, the team analyzed the main obstacles of deep-space habitation such as radiation, limited energy, and ecological instability. A modular system of four rotating cylinders was proposed, providing 0.95 g artificial gravity and complete protection from cosmic radiation through a two-meter water shield.

At the core of the colony operates Lumora AI, which monitors temperature, humidity, air composition, and energy balance, automatically maintaining environmental stability. All life-support processes form a closed ecological loop where air, water, and waste are continuously recycled. Resource extraction from Kuiper Belt ices ensures full independence from Earth.

From a scientific point of view, Lumora contributes to the development of space-habitat research, artificial-gravity engineering, and autonomous environmental control. It demonstrates how AI and ecological design can merge into one sustainable system.

Practically, Lumora may serve as a model for future orbital settlements, long-term missions, and planetary-defense infrastructure. The experience gained can also support studies in robotics, environmental science, and renewable-energy integration.

Thus, Lumora represents a scientifically grounded and technologically feasible model of a long-term autonomous orbital habitat.

References

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6. Los Alamos National Lab (2020). Small Modular Reactors for Deep-Space Energy Applications.

Methods and tools

Methods:

- Analytical modeling: used to calculate artificial-gravity parameters, power balance, and radiation shielding.
- Simulation tools: CAD-based structural visualization and environmental balance models for temperature, CO_2, and water cycles.
- Scientific review: comparative analysis of NASA and ESA life-support research.
- Validation approach: empirical correlation of resource loops and energy output with existing orbital-habitat studies.

Tools:

- AI assistants: project report was partially prepared with the assistance of OpenAI ChatGPT (GPT-5, 2025) for text organization, grammar refinement, and visual diagram generation. All engineering models, numerical data, and conceptual ideas were independently developed, reviewed, and validated by the 4Brain team members. The use of AI tools followed ethical guidelines for responsible research and documentation transparency.
- 3D and design software: Fusion 360 for structural visualization.
- Graphics and layout: Canva for schematic visualization.