Lunar Habitats

Research Document

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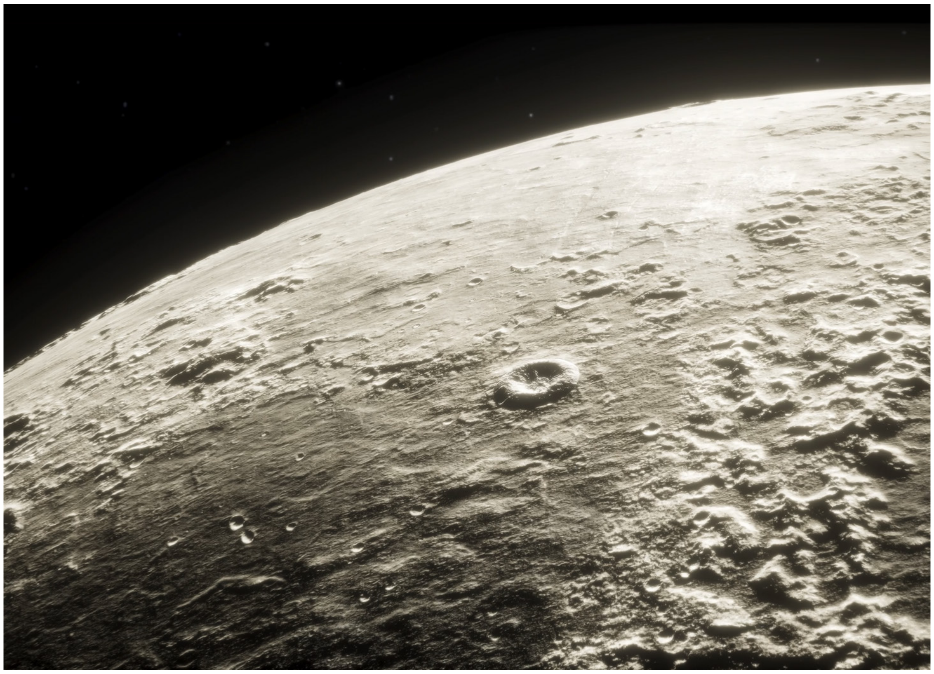

Fig. 1

The Race to the Moon

The next giant leap for mankind is fast approaching, with the race to inhabit the Moon likely to become a reality by 2030. In the past year alone, China, India, Japan, and the United States have all landed missions on the lunar surface. Both NASA and China plan to send astronauts there before the end of the decade with the intent to establish permanent bases. At the center of this new space race is a quiet but urgent competition: who will claim the most strategic locations first?

With only a handful of prime sites near the lunar poles, the Moon's surface is becoming contested terrain. While treaties like the 1967 Outer Space Treaty aim to keep space peaceful and shared, national laws now allow countries to extract and profit from space resources. In this landscape of accelerated ambition and legal ambiguity, the need for fast, efficient, and adaptive lunar architecture is growing.

A Fragile Exosphere

The Moon's environment is defined by extreme temperature swings, constant radiation, and frequent impacts from space debris. Without a protective atmosphere like Earth's, temperatures fluctuate rapidly—from over 250°F (121°C) in daylight to -208°F (-133°C) at night. A cubic centimeter of lunar air holds a hundred trillion times fewer molecules than Earth's, making the surface environment nearly a vacuum. This thin envelope is known as the exosphere, which cannot trap or distribute heat.

Fig. 1 Moon surface rendering
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Fig. 2 Moon's axis tilt
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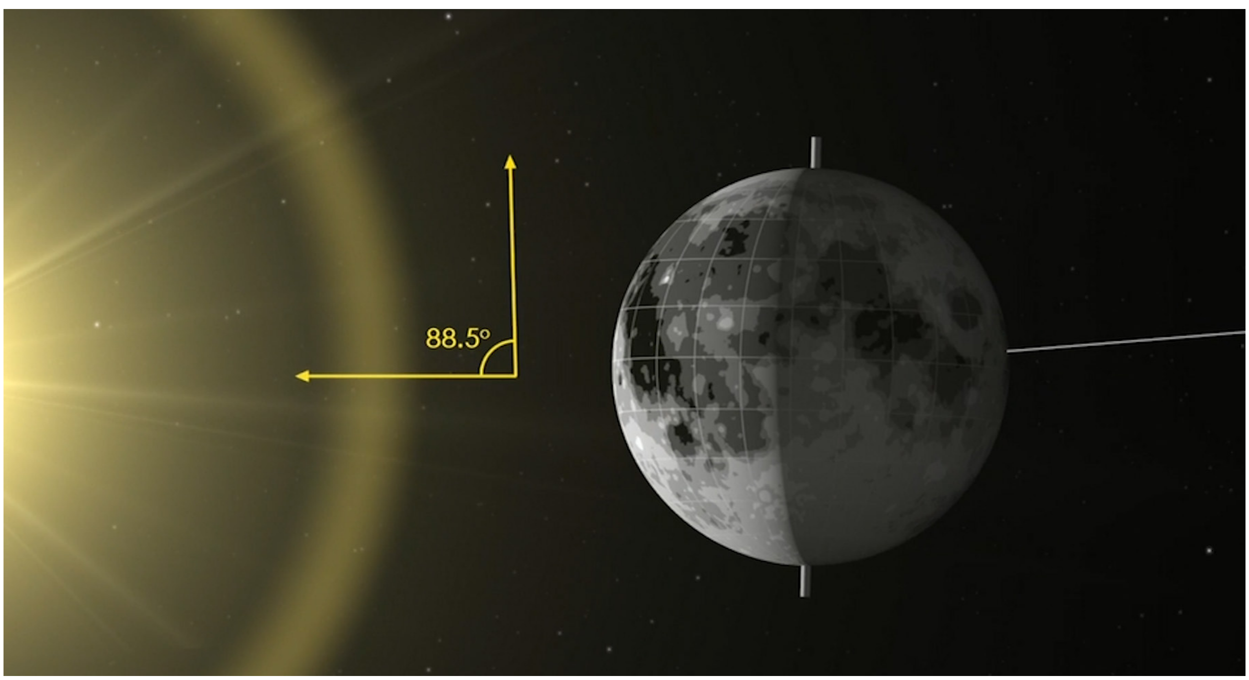

Fig. 2

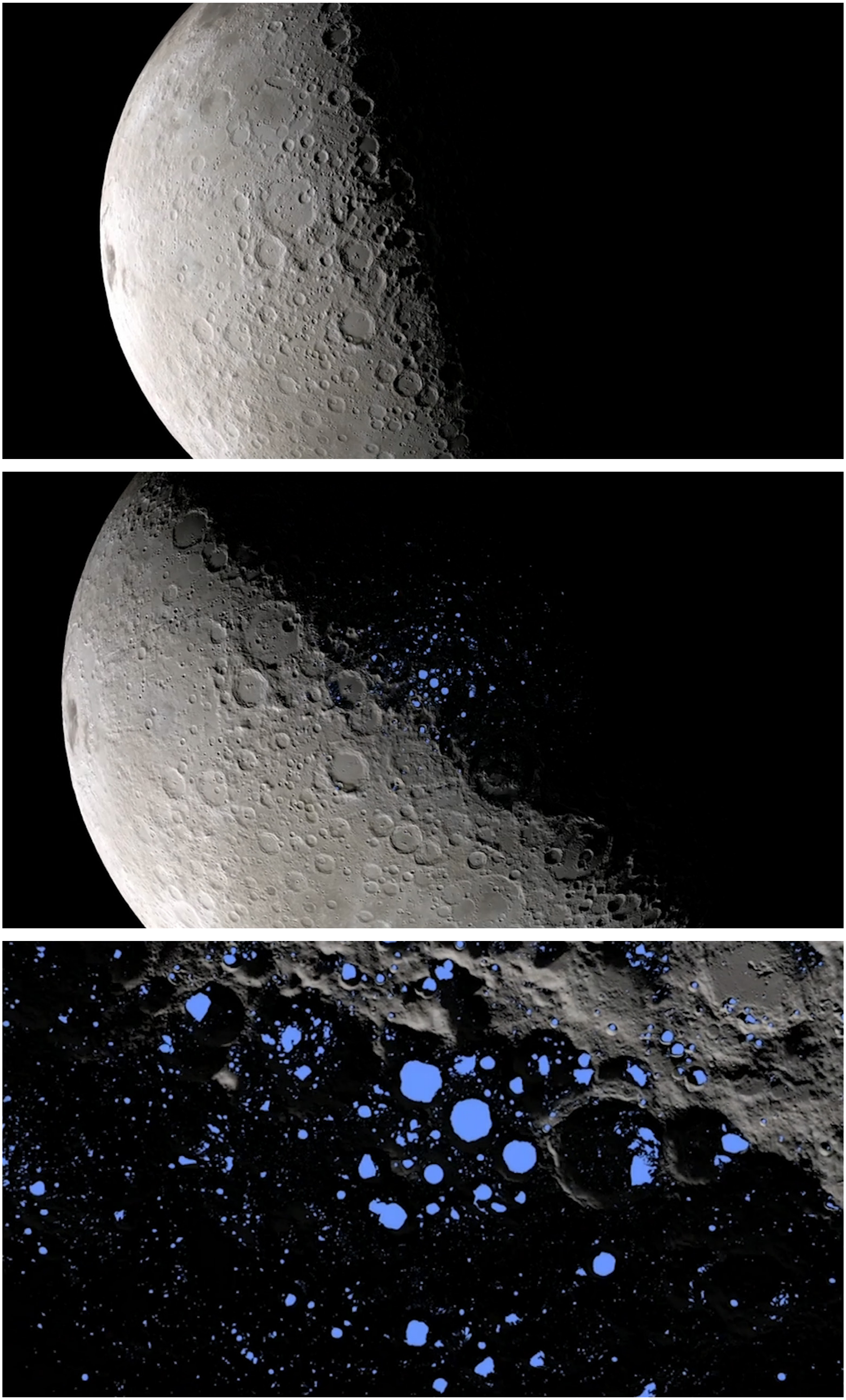

Fig. 3

Because the Moon's axis is tilted only 1.54˚, the Sun remains low on the horizon at the poles. As a result, some craters near the south pole—known as Permanently Shadowed Regions (PSRs)—never receive direct sunlight. In these craters, temperatures can plunge to -410˚F (-246˚C), preserving ancient ice deposits that may be billions of years old. Far from bleak, this offers hope: the ice can be converted into drinking water, breathable oxygen, and hydrogen for fuel—essential for sustaining lunar life.

Just above these PSRs, crater rims receive sunlight up to 90% of the time, making them prime sites for solar energy.

Fig. 3 PSR craters on the Moon
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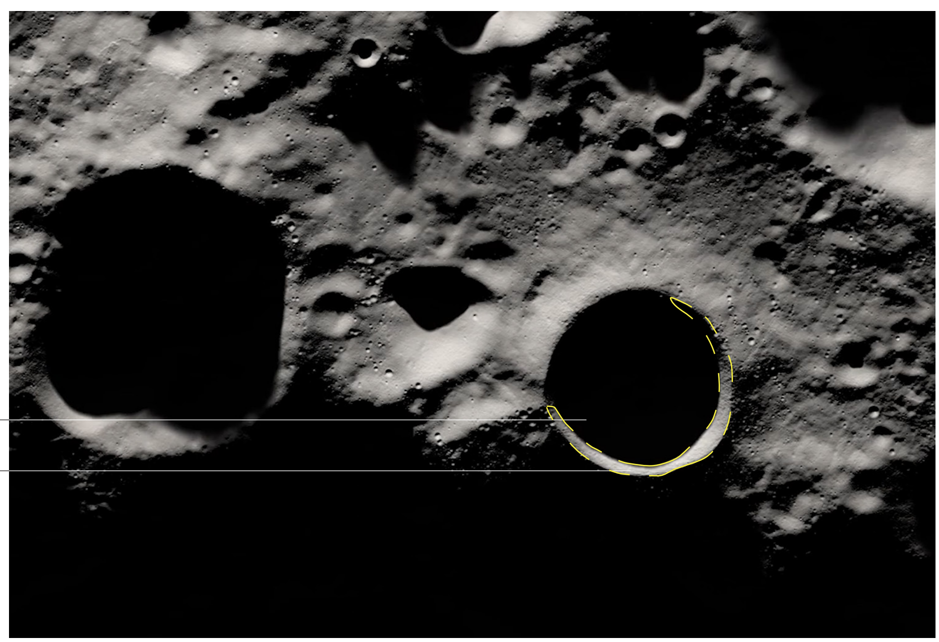
Fig. 4 PSR and sunlit rim
Nollistudio

Fig. 4



Permanently Shadowed Region

Sunlit rim

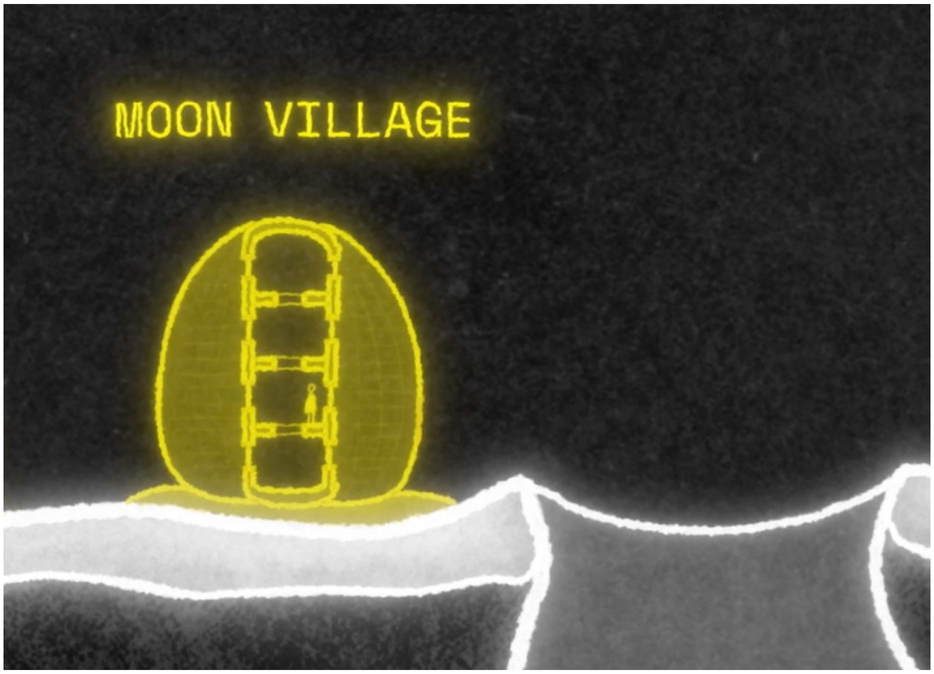


Fig. 5

Moon Village

Skidmore, Ownings, & Merill (SOM), Massachusetts Institute of Technology (MIT), and the European Space Agency (ESA)

The Moon Village is a joint initiative by Skidmore, Owings & Merrill (SOM), the European Space Agency (ESA), and Massachusetts Institute of Technology (MIT) to design the first permanent human settlement on the Moon. The project combines space engineering with architectural planning to create a modular, scalable infrastructure that supports long-term human presence. Located at the lunar south pole, the settlement will take advantage of local resources like solar energy and water ice to reduce reliance on Earth-based supply chains.

The vision emphasizes international collaboration, sustainability, and adaptability. Rather than a single structure, the Moon Village is planned as an open-ended framework that can expand over time to support scientific research, industrial activity, and eventual commercial use. It relies on in-situ resource utilization (ISRU) to produce water, oxygen, and building materials from the Moon itself. Human-centered design principles guide the layout and systems of the habitat, prioritizing safety, operational efficiency, and crew wellbeing in extreme lunar conditions.

Design Strategies

The Moon Village is designed to be flexible and easily expandable. To achieve this, the team developed a clear layout inspired by urban planning models: the settlement follows a “linear city” structure, with parallel zones for living, infrastructure, work activities, and energy systems. This layout makes it easy to connect new modules, ensures every section has backup paths in case of emergency, and can adapt to the Moon’s uneven terrain.

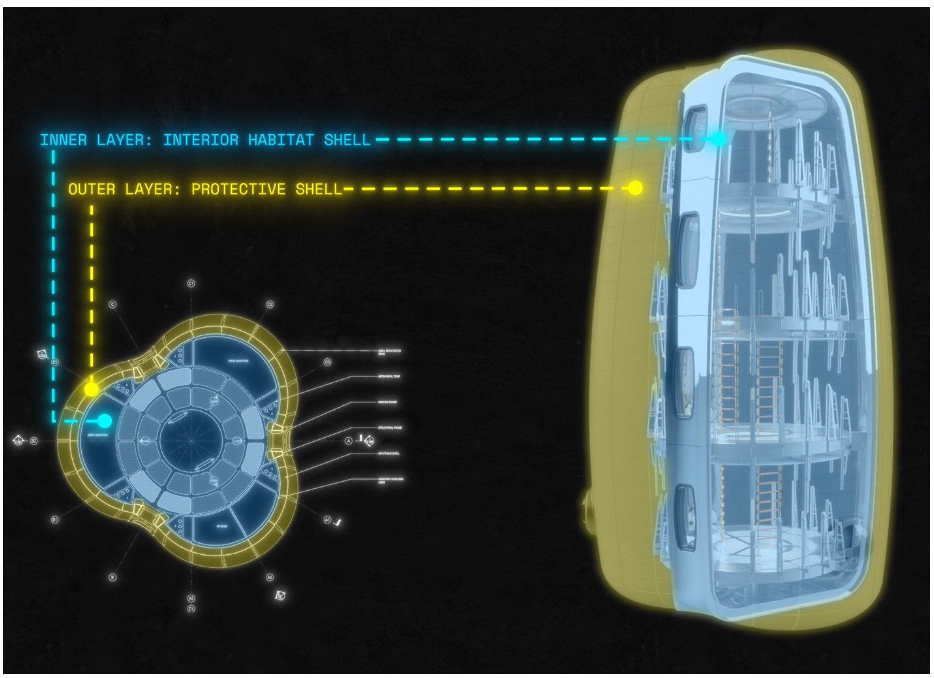


Fig. 6

Fig. 7

Fig. 5 Moon Village diagram
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Fig. 6 Moon Village layers
Base Image from SOM

Fig. 7 Moon Village systems
Base Image from SOM

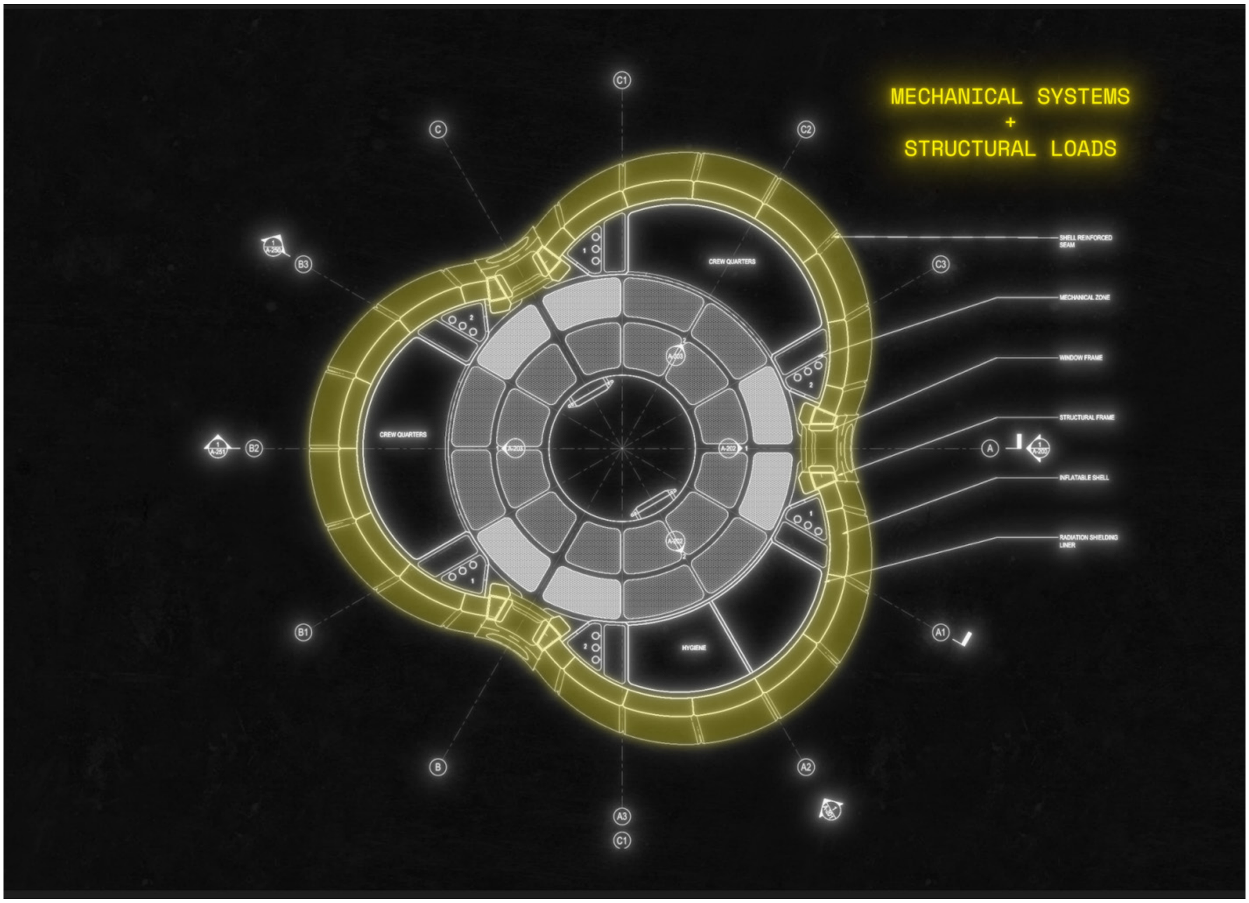

Fig. 8

The primary habitat is called One Moon, a tall, four-level living module. It arrives folded up for launch, then expands on the Moon. Unlike traditional space habitats that are small and cramped, One Moon uses a hybrid design: the strong outer frame holds the structure together, while the soft, inflatable walls save space and weight. This vertical organization makes efficient use of limited space and helps create a clear separation between different types of activities.

The Moon Village habitat is organized across four stacked levels, each designed to support different types of activities:

Ground Level: Dedicated to EVA (spacewalk) support stations and Command Center operations.

Second Level: Houses workstations, experimental laboratories, kitchen preparation areas, and a medical station.

Third Level: Contains crew quarters and hygiene facilities, offering private spaces for sleep and personal care.

Fourth Level: Includes hydroponic labs and food production spaces, helping the crew grow fresh food and study biological systems.

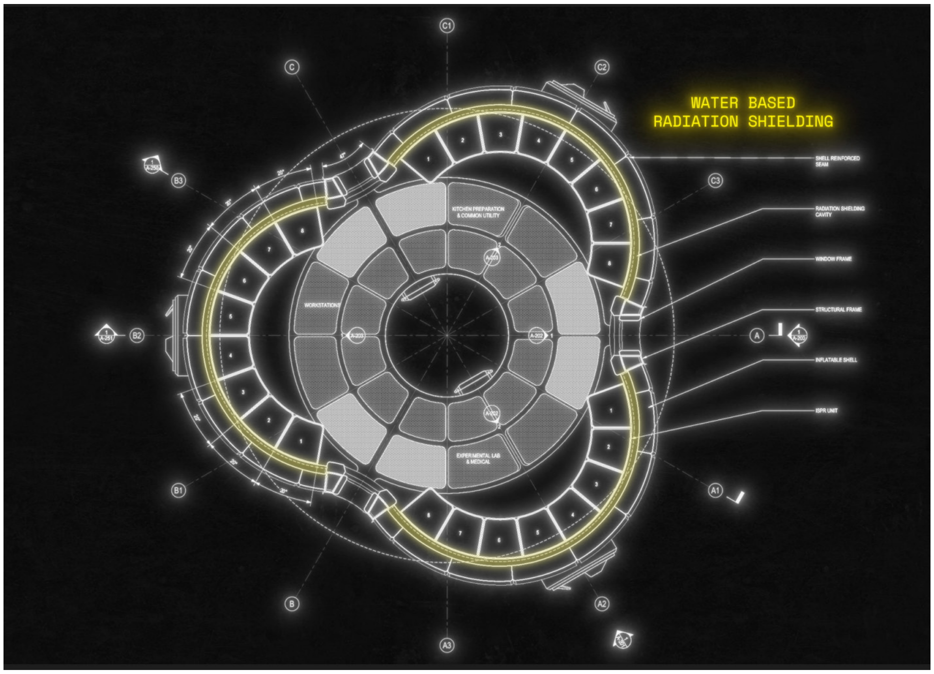

Fig. 9

The entire design is built around modularity—meaning parts can be added, rearranged, or specialized as the village grows. Early modules might combine multiple uses, but over time, specific habitats can focus on housing, science, or food production. This flexible approach allows the base to evolve alongside human needs and new technology.

To keep astronauts safe from radiation, the habitat walls are layered with water-filled shielding, using stored non-drinking water as a natural barrier. Windows and open layouts improve mood and reduce the stress of living in confined spaces, while lighting and air systems are carefully calibrated to mimic natural conditions as much as possible.

Fig. 8 Moon Village mechanical systems
Base Image from SOM

Fig. 9 Moon Village radiation sheilding
Base Image from SOM

Limitations

Despite its thoughtful design, the Moon Village faces significant logistical and financial challenges.

Every single component of the habitat must be launched from Earth and landed safely on the Moon. But rocket launches come with strict limitations—both in terms of weight and volume. This means each module must be lightweight, compact, and durable enough to survive the intense forces of launch, space travel, and lunar landing.

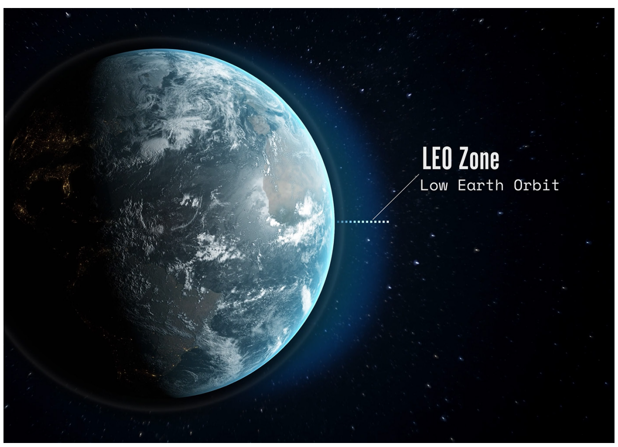

Fig. 10

Fig. 11

Even with weight-saving designs, launching materials to the Moon is extremely expensive. For example, NASA's Commercial Lunar Payload Services (CLPS) program estimates costs of up to $1 million per kilogram for small payloads delivered to the lunar surface. That's the equivalent of paying $330,000 to send a single can of Coke.

To compare, traditional rocket launches to Low Earth Orbit (LEO)—the first 2,000 kilometers above Earth—cost around $10,000 per kilogram, though newer vehicles like SpaceX's Starship could reduce this to $2,700/kg. However, these estimates apply only to LEO. Reaching the Moon—roughly 384,000 kilometers away—involves far more energy, precision, and risk, which significantly drives up the cost.

And while next-generation rockets may eventually reduce prices, they're unlikely to be fully operational before the first lunar habitats are deployed—projected between 2025 and 2030.

This presents a critical design trade-off:

1. **Should we rely on heavy, prefabricated structures that offer strength and reliability but are expensive to launch?**

2. **Should we explore lightweight alternatives, such as deployable systems, or even building directly with local lunar materials like regolith (the Moon's loose surface dust and rock)?**

Ultimately, reducing launch mass isn't just about economics—it's about investing in the quality of life for the first people who will call the Moon home.

Fig. 10 Low Earth Orbit diagram
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Fig. 11 Distance from Earth to Moon
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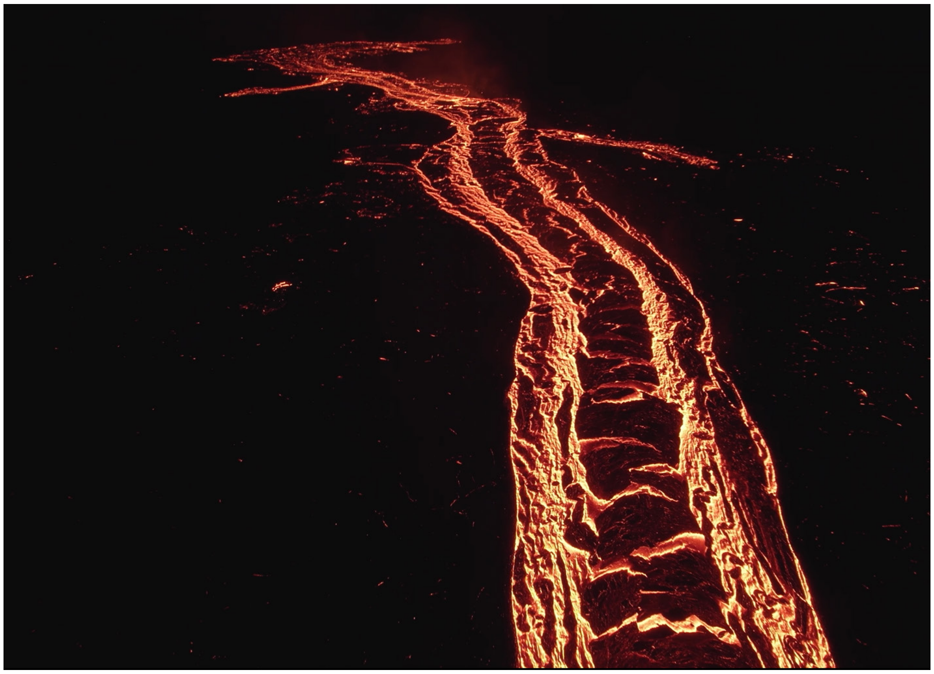

Fig. 12

Lava Tubes

In July 2024, a new discovery has motivated further lunar exploration: the confirmation of ancient lava tubes—massive underground tunnels that could become humanity's first real foothold beyond Earth. An international team of researchers discovered the first direct evidence of an accessible lava tube beneath the surface of *Mare Tranquillitatis*, using radar data from NASA's Lunar Reconnaissance Orbiter. This region, once famous as the Apollo 11 landing site, may now offer new possibilities for future lunar exploration and habitation. After decades of speculation, these hidden cavities have moved from theory into reality.

Lava tubes are natural tunnels formed when rivers of molten lava flowed beneath the surface during ancient volcanic eruptions. As the outer layers of the lava stream cooled and solidified, the molten interior kept moving, eventually draining away and leaving behind a hollow, cave-like structure.

Fig. 13

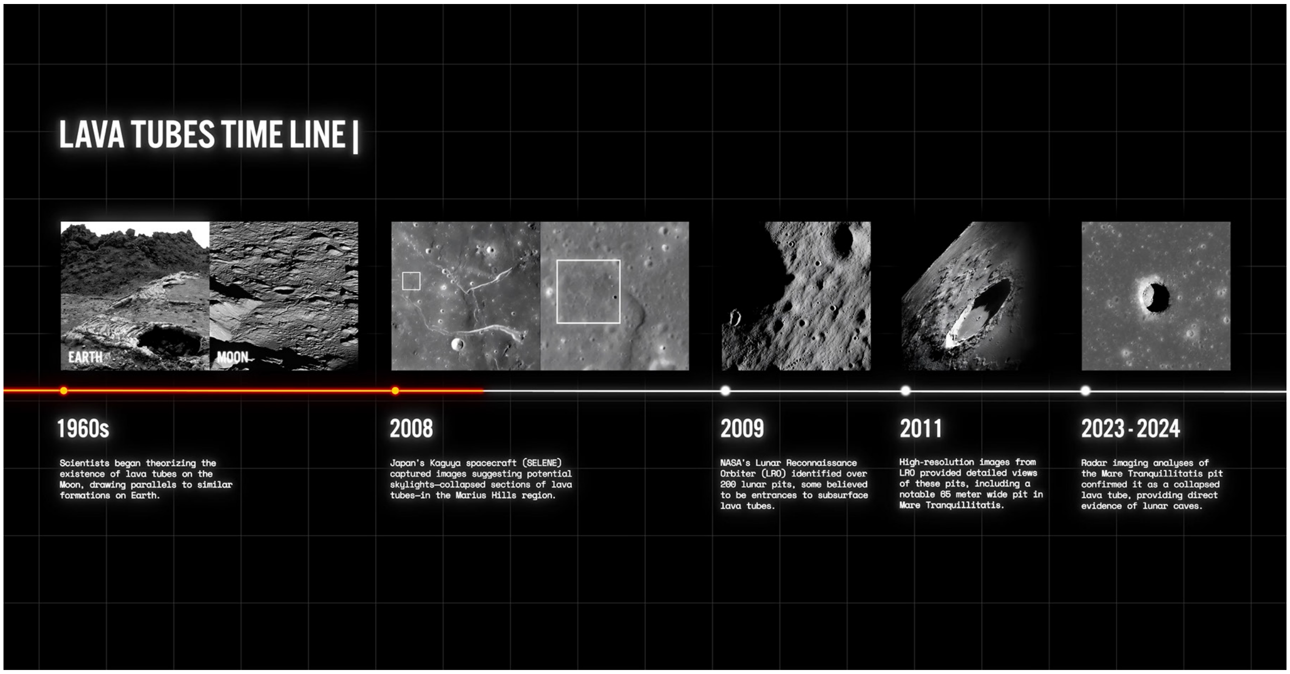

Fig. 13

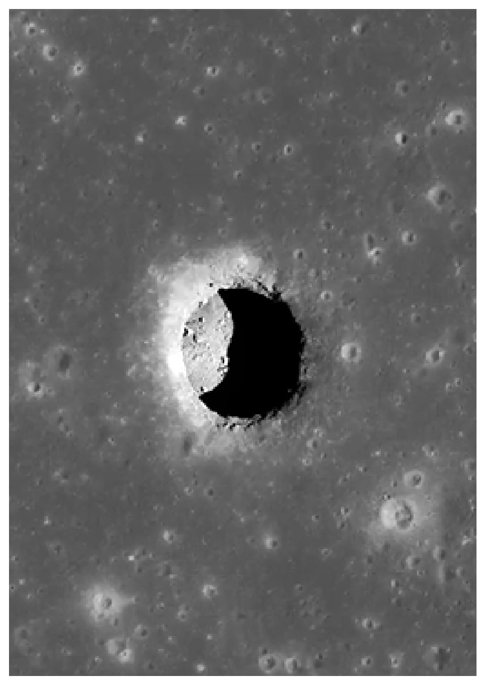

Fig. 14

Fig. 12 Lava stream before lava tube formation

Fig. 13 Lava tube discovery timeline
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Fig. 14 Lava flowing within lava tube

Fig. 15 Lava tube crater
Base Image from NASA

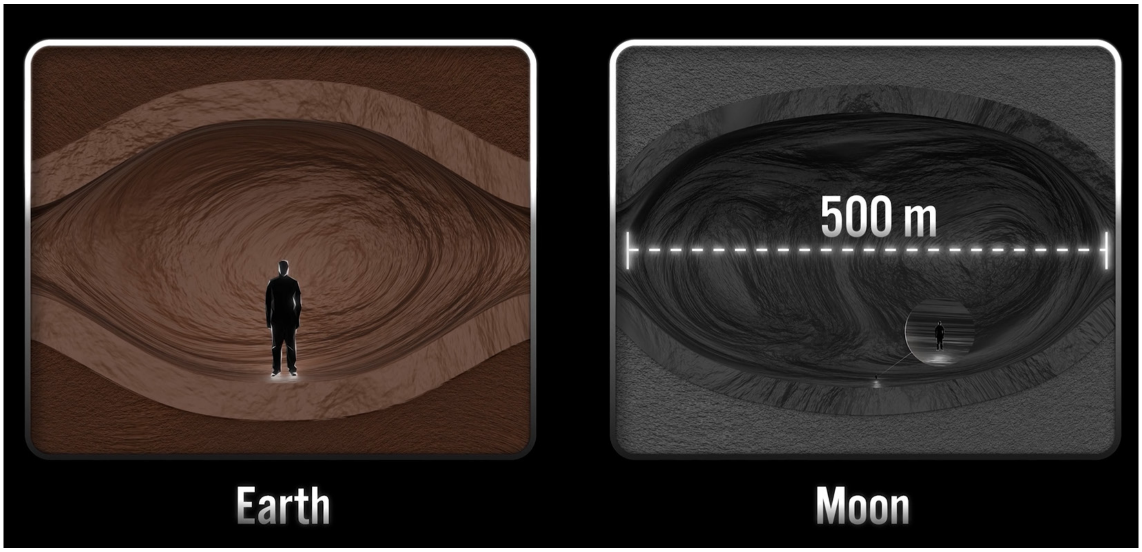

Fig. 16

On Earth, lava tubes are relatively modest—usually no more than 30 meters wide. But under the Moon's weaker gravity and lack of weathering, these tubes could be enormous, with theoretical widths spanning 500 meters and lengths stretching for kilometers.

Lava tubes offer a ready-made solution to almost all the major threats facing lunar settlers:

> **Radiation Protection:** With no magnetic field or thick atmosphere, the Moon's surface is bombarded by cosmic rays and solar radiation. Lava tubes, buried beneath meters of solid rock, provide natural shielding.

> **Meteorite Safety:** Without atmospheric friction to burn them up, even tiny meteoroids slam into the lunar surface at high speed. Settling beneath the surface avoids this constant hazard.

> **Temperature Regulation:** The interior of a lava tube stays around -20˚C. This might still sound cold, But near the entrance, close to the surface, it can actually reach up to 17˚C. Especially compared to the 300˚C swing on the surface, that's not so bad. it's basically Canada!

Instead of building heavily fortified bases on the surface, future lunar architects could deploy inflatable habitat modules inside these tubes, saving mass, cost, and complexity.

This knowledge has given researchers and scientists immense hope about our future in space.

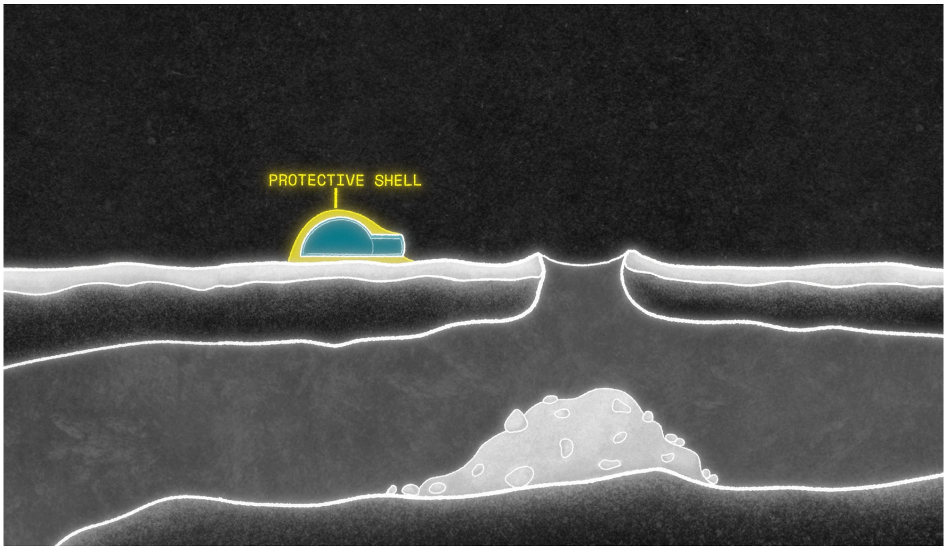

Fig. 17

Fig. 18

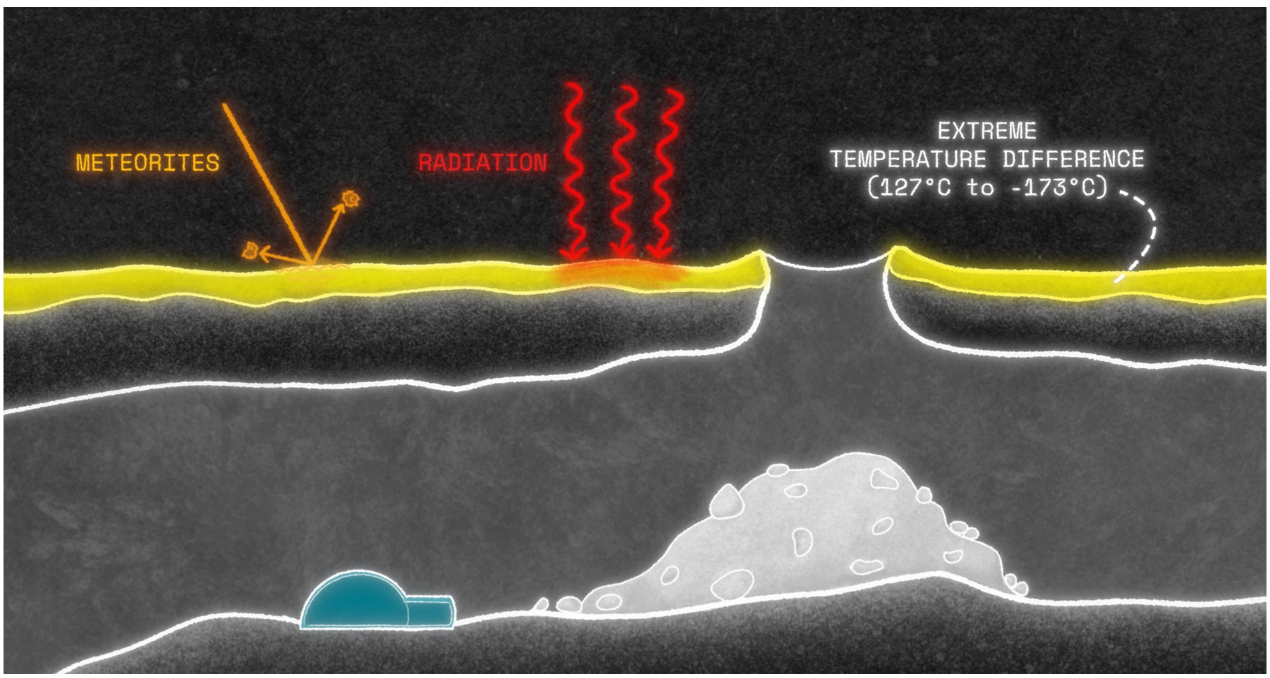

Fig. 16 Lava tube size comparison
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Fig. 17 Typical conception of a Lunar Habitat positionning
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Fig. 18 Lava tube acting as a natural shelter
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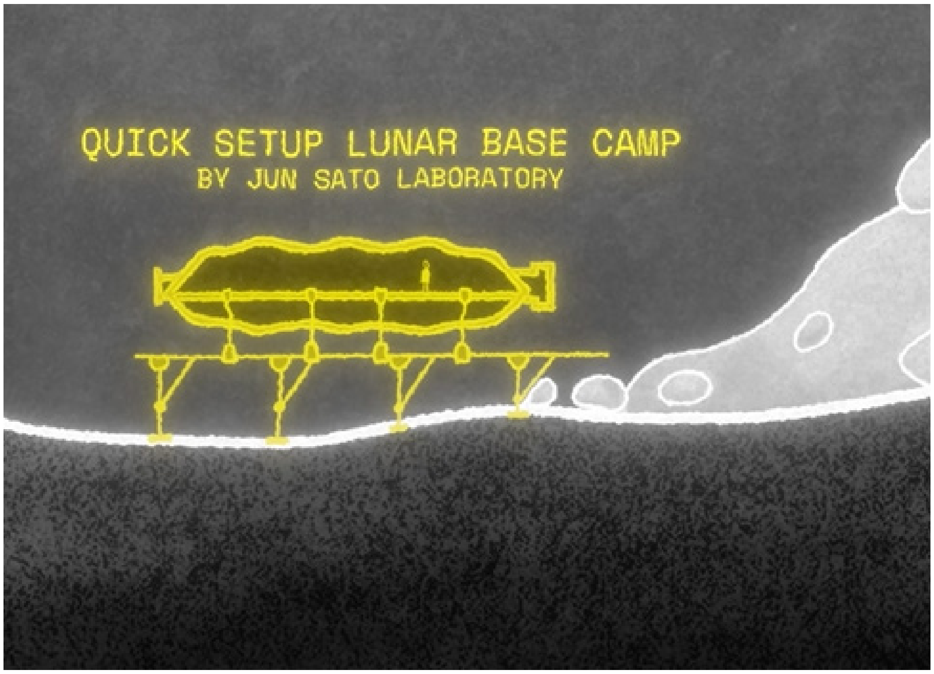

Fig. 19

Quick Setup Base Camp

Jun Sato Laboratory, The University of Tokyo, JAXA, Takenaka Corporation, and others

Building on the promise of lava tubes as natural shelters, researchers are now exploring how to adapt our technologies to this unique underground environment. One of the most compelling responses comes from Japan, where scientists are pioneering a new kind of lunar architecture that embraces the protective qualities of the Moon's subsurface. This effort is part of Japan's STARDUST Program, it is not yet in official implementation.

This project, led by researchers from the University of Tokyo and JAXA, explores a lightweight, rapidly deployable habitat designed specifically to sit inside these natural shelters. By leveraging the protective features of the site, the focus shifts from brute-force protection to material and mechanical optimization. The goal is to provide a flexible, easily transportable habitat that minimizes setup time and infrastructure demands. The system features a compact, inflatable, pillow-shaped habitation module paired with deployable solar power systems and an overhanging cable lift structure to connect shaded and sunlit zones.

Although still experimental, development of the structural framework has begun and many of the ideas researched so far will be utilized.

Design Strategies

The core of the base camp is a rapidly deployable habitation module shaped like a multi-faceted pillow. This structure is fabricated from 1–2 mm thick aluminum panels and relies on a unique deployment method.

Fig. 20

Fig. 19 Diagram of Quick Setup Base Camp
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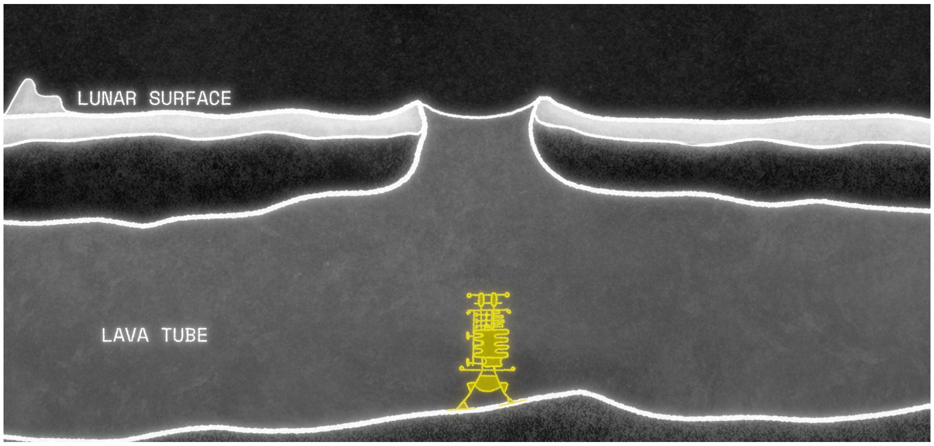
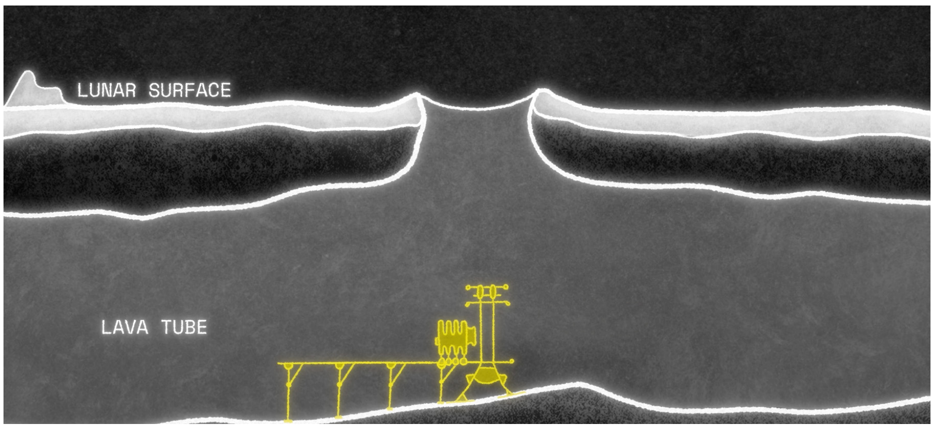
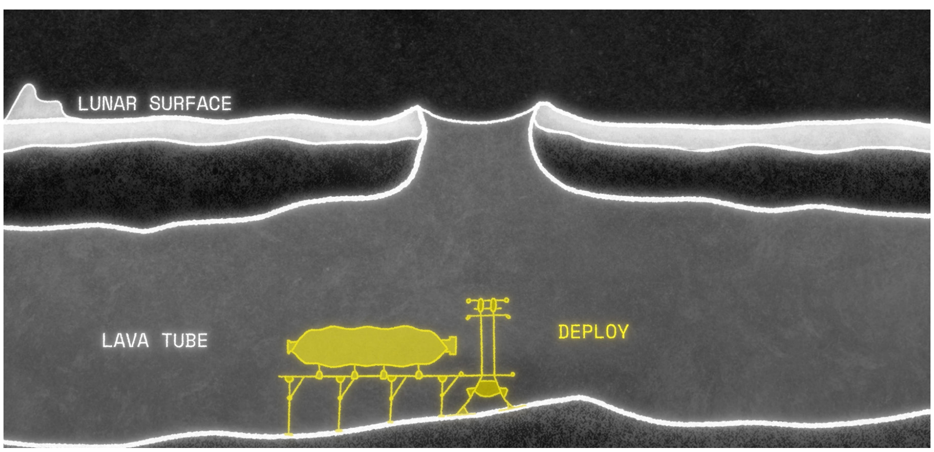
Fig. 20 Dami Lee and Jun Sato discuss the lunar habitat mockup
Nollistudio



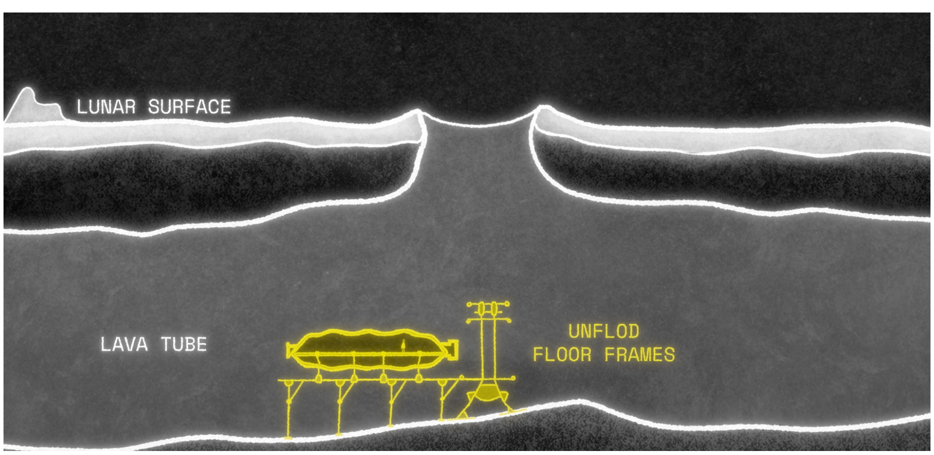
Landing



Touchdown



Deployment



Unfold Floor Frames

Deployment is largely passive. Once the module reaches the floor of a lava tube, it is inflated using internal air pressure. This inflation activates a synchronized sequence: the internal floor expands, sliding rails extend outward, and adjustable legs deploy automatically to stabilize the structure on uneven terrain. This entire sequence happens without the need for external cranes or human assembly, which are both impractical in low-gravity, high-risk environments.

To prepare the module for extended stays and protect its occupants from cosmic radiation, an additional laminated shield layer can be attached post-inflation. This layer includes both insulation and radiation-absorbing materials, effectively enhancing the survivability of the habitat while maintaining its lightweight and deployable nature.

Fig. 21 Lunar Habitat landing inside lava tube
Nollistudio

Fig. 22 Lunar habitat unfolds after touchdown
Nollistudio

Fig. 23 "Pillow" structure deploys and inflates
Nollistudio

Fig. 24 Floor plates unfold. Complete.
Nollistudio

Fig. 21

This project highlights a critical flaw in other lunar habitat proposals: fatigue failure. Since most habitats are designed to be constructed on-site—typically by inflating or unfolding—these repetitive deployment actions can gradually weaken the material, leading to compromised structural integrity. To overcome this, the team is using curved crease folding, which forms the primary geometry of the module. These folds allow the rigid panels to bend into shape while maintaining their strength. The hardest-to-deploy corners of the structure were identified through physical testing, and partial mock-ups at full scale confirmed that the design could deploy under internal pressure up to 0.10 atm without damage.

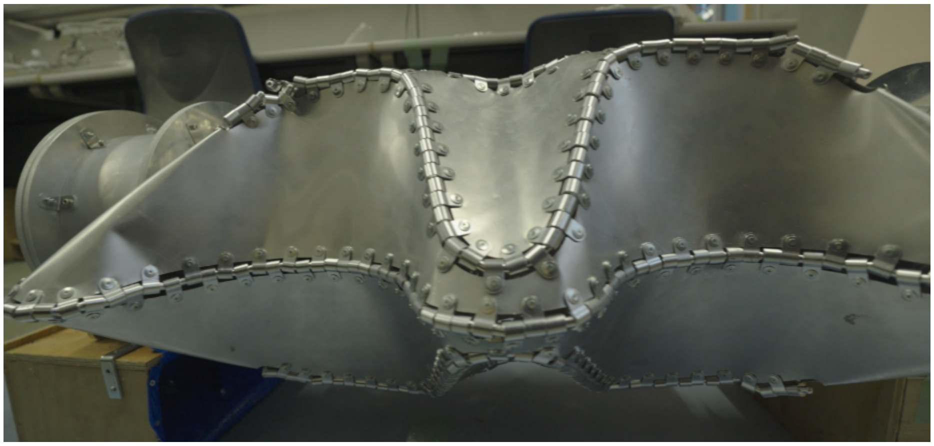


Fig. 22

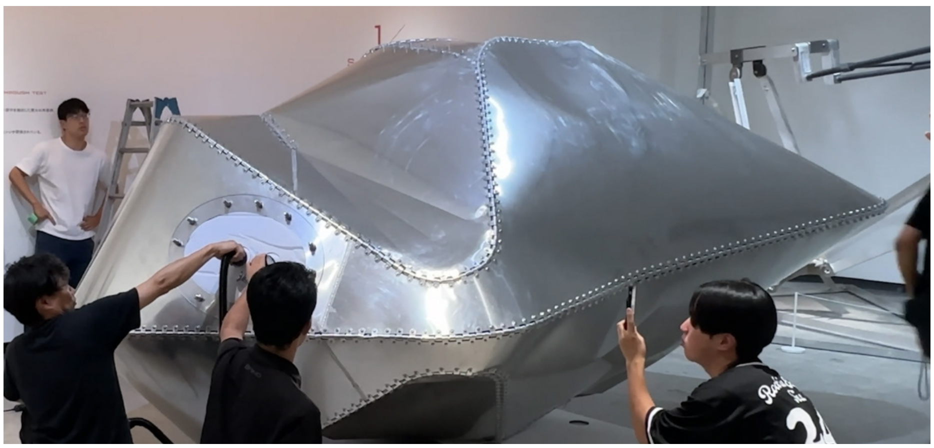


Fig. 23

Fig. 24

Fig. 21 Curve crease structure prototype
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Fig. 22 Curve crease structure to scale
Nollistudio

Fig. 23 Students inflate the “pillow” structure
Nollistudio

Fig. 24 Interior view of “pillow” structure
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Fig. 25

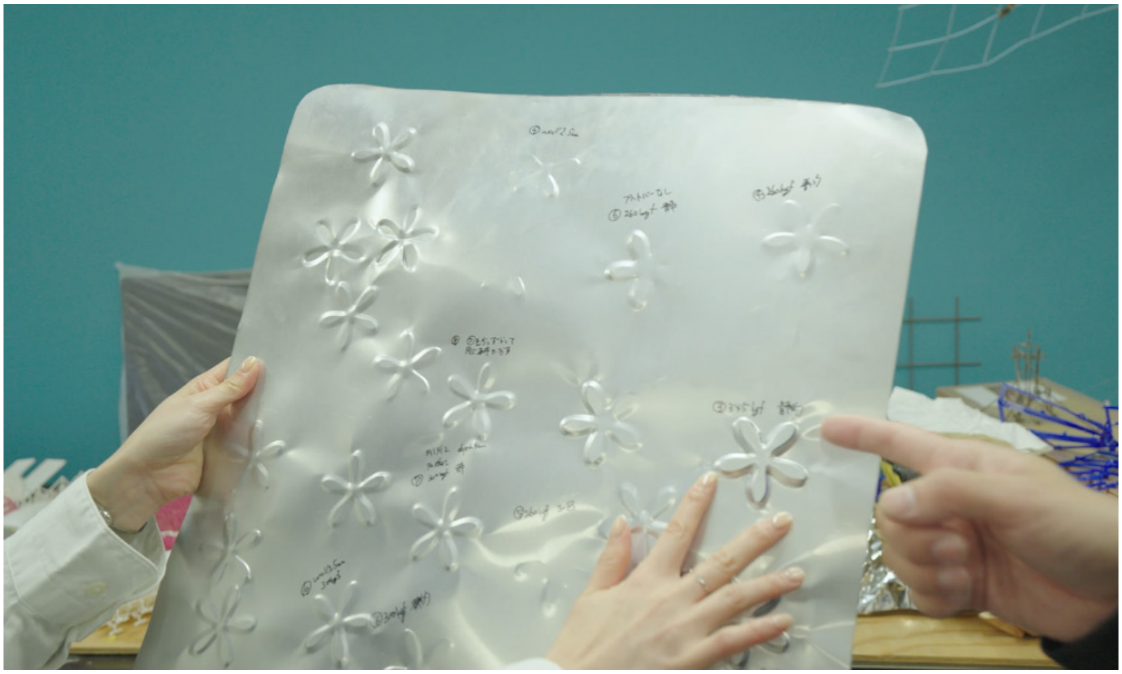

Fig. 26

To enable smooth and reliable unfolding, the rigidity of the panels are manipulated through “Sakura dimples”—a key innovation named after the cherry blossom. These are small indentations scattered across the surface of the metal panels. Their purpose is to guide the folding and unfolding of the material, acting as energy release points during inflation. These dimples allow the panels to snap into place more easily, reducing the risk of structural misalignment or buckling. This technique was inspired by natural principles of energy minimization and distributed deformation, much like how petals unfold in plants.

Fig. 27

A major innovation in the base camp design is its use of biomimicry, particularly inspired by the efficient movement and structural mechanics found in insects. The design team closely studied biological strategies to solve complex engineering challenges such as compact storage, lightweight strength, and rapid deployment.

One of the most striking examples is the solar power module, which takes direct inspiration from the hind wings of the earwig. Despite their small body size, earwigs can fold and unfold their wings with incredible compactness and efficiency. These wings fold along multiple axes into a fan-like shape, reducing volume while maintaining full functionality when expanded. The research team adopted this natural strategy to design a solar panel array that can be tightly packed for transport and then unfold in a radial motion once deployed on the Moon. This mechanism allows for maximum surface area without requiring heavy or rigid mechanical arms, which would add mass and complexity.

The earwig-inspired solar panels are supported by three-hinge bracings, a structural solution that mimics how joints in insect wings distribute mechanical load while allowing fluid motion. These bracings keep the panels stable in the Moon's low gravity and can withstand deployment on uneven terrain.

Fig. 25 Close up of Sakura Dimples
Nollistudio

Fig. 26 Small changes, such as shape, depth, density, and sharpness, in Sakura Dimples affect the material properties
Nollistudio

Fig. 27 Sakura Dimples applied to "pillow" structure
Nollistudio

Limitations

The current system focuses on structural deployment. However, for a complete habitat, several other systems must be integrated:

> **Life support (ECLSS)**

> **Thermal regulation**

> **Communications**

> **Power storage**

> **Interior furnishing and crew interfaces**

Additionally, precision landing and autonomous navigation remain open challenges, especially for delivering habitats into deep, rugged lava tubes.

The full deployment has only been demonstrated in controlled environments. It's unclear whether the current structure can be repacked or reused for future missions. Also, while the system works well for 2–4 crew configurations, it may require significant adaptation to support larger populations or extended mission durations.

Fig. 28-
Fig. 30 Experimental models used to develop the Quick Setup Base Camp
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Fig. 28


Fig. 29


Fig. 30

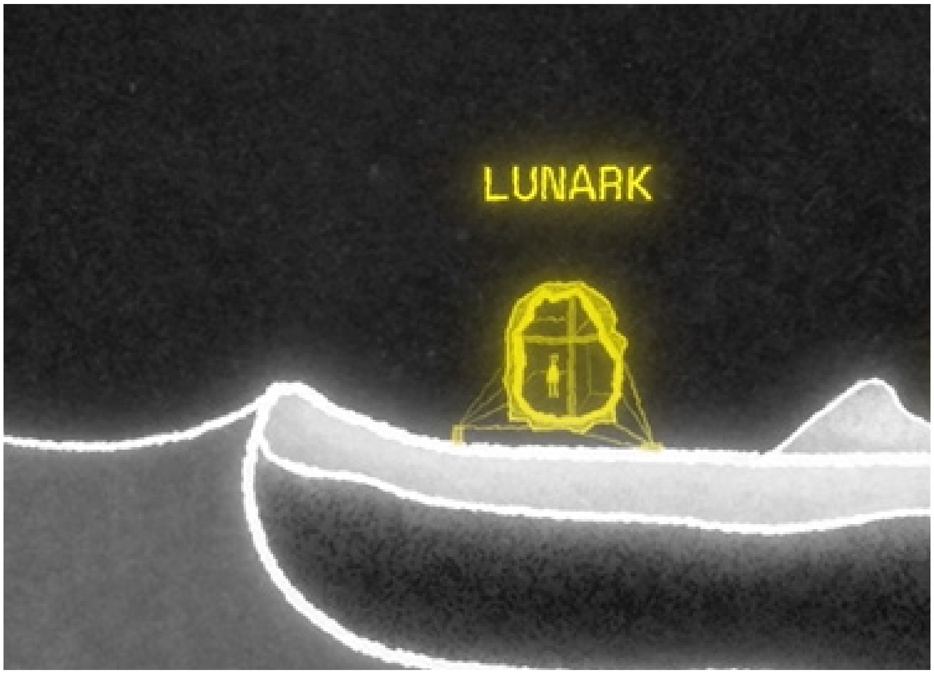

Fig. 31

L U N A R K H a b i t a t

SAGA Space Architects

Unlike most Lunar habitat proposals, the LUNARK project took a radically different approach—testing a full-scale prototype in hostile environments on Earth. Rather than simulating conditions through models or renderings, the architects behind LUNARK chose to live inside their design, using lived experience as a form of spatial research. This shift from concept to direct field immersion offers unique insight into the psychological and practical realities of extreme environment habitation. Through these holistic experiments, we can evaluate the true feasibility of lunar habitation—not just in meeting our physical needs, but also our mental and emotional well-being.

The LUNARK habitat is a prototype lunar module developed by SAGA Space Architects and tested in Northwest Greenland as part of a three-month Arctic analog mission. Designed for a two-person crew, this deployable structure aimed to simulate aspects of NASA's upcoming Artemis missions. The overarching objective was to explore not only the technical feasibility of the habitat in an isolated, confined, and extreme (ICE) environment, but also the psychological and interpersonal dynamics of long-term cohabitation under duress.

Inspired by the unfolding of a leaf, the habitat combines biomimetic design principles with practical constraints of spaceflight—most notably its ability to fold into a compact volume suitable for transport and then expand into a livable, double-story shelter. Its performance under extreme cold, darkness, and isolation was a critical testbed for future lunar habitation.

Fig. 31 LUNARK Habitat Diagram
Nollistudio

Design Strategies

LUNARK unfolds from a compact 2.2m^3 unit into a 17.2m^3 habitat—a 750% increase in volume. The structure features a carbon fiber shell with foam-core insulation, capable of withstanding Arctic conditions, and is supported by an internal aluminum frame. The habitat's exterior is equipped with solar panels, while the interior emphasizes comfort through soft materials, circadian lighting, and layered acoustic insulation. Together, these create a space that balances the demands of survival with the need for psychological comfort.

In environments where natural light is absent or unnatural—such as the Moon, polar regions, or deep space—time can lose its meaning. This disruption poses serious risks to human health, especially sleep, mood regulation, and cognitive function. To address these challenges, the LUNARK habitat incorporated an advanced circadian lighting system designed to simulate Earth-like day-night rhythms inside a sealed, compact space.

Developed in-house by SAGA Space Architects, the circadian light system was one of LUNARK's most essential tools for preserving psychological balance. Suspended on the ceiling of the habitat, these dynamic light panels created a virtual day by cycling through familiar light phases: dawn, sunrise, daylight, sunset, and dusk. This artificial rhythm helped crew members maintain a sense of time, even as the outside world remained dark, cold, and unchanging.

The Circadian Lights countered this with deliberate daily variation. Not every day was bright or sunny. Some days featured grey, overcast lighting with lower intensity, while others mimicked rich, saturated sunrises or warm clear skies. This subtle fluctuation introduced a much-needed sensory palette into an otherwise sterile environment, reducing the psychological effects of sameness.

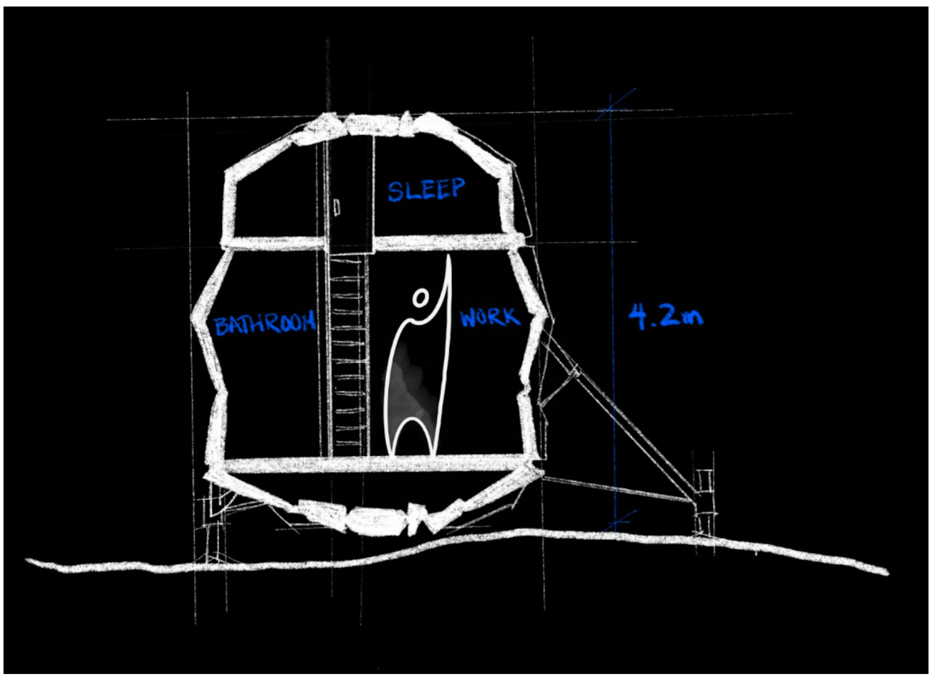

Fig. 32

Fig. 32 Schematic section of LUNARK
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The LUNARK mission findings suggest that staggered crew rotations, or "direct handovers," could significantly improve psychosocial outcomes in future missions. This approach—where new crew members cohabitate with experienced ones before taking over—promotes continuity, trust, and mentorship.

Emerging space mission plans envision a handover system in which a "senior crew" on the Moon overlaps with an arriving "junior crew" for several months. This setup enables technical knowledge transfer, but just as importantly, it fosters social traditions—routines, rituals, and inside jokes—that evolve over time. What begins as a sterile environment can, through repeated human presence, transform into a place of shared meaning.

Fig. 33 Team 1 (Senior Crew) works in space for 3 months before Team 2 (Junior Team) joins them for another 3 months
Nollistudio

Fig. 34 After Team 1 returns to earth, the Team 2 becomes the Senior Crew. They become mentors to the next Junior Crew, Team 3.
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Fig. 35 The cycle of training repeats.
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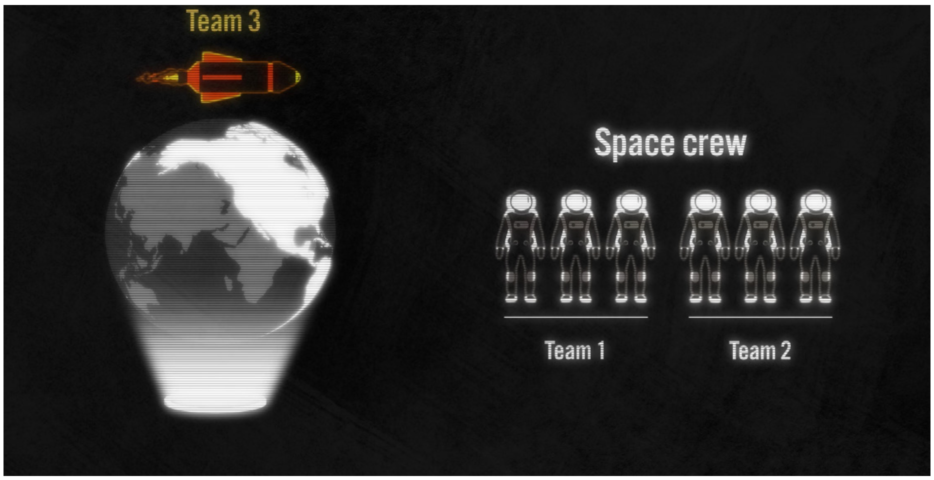


Fig. 33

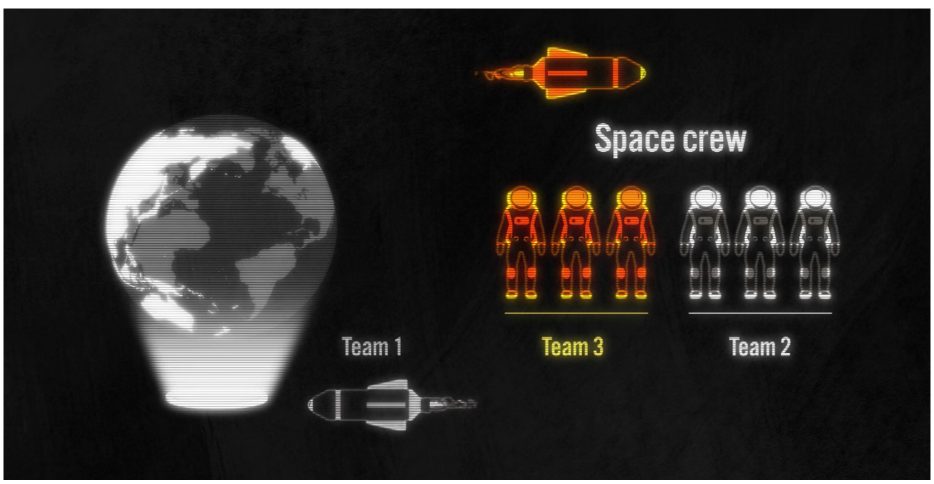


Fig. 34

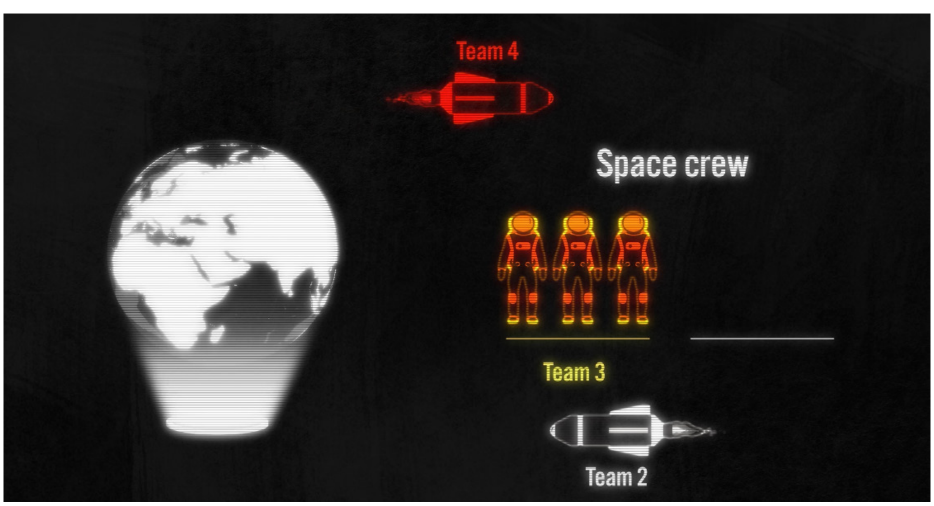
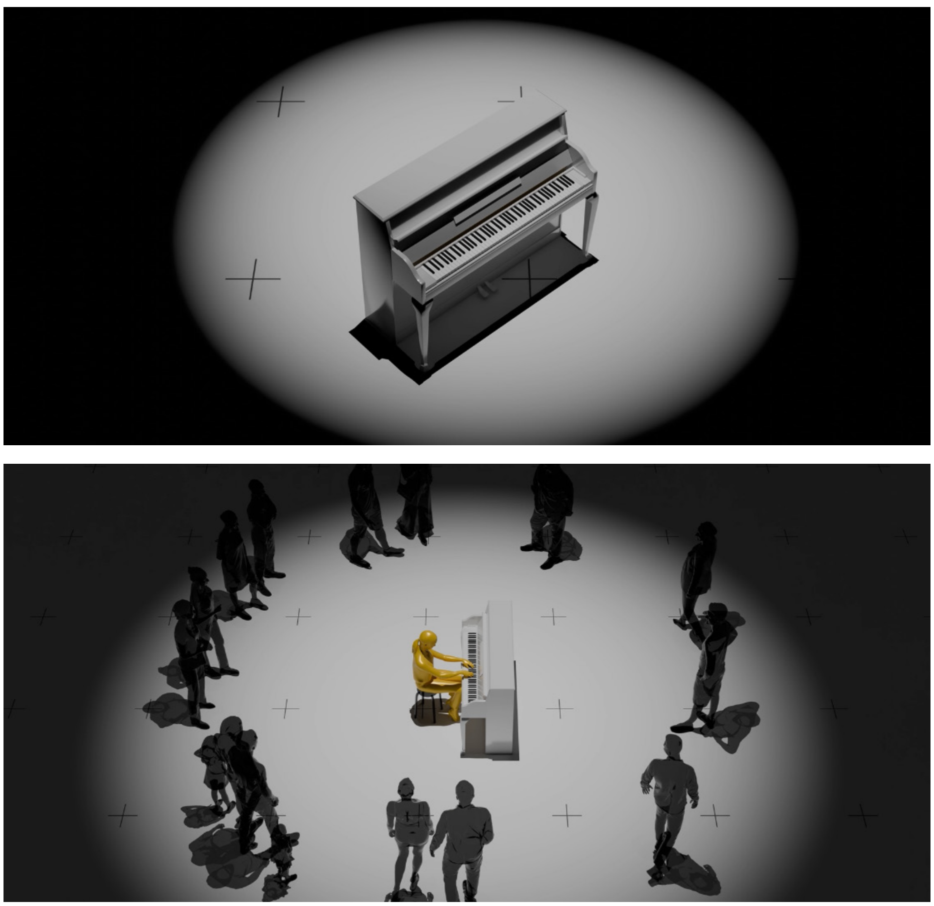


Fig. 35

This dynamic mirrors how public space becomes activated. Just as a piano in a city plaza becomes a social magnet when someone begins to play, even small corners of a habitat can gather emotional resonance.

Fig. 36



Imagine a crew member starts playing guitar in the same spot every evening. Others gather, songs are shared. And when that member leaves, that space—the "music corner"—retains a memory. It becomes part of the habitat's identity.

Fig. 37

Fig. 36 A piano in a space is just an object—until someone plays, others gather, and the space becomes a place.
Nollistudio

Fig. 37 Someone plays guitar in a corner—future crews keep playing there.
Nollistudio

This is the moment a space becomes a place.

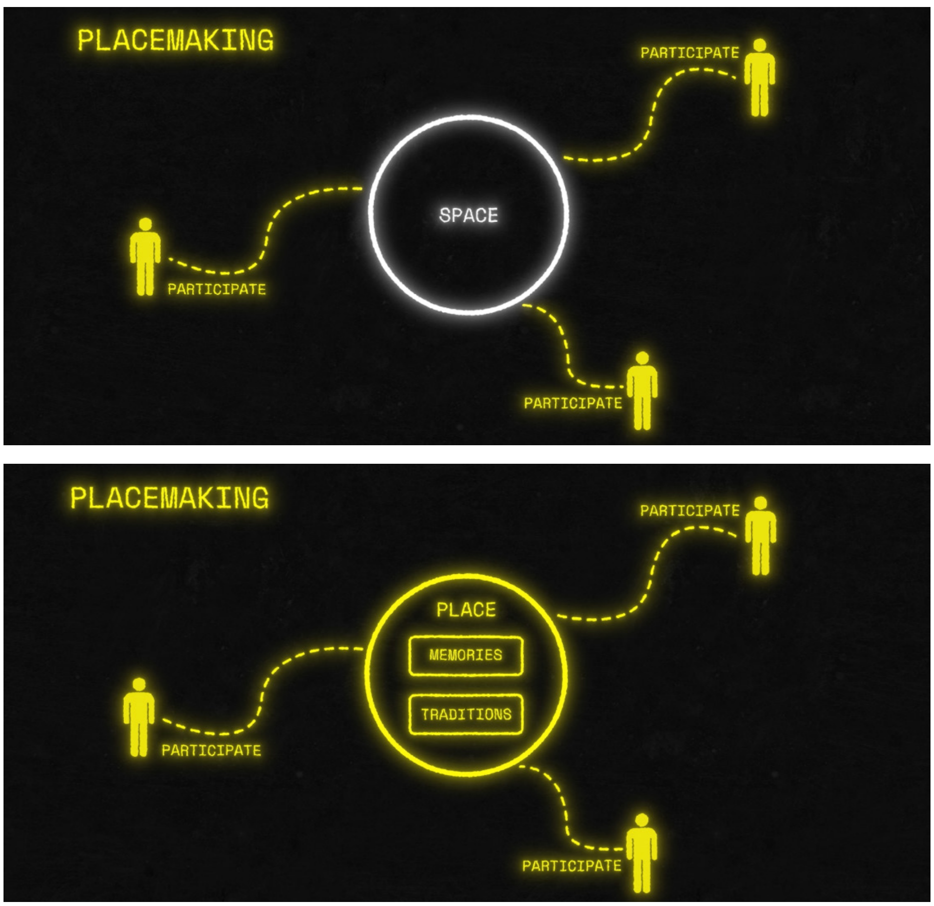


Fig. 38

Limitations

While the LUNARK experiment offered important insights, it also had clear limitations:

> **Small sample size:** Only two individuals participated, making it hard to generalize findings across larger or more diverse crews.

> **Environmental differences:** Even the extreme Arctic environment cannot fully simulate lunar conditions like microgravity or real-time communication delays.

> **Short duration:** Although three months is significant, longer missions (such as those on Mars) would amplify psychological pressures even further.

Nonetheless, the fundamental placemaking dynamics—privacy, ritual, memory-making—are universal human needs, wherever we go.

Fig. 38 A space becomes a place when people give it meaning through repeated use
Nollistudio

Why the Moon Matters

Home. That's the goal. When the first crew members step into a lunar habitat and begin to think of it not just as a mission site—but as a place to live—that will mark the real first step toward becoming a spacefaring civilization. A civilization that doesn't just survive Earth, but extends its presence to the Moon, then perhaps to Mars, and eventually beyond. But to many, this vision raises a serious question: why?

Why are billions being spent designing shelters on a lifeless rock while urgent challenges persist on Earth—climate change, poverty, war, collapsing infrastructure? Some argue humanity needs a backup plan(et). Others point to economic benefits or the innate drive to explore. But the answer may be closer than expected.

It's found in something as ordinary as the camera in a smartphone. CCD sensors—originally developed to capture high-quality images in space—now form the backbone of digital imaging. From phone cameras to medical scanners to traffic systems, this technology has become embedded in everyday life. Many everyday technologies trace their origins to space research—Velcro, scratch-resistant glasses, cordless vacuums, even clear braces. Space exploration isn't necessarily

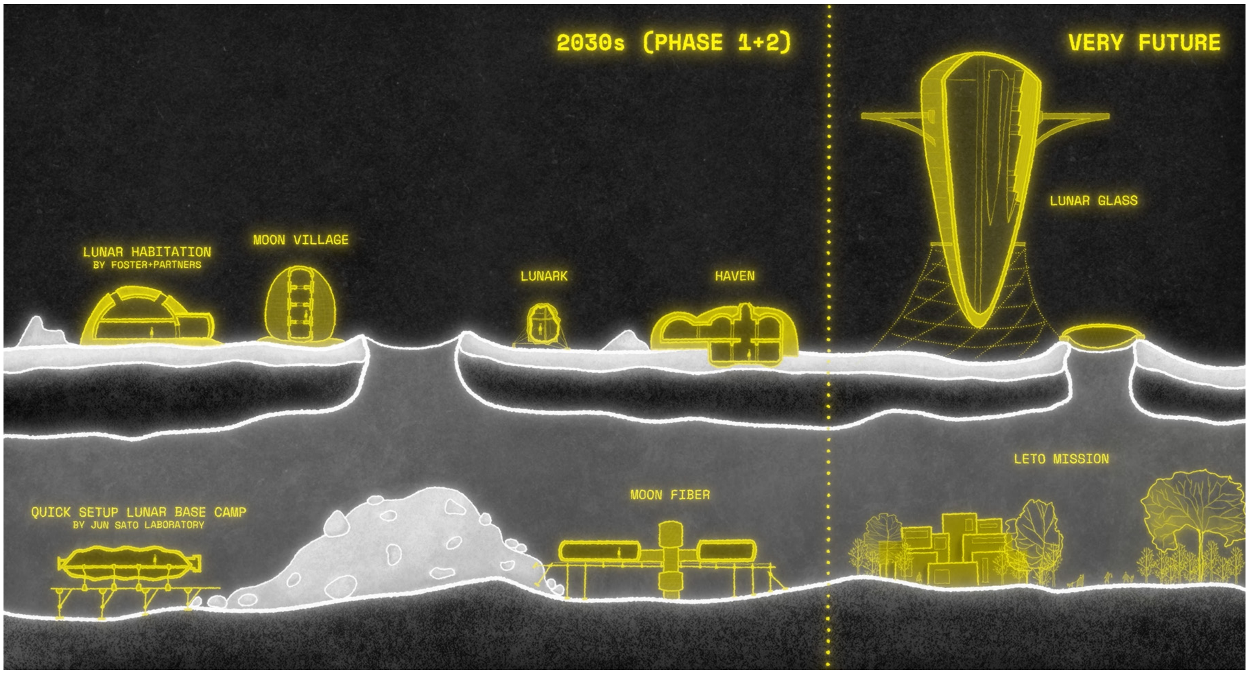
Fig. 39

a distraction from Earth, rather, we see that it has continuously shaped life on it.

Most of the lunar prototypes explored in this document may never be deployed on the Moon. Yet the principles behind them—radiation shielding, lightweight modular systems, designs that prioritize psychological comfort—could influence how buildings and communities are created on Earth.

Designing for the Moon forces designers, engineers, and researchers to rethink what truly matters. It reduces life to its essentials: warmth, safety, light, companionship. And in doing so, it offers a reflection. Perhaps reaching for another world is not about leaving this one behind—

Fig. 39 Moon in space render
Nollistudio



Learn More

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LUNARK

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