HABITATION ON THE MOON

"Designing for a New Frontier"

Politecnico di Torino

Corso di Laurea in Architecture Construction City

a.y. 2022/2023
Graduation Session: September 2023

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Abstract

The Moon has become a major site for human habitation as the world strives to explore and inhabit space. The Moon presents a unique opportunity for humans to establish a permanent presence beyond our planet due to its proximity to Earth, the availability of resources, and the potential for scientific inquiry. However creating structures for lunar colonists is difficult due to factors including harsh temperatures, radiation, and the absence of an atmosphere.

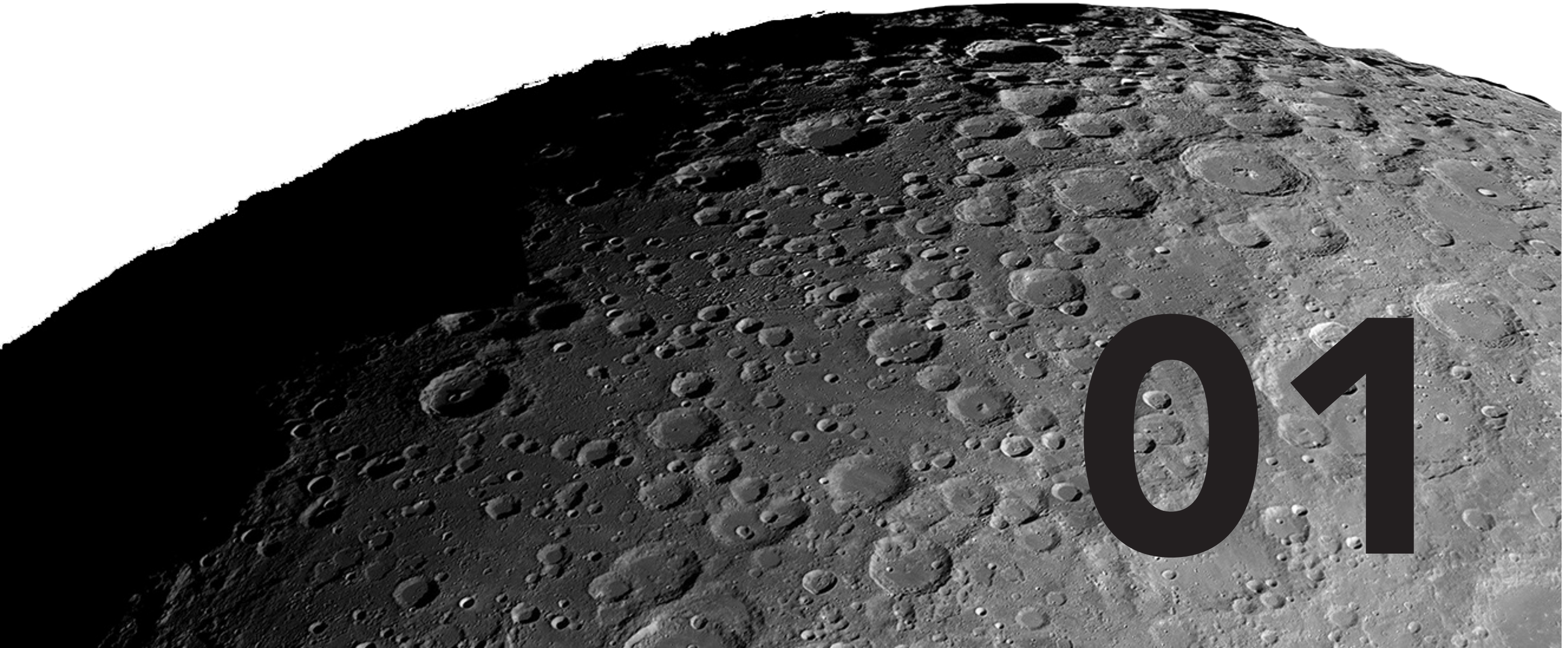
The purpose of this thesis is to investigate the design of reliable and sustainable architecture for future lunar settlements. The research will concentrate on comprehending the special limitations and opportunities of lunar dwellings and establishing design approaches that consider the lunar settlement's social, cultural, and environmental facets. By examining current data, our thesis also seeks to go beyond imagining the structural needs for the infrastructure of a Lunar city. In addition to our objective of creating new life scenarios with sustainable architecture on the Moon, we also plan to include high technology topics like 3D printing and parametric design in our thesis. Plus, we propose to do design research and studies in this area while considering the sociological and psychological challenges of beginning a new existence on a distant planet.

The research will be started by reviewing the current research status on lunar colonization and identifying the main design opportunities and challenges. The thesis will then suggest a theoretical paradigm for designing lunar habitats that emphasizes resilience, adaptation, and sustainability. The framework will be based on a thorough examination of the lunar environment, building supplies, construction methods, and management of energy and water. A case study of a suggested lunar structure will also be included in the thesis to show how the theoretical framework is applied in practical applications. The main topic of the case study will be the design of a small-scale lunar habitat that can house a crew of four astronauts.

The design will take into account the main environmental elements, such as temperature, radiation, and lunar soil characteristics, and will create a construction technique that makes use of local resources and has a minimal negative influence on the environment. The research will conclude by evaluating the effectiveness of the proposed framework and design approach and identifying the potential for future research and development in lunar habitat design. The thesis will contribute to the growing body of knowledge on lunar habitation and provide valuable insights for architects and designers working on space-related projects. We may have the chance to critically reevaluate design and architectural traditions that we are obliviously using on Earth via the lens of space architecture. In addition, extra atmospheric design can be a great place to test out fresh sustainability ideas for the terrestrial environment.

In conclusion, designing for space can provide us with insight and direction on how to enhance design on Earth by utilizing the resources to their full potential.

A Brief Overview



Fifty years have passed since that monumental day in 1969 when the United States astronauts set foot on the Moon during the Apollo 11 mission. The significance of this achievement cannot be overstated. It served as a resounding message to the entire global population, demonstrating humanity's capability to venture beyond the confines of Earth and reach celestial bodies.

The first Moon landing marked the dawn of a new era, one that would soon witness the emergence of increasingly ambitious projects and programs. It was undeniably the starting point, the year zero, from which new international challenges and rivalries began to unfold. This groundbreaking moment propelled the infamous Space Race into full swing (Chua, 2011).

However, in the following years, space activities seemed to dwindle, and the Moon faded into the background of international attention. Many perceived a slow progression in the sector, with a lack of substantial advancements. The Moon, once a symbol of human achievement, became a distant memory for some.

But now, 50 years later, the Moon has once again taken center stage on the international arena. A period of cautious or inconspicuous space activities has given way to a resurgence of interest. Nations across the globe have started viewing the Moon as a new frontier, recognizing the potential it holds. Investments, both lunar and cislunar, are pouring in as nations embrace the possibility of technological and industrial innovation. The Moon has become a tangible demonstration

"One of the few still photographs of Armstrong on the lunar surface, packing the bulk sample at the MESA; the American flag and the Solar Wind Collection experiment can be seen in the left of the photograph."
Image Source: NASA

of an increasingly structured presence in space, signaling a collective commitment to exploring and utilizing the celestial bodies that surround us.

The scientific and economic possibilities are significant factors motivating this renewed interest in lunar exploration. Many scientists and entrepreneurs are excited about exploring the Moon to discover its secrets and use its resources. Recognizing the great opportunities available has energized and motivated people.

As architecture students, we find ourselves at the brink of this new era, witnessing the rekindling of lunar exploration and its impact on the field of space architecture. The challenges and possibilities that lie ahead are both exhilarating and daunting. It is within this context that we embark on this journey, exploring the design of lunar settlements and habitats that will shape the future of human presence on the Moon.

A brief overview in exploration

The history of Moon exploration is a remarkable journey of human achievement and scientific discovery is. This is a quick rundown of the significant achievements and missions in Moon exploration:

The first observations were made long before the space age. Astronomical observations and lunar observations were done by ancient civilizations. More thorough observations were possible thanks to the 17th-century invention of the telescope.

"Aldrin setting up the Solar Wind Collection experiment."
Image Source: NASA

The first robotic Moon missions were driven by the space competition between the US and the Soviet Union in the middle of the 20th century. The Soviet Luna 2 was the first spacecraft to strike the Moon, doing so in 1959. With a number of successful missions, including Luna 9, which accomplished the first soft landing on the Moon in 1966, the Luna program was carried on.

Undoubtedly, one of the most iconic chapters in lunar exploration history is the NASA Apollo program. On July 16, 1969, astronauts Neil Armstrong, Buzz Aldrin, and Michael Collins embarked on the Apollo 11 mission and set foot on the lunar surface on July 20, 1969.

Simultaneously with the Apollo missions, uncrewed lunar sample return missions played a vital role. Between 1970 and 1976, the Soviet Union conducted Luna missions, including Luna 16, Luna 20, and Luna 24, retrieving precious lunar samples. NASA's Apollo program significantly contributed by bringing back a trove of lunar samples, offering insights into the Moon's geological composition.

Both the USSR and the US sent lunar orbiters to map the Moon's surface. NASA's Lunar Orbiter program, operational from 1966 to 1967, carefully produced detailed images, helping in the selection of Apollo mission landing sites. The Soviet Union's Lunar Orbiter series (1966–1970) provided crucial topographical data about the lunar terrain.

"Earthrise, the iconic 1968 image from Apollo 8 taken by astronaut William Anders."
Image Source: NASA

Following the Apollo missions, human lunar exploration faced financial constraints and changing priorities, leading to a focus on robotic exploration. The Soviet Luna program continued with missions such as Luna 25, 26, and 27, stand by for lunar landings in the near future.

In 2009, NASA launched the Lunar Reconnaissance Orbiter (LRO), a persistent presence that has carefully documented the lunar surface, offering invaluable insights into lunar resources, radiation levels, and potential landing sites.

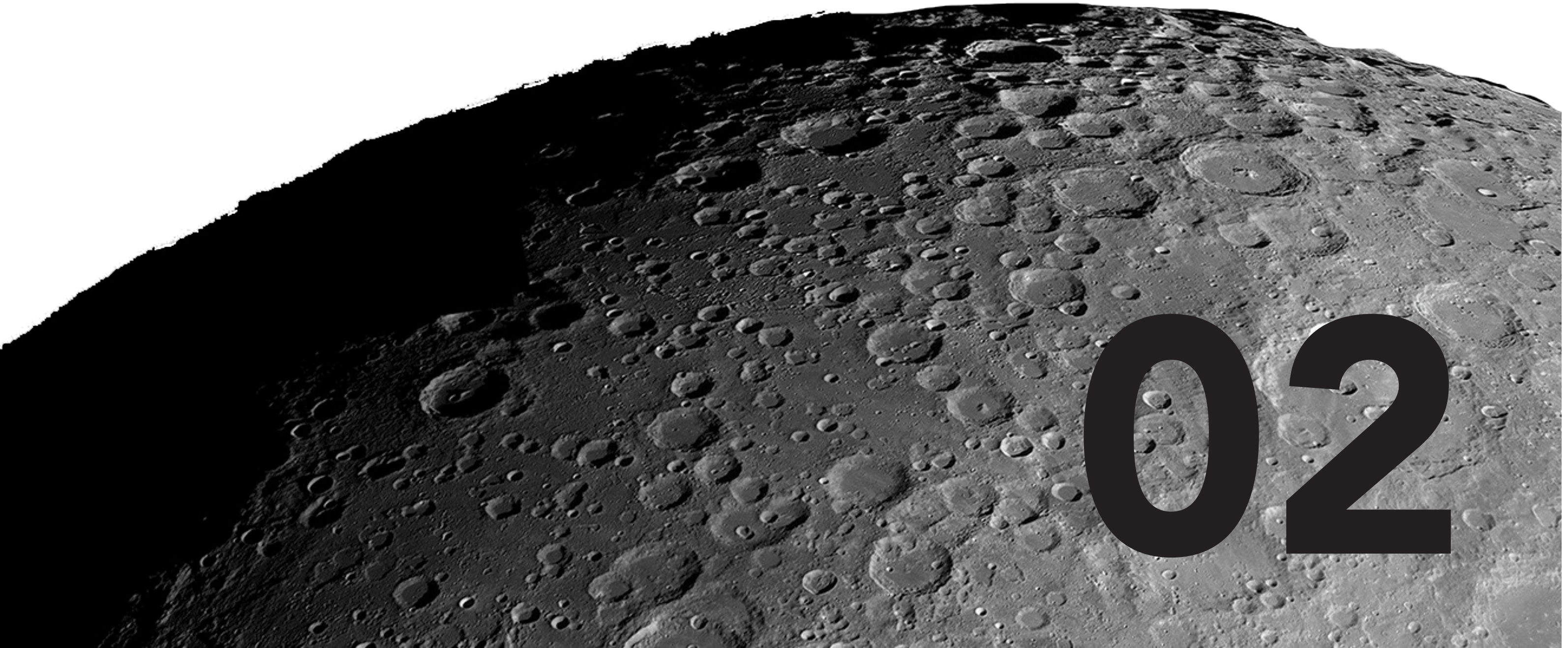
China's Chang'e program has made substantial strides, with Chang'e 3's soft lunar landing in 2013, featuring the deployment of the Yutu rover. China, the third nation to achieve a successful lunar soft landing after the Chang'e 1 and Chang'e 2 missions in 2007 and 2010, has left a lasting impact on lunar exploration.

Recent years have witnessed significant lunar missions, including India's Chandrayaan-1 satellite, launched in 2008, which made a groundbreaking discovery of water ice on the Moon's surface. Israel's Beresheet mission, despite a descent mishap in 2019, symbolizes the enduring global interest in lunar exploration (Williams, 2023).

Looking ahead, NASA's ambitious Artemis mission, unveiled in 2019, aims to return humans to the Moon by 2024. Beyond establishing long-term lunar exploration, Artemis represents a crucial stepping stone toward future human expeditions to Mars, ushering in an exciting chapter in lunar exploration (NASA Office of Inspector General, 2021).

These discoveries and lunar efforts represent centuries of dedicated scientific exploration, technological advancement, and human curiosity. With missions like Artemis on the horizon, our journey to uncover the Moon's mysteries and enhance our presence in space is expected to lead to even more fascinating findings and significant achievements.

Mapping of Design Process



Creating an Outline

For the first meeting, we prepared an outline to list our potential steps for the thesis as it can be seen in the next page (outline version 1).

Outline Version 1 was following a linear progression, where data is collected, analyzed, and interpreted in a predetermined order. However during the meeting, our thesis co-supervisor, Federica J. Gardella, explained the thesis writing methodology. As a result, we decided to revise and improve the thesis outline for our next meeting.

It is critical to take into account that the actual research process is frequently iterative and non-linear, with researchers going back and improving previous phases in light of new data or challenges they faced along the way.

A non-sequential or non-linear research strategy, on the other hand, uses a more adaptable and exploratory methodology. It enables researchers to take a different path and investigate several facets of a research subject concurrently or in a non-linear manner. This method emphasizes the complexity and dynamic nature of research while allowing for more adaptation and flexibility in the face of unexpected discoveries or insights. (Cresswell, 2003)

There is also a mixed method research, where qualitative and quantitative data are gathered and analyzed simultaneously. In contrast, iterative approaches like action research or grounded theory, where data collection and analysis inform each other in a continuous cycle, are examples of non-sequential research approaches. (Lingard, Albert, & Levinson, 2008)

In summary, adopting a non-linear, and adaptive methodology allows us, as researchers, to explore various pathways and iterate on our research process as needed.

For the second meeting, we refined the outline and we decided to use a non-linear methodological way, we decided to study simultaneously both part of the project as it can be seen in the next page (outline version 2). That is why we rescheduled our work flow.

Outline Version 1

A

A. Technical Research Part

Origin of the Moon
Past Moon Missions
Lunar Factors
   3.1 Gravity
   3.2 Meteorites
   3.3 Radiation
   3.4 Atmosphere and Temperature
4. Human Factors
   4.1 Environment Control and Life Support Systems
   4.2 Sociological and Psychological Factors
5. Lunar Materials
6. Logistic Factors

A

Identify the Research Topic
Literature Review
Research Design
Data Collection

B

B. Architectural Part

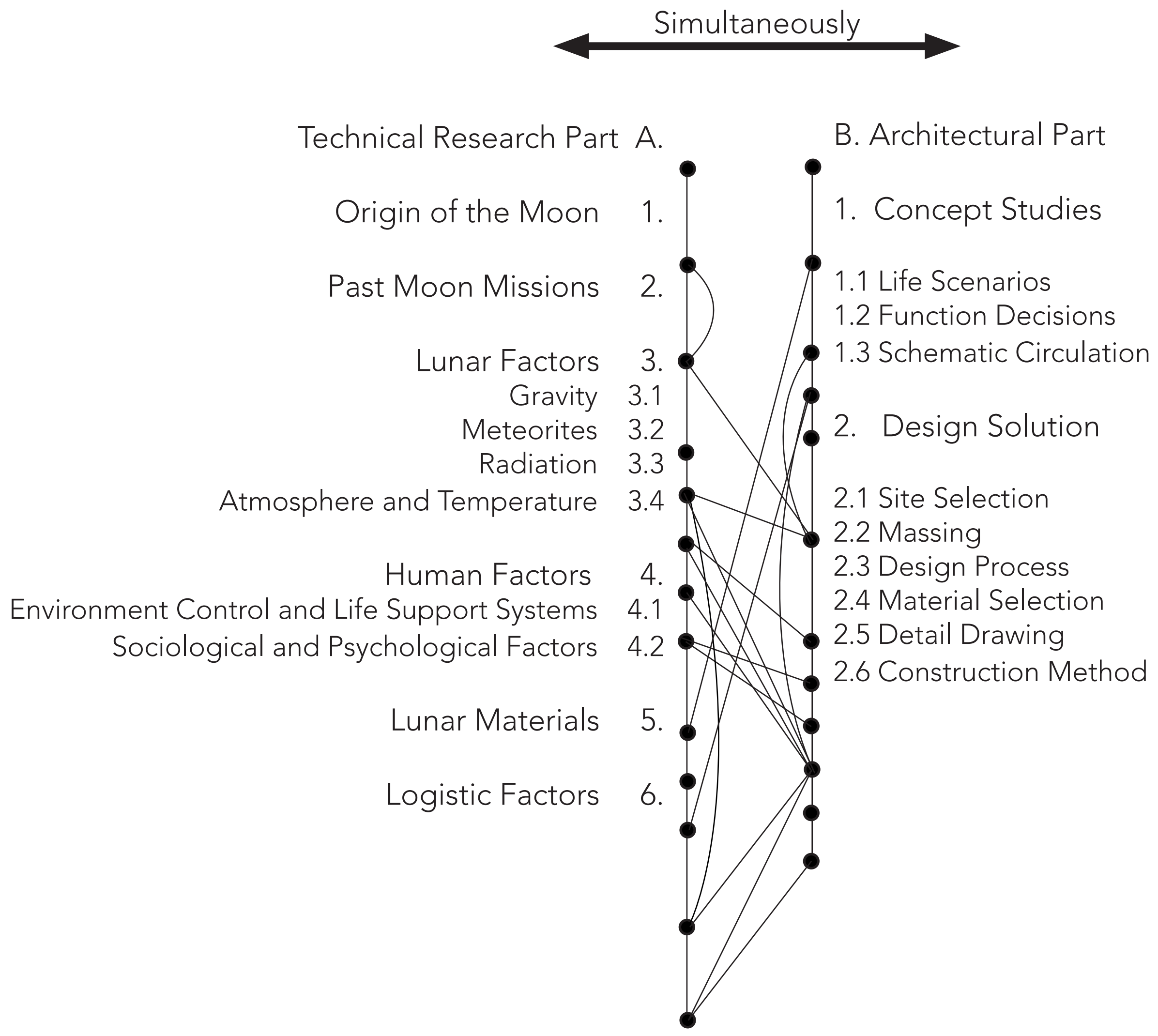
Concept Studies
   1.1 Life Scenarios
   1.2 Function Decisions
   1.3 Schematic Circulation
2. Design Solution
   2.1 Site Selection
   2.2 Massing
   2.3 Design Process
   2.4 Material Selection
   2.5 Detail Drawing
   2.6 Construction Method

B

Data Analysis
Results and Findings
Conclusion
Reporting and Publication

Final

Outline Version 2



Mapping of Design Process

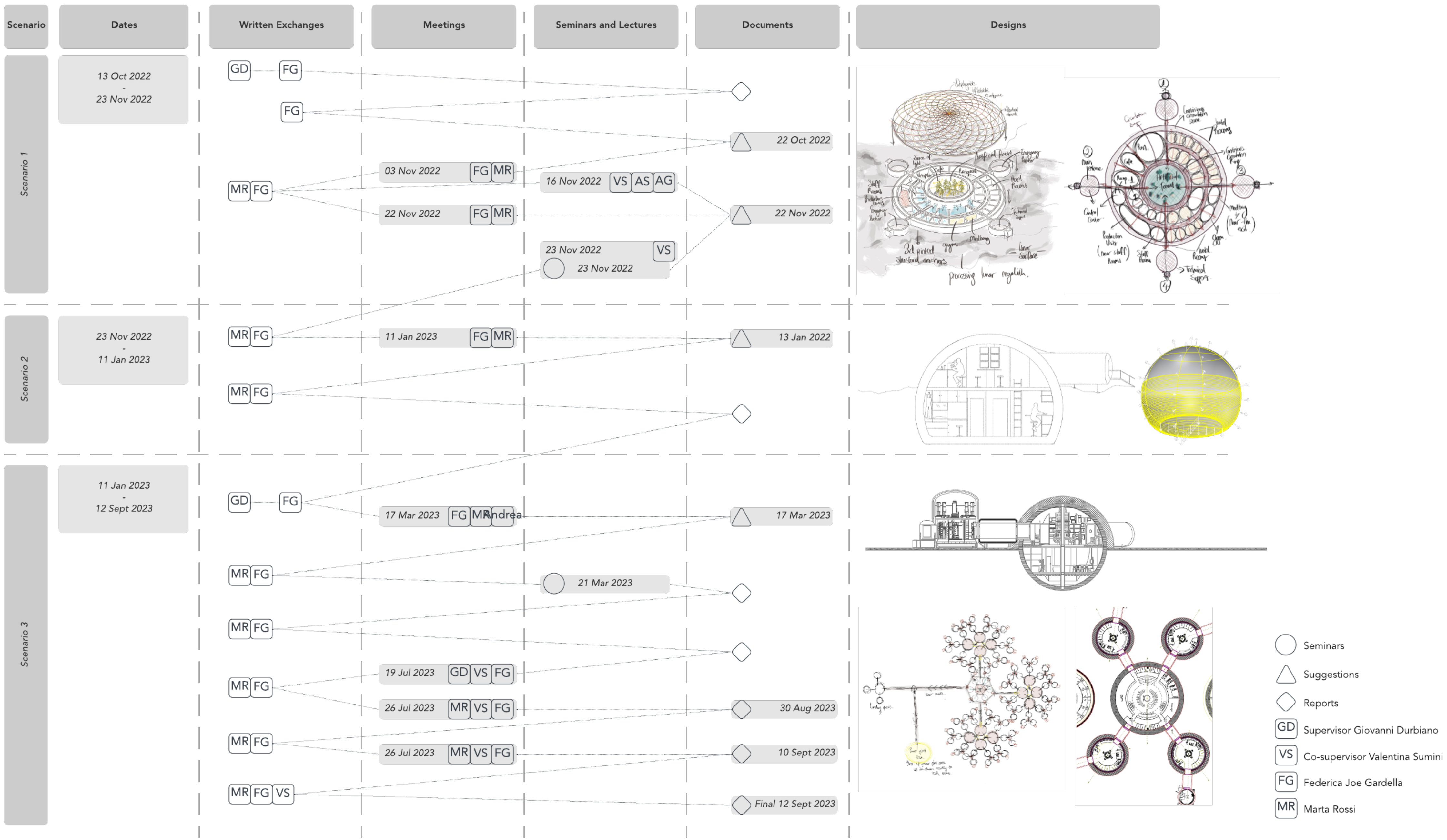
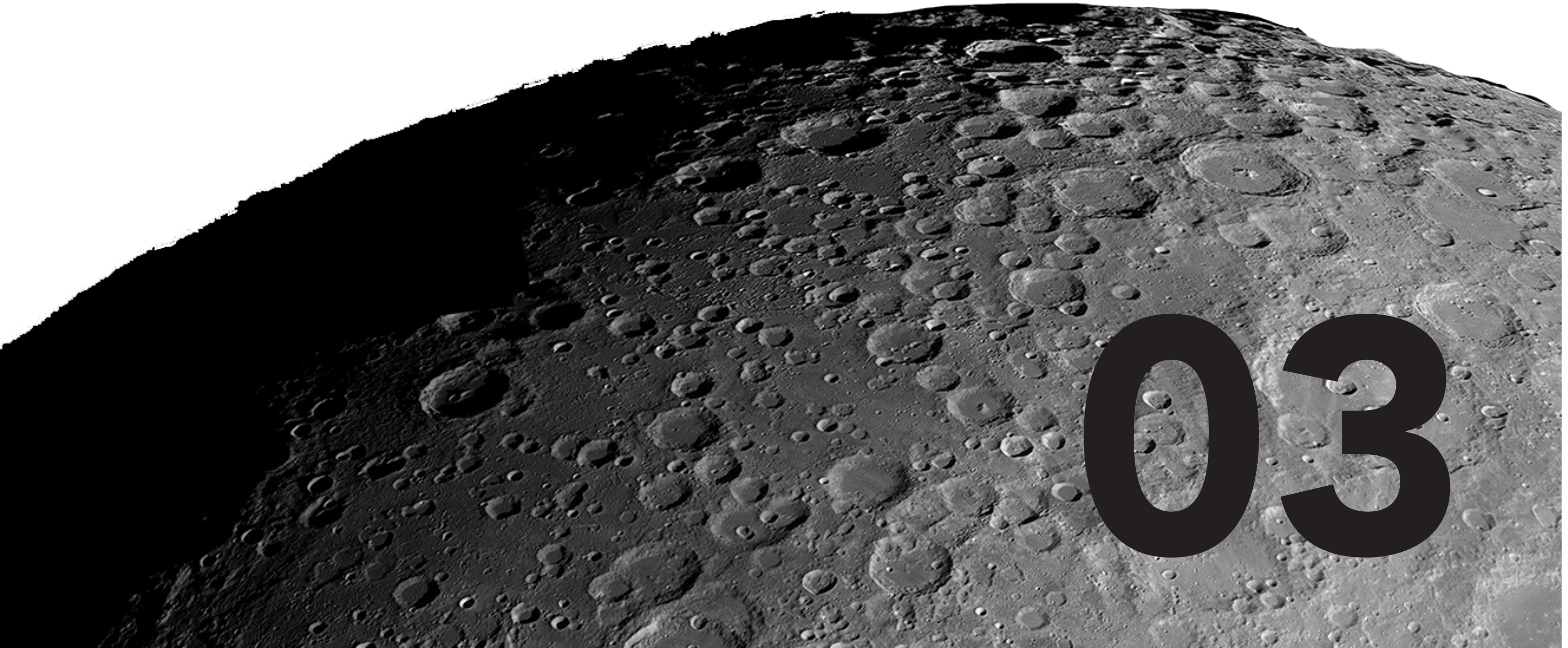


Diagram shows the pathways we followed during the design process
Created by E. Kirmiziyesil, E. N. Yavuz

Lunar Hazards and Their Impact on Design

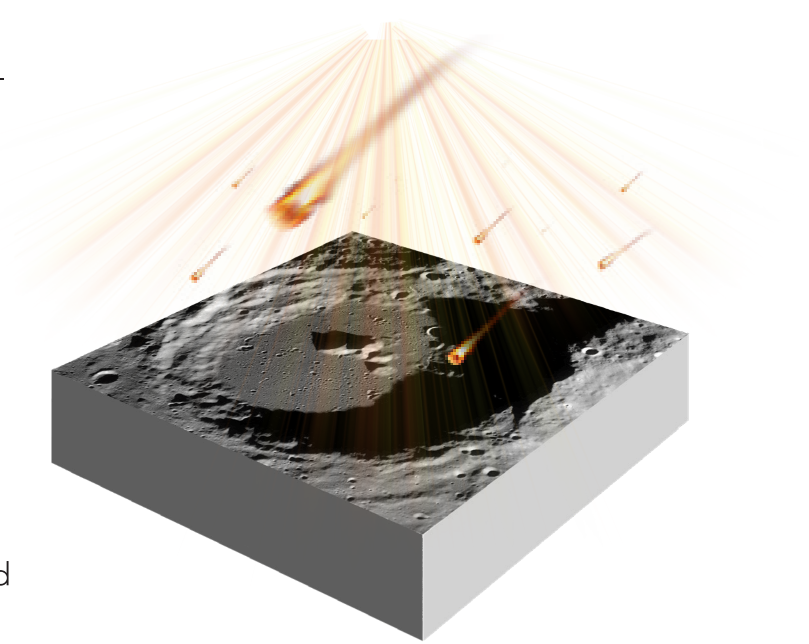


03

The Moon’s calm and peaceful setting comes with numerous challenges and risks that require careful planning to ensure the safety and durability of structures built on its surface.

One of the primary hazards is the presence of micrometeoroids and the consequent potential for meteoroid impacts. These minuscule solid particles, originating from interplanetary or interstellar sources, pose a significant threat to structures and astronauts during Extravehicular Activities (EVAs) due to their high velocity impacts with typical velocities reaching tens of kilometers per second. The magnitude of damage resulting from meteoroid impacts hinges upon factors such as size, density, porosity, speed, and direction of the impacting particles. Annually, over 33,000 meteoroids collide with the Moon, progressively degrading surfaces and materials through erosion and cratering, impacting components such as mirrors, lenses, and sensors. Larger particles have the potential to penetrate insulation layers, optical baffles, pressurized vessels (such as manned habitats and propulsion tanks), batteries, coolant lines, and spacesuits, as well as sever cables, tethers, and springs. Structural damage can be caused by millimeter-sized grains, resulting in penetration or spallation, which can lead to component or subsystem failure, and in the worst-case scenario, the complete destruction of the structures or loss of the crew.

The absence of a substantial atmosphere on the moon allows these tiny particles to travel through space unhindered, posing a constant threat to our structures and habitats. While we were se-



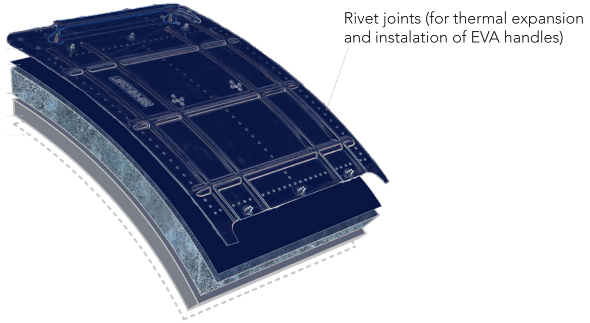
This image shows the lunar surface, highlighting its susceptibility to meteoroid impacts and the intense radiation emitted by the Sun.
Image Source: E. Kirmiziyesil, E. N. Yavuz

arching for innovative shielding strategies, such as protective coatings and structural reinforcements, to mitigate the potential damage caused by micrometeoroid impacts, enhance the resilience of our architectural designs, and ensure the protection of both the infrastructure and the inhabitants on the lunar surface, we found a protective layer called the Whipple shield invented by Fred Whipple. When a high-speed projectile strikes the shield, its laminated layers of stainless steel and age-hardened aluminum cause the projectile to shatter, effectively reducing its kinetic energy and impact density. Subsequently, the multiple laminated Kevlar layers absorb and halt the tiny particles, providing enhanced protection for the inner pressure shell.

Radiation also stands as a critical hazard on the Moon, given its lack of a protective atmosphere or magnetic field, leaving the lunar surface exposed to harsh solar radiation and cosmic rays. Long-term exposure to radiation can have detrimental effects on human health. To confront this challenge, we are researching radiation shielding materials and developing layouts that maximize protection for our habitats. Additionally, we are exploring the possibility of locating critical infrastructure, such as radiation-sensitive equipment and living quarters, within shielded areas to minimize radiation exposure. (Cucinotta, Kim, & Chappell, 2013)

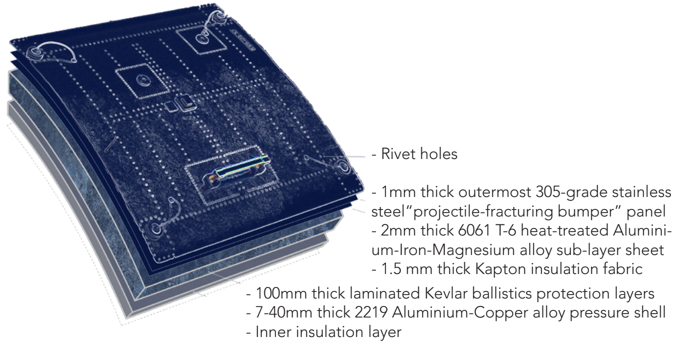
The lunar landscape itself poses challenges concerning mobility and transportation (Greeley & Batson, 2001). The uneven terrain, presence of craters, and steep slopes necessitate thoughtful

Type 1 (used on Japanese Experiment Module, Quest airlock, Node 1 and US lab)



- 2mm thick outermost 305-grade stainless steel "projectile-fracturing bumper" pane (with structural ribs)
- 2mm thick 6061 T-6 heat-treated Aluminium-Iron-Magnesium alloy sub-layer sheet (laminated)
- 110 mm thick laminated Kevlar ballistics protection layers
- 50 mm thick 2219 Aluminium-Copper alloy pressure shell
- Inner insulation layer

Type 2 (used on Columbus, Node 2, Node 3 and PMM)



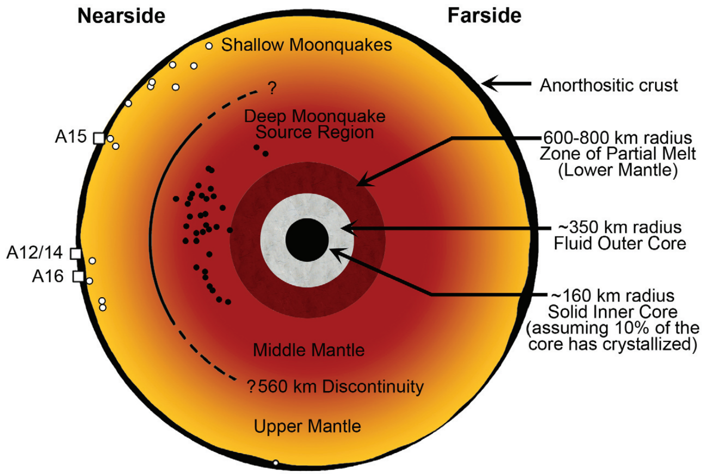
"A blueprint of a spacecraft' debris Whipple Shield design, in this case the steel composite panels on the International Space Station. Designed by Raphael Chryslar."
Image Source: Rafael Jean-Luc Alexandre

considerations in our design process to ensure safe transportation and efficient logistics within the lunar settlement.

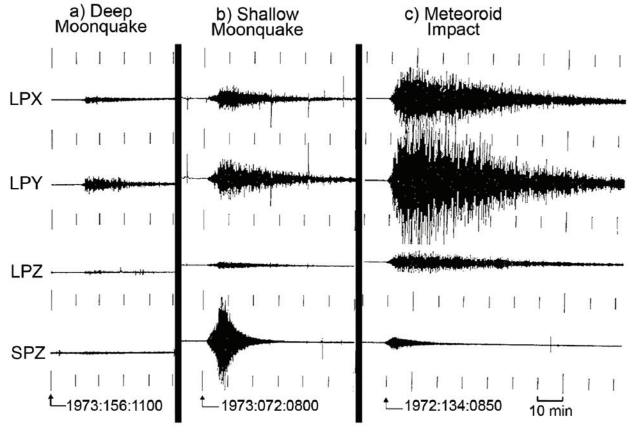
Understanding the internal structure of the Moon, including its core, mantle, and crust, is an ongoing endeavor. Studies involving lunar samples and remote sensing techniques offer valuable insights into lunar geology and seismic activity. Seismic activity on the Moon, similar to that on Earth, resulting from gravitational forces, meteorite impacts, and thermal shocks, must be accounted for when planning for human presence and constructing structures on the moon (Ge & Liao, 2017).

The Moon takes approximately 28 days to make one orbit around the Earth. As the Moon orbits the Earth, it also makes one complete revolution about its axis. This unique relationship results in the same side of the Moon always facing the Earth. It also means that each lunar day lasts 14 Earth days (one-half of the amount of time it takes the Moon to rotate once about its axis). Similarly, a lunar night lasts 14 Earth days. The Moon lacks an atmosphere that would limit extreme temperatures by transferring heat around the planet. Measuring how the Moon heats up and cools down therefore says a lot about what is on the surface.

Everything has its own unique amount of time it takes to heat up and cool down. For example, lunar rocks take longer to heat up and cool down than lunar regolith (soil). The different heating and cooling rates make it possible for scientists



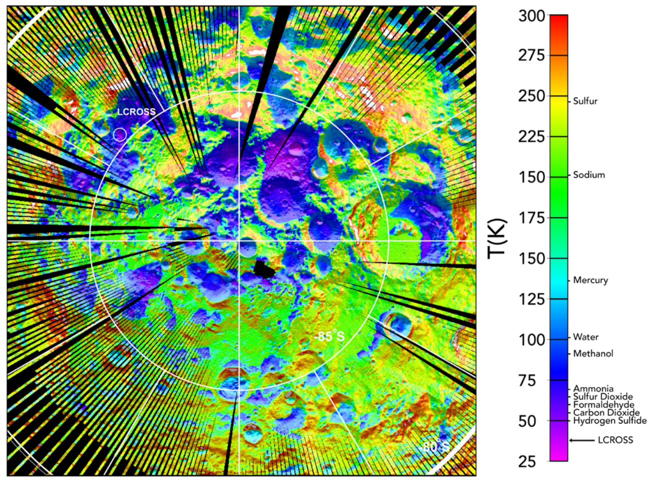
"Notional view of lunar interior showing the thin crust, mantle and possible inner and outer cores. Also illustrated are the locations of the Apollo seismometers and the distribution of shallow and deep moonquakes. After Wieczorek et al. (2006)."
Image Source: NASA



"Compressed-timescale seismograms of a) a deep moonquake (category AI); b) a high-frequency teleseismic (HFT) or shallow moonquake event; and c) a meteoroid impact (from Nakamura et al. 1974). All of these seismograms were recorded at the Apollo 16 station. LPX, LPY, and LPZ are the three orthogonal (X, Y, and Z) components of a long-period (LP) instrument peaked at about 0.45 Hz, and SPZ is the short-period vertical component peaked at 8 Hz. The amplitude of the moonquake signal was amplified in playout by a factor of four relative to the other two signals."
Image Source: NASA

to identify areas with large quantities of rocks. The amount of rocky material in an area is called rock abundance.
In order to determine the rock abundance of a surface, scientists must first account for other controls on the Moon's temperatures. In addition to rock abundance, the temperature on the surface of the Moon is controlled by latitude and elevation. Once latitude and height factors are removed, scientists can examine the relative heating and cooling rates of different areas on the surface to determine rock abundance.

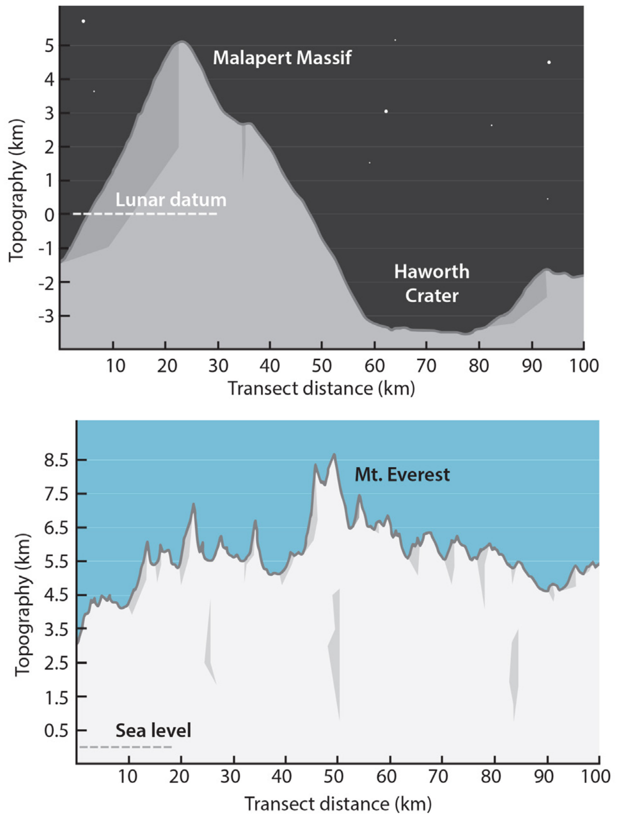
The unique geographical conditions of the Moon, encompassing temperature variations, atmospheric pressure, sunlight, and gravity, significantly influence the lunar territory. The average temperature on the Moon falls within a range higher than that of terrestrial Antarctica but lower than Earth's average, fluctuating between -20°C and +15°C. Nevertheless, non-polar regions, such as the equatorial belt, experience drastic temperature variations ranging from 250 degrees Fahrenheit (120° C, 400 K) during the day to -208 degrees Fahrenheit (-130° C, 140 K) at night. In contrast, the lunar poles receive sunlight at grazing angles, resulting in narrower temperature variations between -50°C and 200°C. Diviner even found a place in the floor of the Moon's Hermite Crater that was detected to be -410 degrees Fahrenheit (-250° C, 25 K), making it the coldest temperature measured anywhere in the solar system (Moon et al.,2014). Extremely cold regions similar to the one in Hermite Crater were found at the bottoms of several permanently shadowed craters at the lunar south pole and were measured in the depths of winter night.



"This temperature map from the Diviner instrument on the Lunar Reconnaissance Orbiter shows the locations of several intensely cold impact craters that are potential cold traps for water ice as well as a range of other icy compounds commonly observed in comets."
Image credit: NASA/GSFC/UCLA |

The absence of a substantial atmosphere on the Moon allows for localized temperature effects, which can prove advantageous for human survival. The lunar atmosphere is extremely thin, comprising only about 1 million molecules per cubic centimeter, a significant difference compared to Earth's atmosphere. This rarity provides opportunities for radio silence and the detection of previously undetected frequencies. However, the lunar atmosphere primarily consists of gasses such as hydrogen, neon, and argon, lacking the necessary oxygen for human survival. While lacking the necessary oxygen for human survival, recent research suggests the presence of trapped oxygen in the lunar crust, which could sustain human life for hundreds of thousands of years (European Space Agency, 2021). Efforts are also underway to extract water on the Moon by converting trapped oxygen in lunar regolith. These initiatives are essential for achieving self-sufficiency in resources and supporting human survival in the lunar environment.

As lunar settlement becomes a reality, addressing issues related to property rights, resource extraction, and governance becomes of utmost importance. The Outer Space Treaty (OST), signed in 1967, lays the foundation for international space law and regulates activities in extraterrestrial territories such as the Moon. It prohibits the claiming of sovereignty over celestial bodies, but private or commercial ownership is not explicitly covered. Establishing property rights and regulating lunar resource extraction necessitate international frameworks and agreements to ensure equitable access and bene-



"Scale of Lunar South Polar Mountains – v1

The south pole occurs in the midst of several mountains, called massifs on the Moon. Those massifs may have been created by the impact event that produced the 2,500 km diameter South Pole-Aitken basin, the largest and oldest impact basin on the Moon. One of those massifs is Malapert massif. Human missions to Malapert massif have been proposed. Traverses from the south pole to Malapert massif and vice versa have also been proposed. The topography generated by those massifs and juxtaposing impact craters is dramatic. Here that topography is illustrated with a transect across the Malapert massif and the adjacent Haworth crater. The change in elevation exceeds 8 km (left panel), a value very close to elevation of Earth's Mt. Everest above sea level (right panel)."

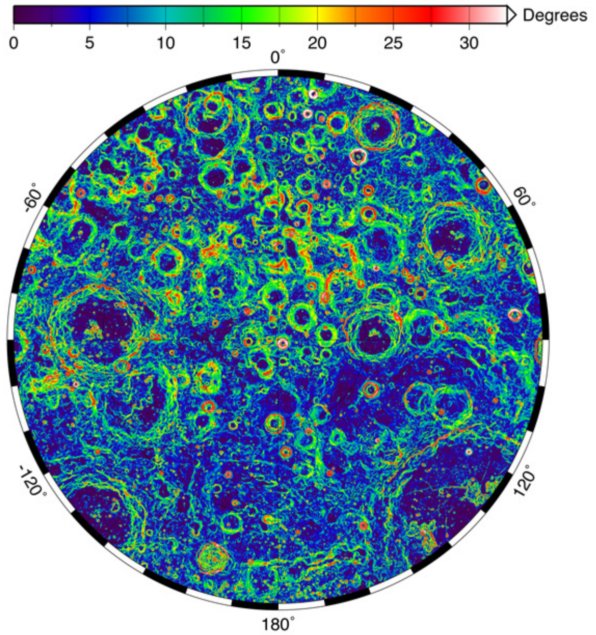
Illustration credit: LPI/CLSE

fit-sharing. Effective coordination, collaboration, and adherence to common standards are also vital for governance and the long-term sustainability of lunar activities.

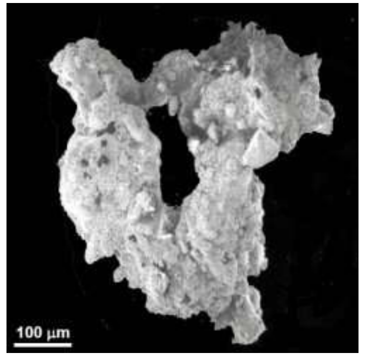
Furthermore, managing the environmental impact of lunar activities and mitigating the risks associated with space debris accumulation are critical considerations. Any human presence on the Moon, whether temporary or permanent, will inevitably have an impact on its environment. Preserving scientific sites, minimizing contamination, and protecting the Moon's unique geological features are of utmost importance. Proper protocols and regulations must be established to mitigate the generation of space debris and ensure the long-term sustainability of lunar missions (United Nations Office for Outer Space Affairs, 2017).

Lastly, the hazardous nature of lunar dust should not be overlooked. Lunar dust is abrasive, sharp, and has the potential to penetrate deeply into the lungs. Its electrostatic charge and the Moon's low gravity make it more likely to infiltrate equipment and pose health risks to astronauts. Ongoing efforts are focused on understanding and mitigating the potential damage caused by lunar dust (Stubbs, Vondrak, & Farrell, 2005).

Each of these lunar hazards presents distinctive challenges and considerations that shape our design decisions, requiring comprehensive planning. By understanding and addressing these challenges, we can ensure the safety, sustainability, and success of lunar missions, thereby unlocking the full potential of the Moon as a future destination for human presence and exploration.

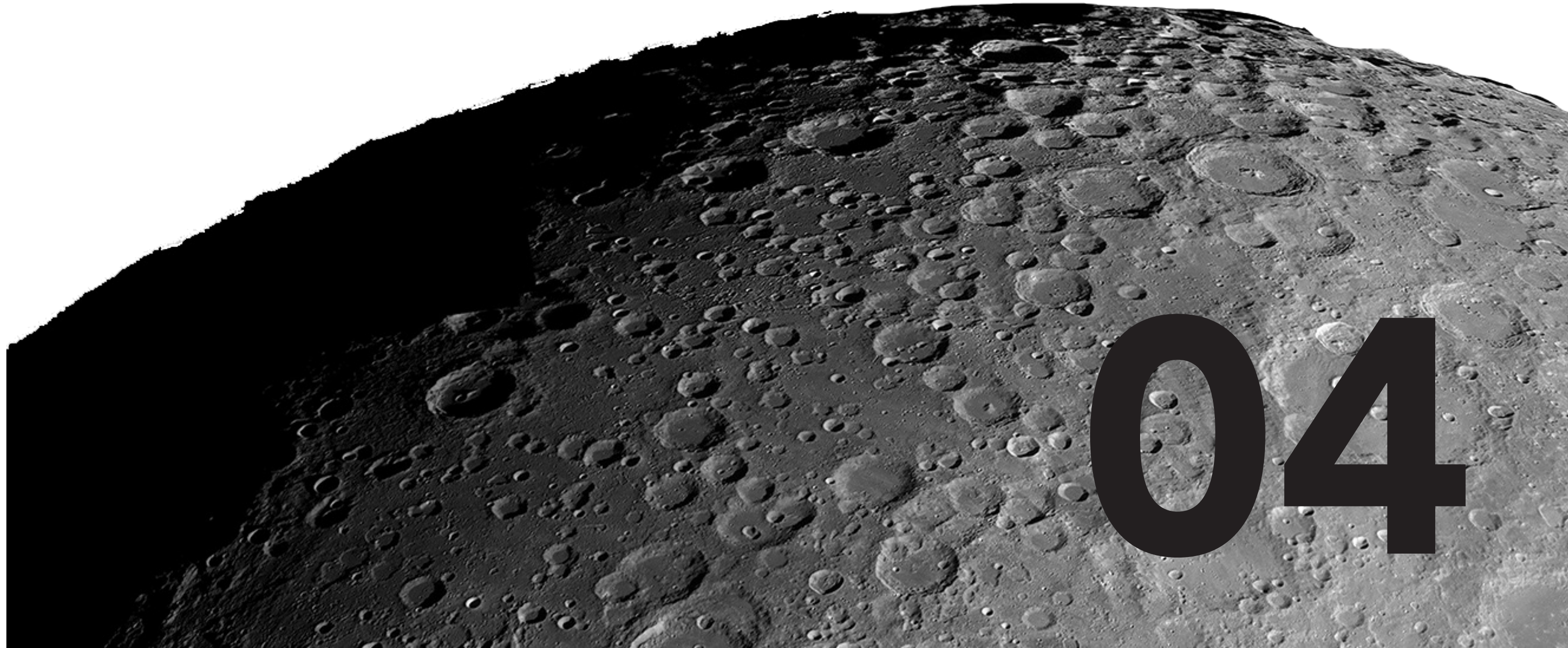


"Degree of the slopes found near the south pole of the Moon This image shows the slopes found near the south pole of the Moon, poleward of 75 degrees South. The bright red to white areas have the highest slopes (25 degrees or more) while the dark blue to purple areas have the smallest slopes (5 degrees or less). The largest slopes are found in impact crater rims, which appear as brightly colored circular features throughout the image."
Image Source: NASA/GSFC/MIT



"Micro-photograph of a tiny, jagged speck of moondust."
Image Source: David McKay, NASA/JSC

Initial Phase



04

Moon Habitation Phases Version 1

Before moving on to the design process, we needed to make a flowchart showing the phases of life on the Moon in order to decide what to design.

Phases Diagram Version 1
A thorough visual portrayal of the different steps needed in building infrastructure on the lunar surface is provided by the Lunar Construction Phases Diagram. This flowchart shows the progressive development of tasks and significant turning points necessary to build a usable lunar base or other buildings.

The graphic is divided into 4 stages, each of which stands for a certain set of tasks and goals. The chronological order of these phases reflects the sequential progression of construction activity. The diagram's major phases are briefly described in the passages that follow:

In the first phase, there was the establishment of a temporary space base on the lunar surface. This phase could be thought of as a stepping stone to better explore the Moon and build subsequent phases. The second phase was the construction of a tourist resort. Bringing fewer civilians in a controlled manner before a permanent life can be considered as a preparation for the next step.
The third phase was to create a habitat for space station workers and astronauts that will expand over time.

Finally, the fourth phase was offering completely different life scenarios to civilians who want to live on the Moon.

The Lunar Construction Phases Diagram offered a useful overview of the sequential steps required to construct a self-sufficient lunar outpost. It served as a guide for organizing and carrying out building functions on the Moon and demonstrates the complexity and difficulties involved in establishing a human presence there.

Phases Diagram Version 1
Image Source: Photo by E. Kırmızıyeşil, E. N. Yavuz, 2022

*it indicates which phase design we have decided to work on.

Triennale di Milano Visit

In November, we had the opportunity to visit the thought-provoking exhibition, "Unknown Unknowns: An Introduction to Mysteries," held at the Triennale di Milano. Curated by Ersilia Vaudo, astrophysicist and Chief Diversity Officer of the European Space Agency, this exhibition illuminates potential future life scenarios in the Lunar and the Martian environments.

As we entered the exhibition space, we were greeted by several projects and their models, each offering unique perspectives. The collection of works encouraged us to question the boundaries of our understanding and explore new possibilities. Two particular projects left a lasting impression on our design process: the Olympus and Lunar City projects by NASA, BIG, and Icon.

The Lunar City Project was a highly detailed project designed in collaboration between NASA, BIG, and Icon. It inspired us as we explored the complexity of this concept of Moon settlement in a lava tube, as it covered every aspect of life in this surroundings. We had the opportunity to examine the design principles for lunar settlements, including radiation protection, resource use, and long-term sustainability, through the projects. The Lunar City project emphasized the significance of utilizing in-situ resources, to establish a self-sufficient lunar habitat in the Lunar lava tube. The modular and adaptable nature of the design resonated with our own aspirations for creating resilient and dynamic living spaces. We were inspired by the ability required

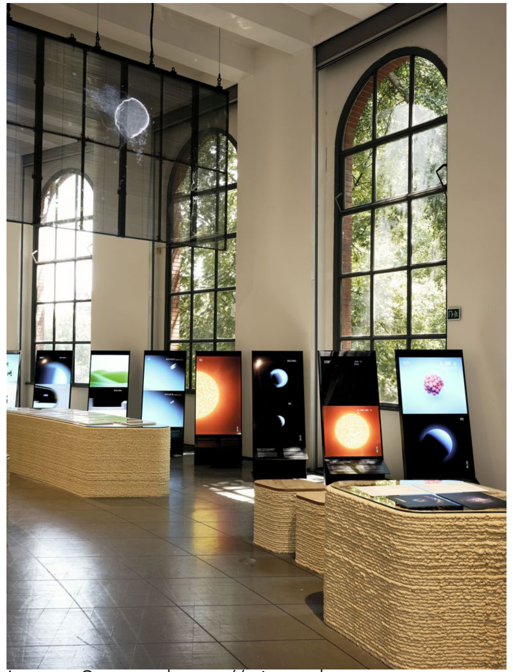


Image Source: https://triennale.org

to overcome the challenges posed by the lunar landscape and the potential for humanity to establish a presence beyond our planet Earth.
The projects we had the chance to examine closely reminded us that our designs should not be bound by preconceived limitations, but rather push the limits, and that challenging conditions can be overcome thanks to technology. The combination of scientific creativity, architectural innovation, and forward-thinking exhibited in the Olympus and Lunar City projects have been the primary projects that have guided us on our own design journey.

Finally, the visit to the "Unknown Unknowns" exhibition expanded our perspectives. As we continue to shape our own design, we carry with us the spirit of exploration and the decisive belief that even the most profound mysteries hold the potential for extraordinary discoveries.

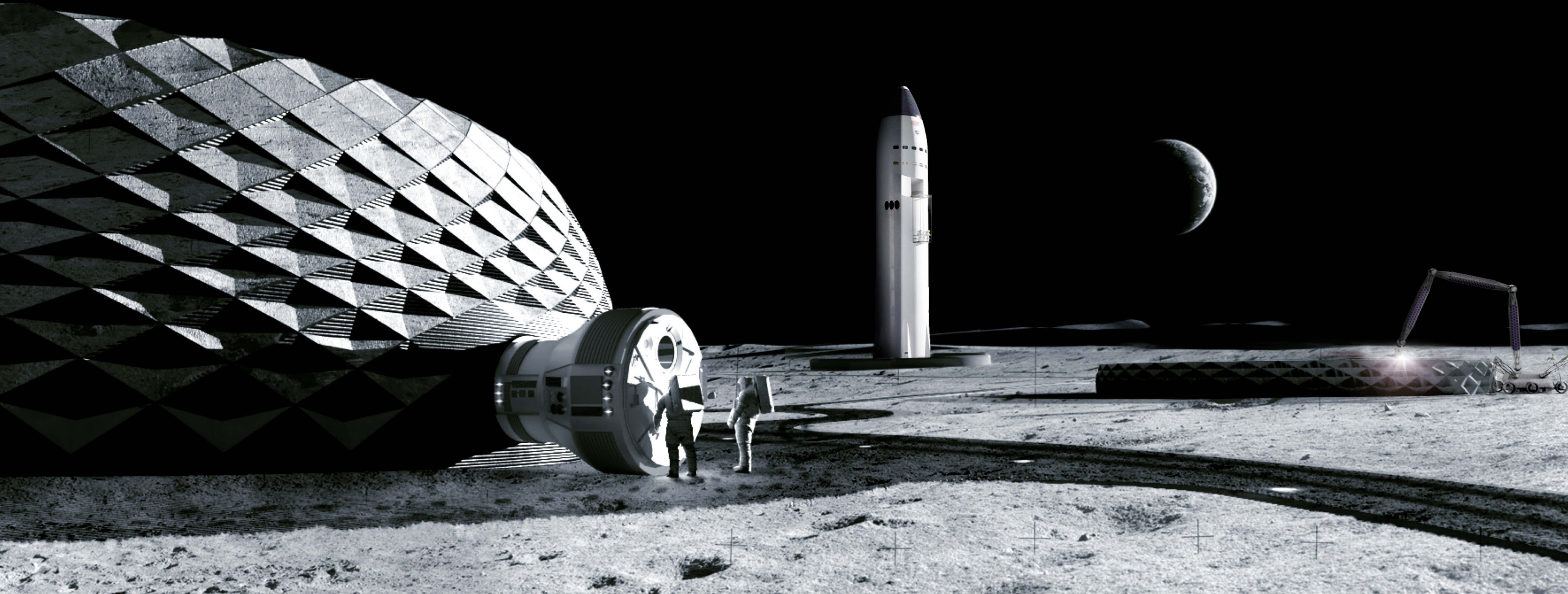
Equally captivating was **The Olympus Project,** with its vision of a self-sustaining city on the Moon's surface. We had a chance to examine the technical details behind the design process and we realized that the process would proceed with technical constraints. We were inspired by the design approach displayed in the Olympus project, which pushed us to consider grand ideas and reimagine the possibilities of our own designs.

Maquette of Lunar City Project in Triennale.
Image Source: Photo by E. N. Yavuz, 2022

Reference Project 1

Project Olympus by ICON

Image Source: BIG Bjarke Ingels Group, 2020



We came across an intriguing project called Olympus, initiated by a company called ICON. It falls under NASA's Artemis program, which plans for long-term human exploration of the Moon, and the infrastructure is designed to allow for human habitation on the Moon in the future. It is a project that caught our attenti- on due to its ambitious goal of establishing a sustainable human presence on the Moon. We decided to delve deeper into it and explore what this project entails.

Olympus, led by ICON, aims to revolutionize lunar exploration and settlement by utilizing ad- vanced technology and innovative approaches. The primary objective of the project is to create a fully operational, self-sustaining outpost on the Moon, providing a stepping stone for furt- her space exploration and scientific endeavors.

The project begins with the deployment of an initial lunar lander, which will serve as the foundation for the outpost's infrastructure. This lander will be equipped with the necessary resources and technologies to support human habitation, such as life support systems, power generation capabilities, and communication networks.

One of the key aspects of the Olympus project is its focus on 3D printing technology. ICON plans to leverage its expertise in this area to construct the lunar outpost using in-situ resour- ces, specifically the regolith (lunar soil) found on the Moon's surface.

Design Process

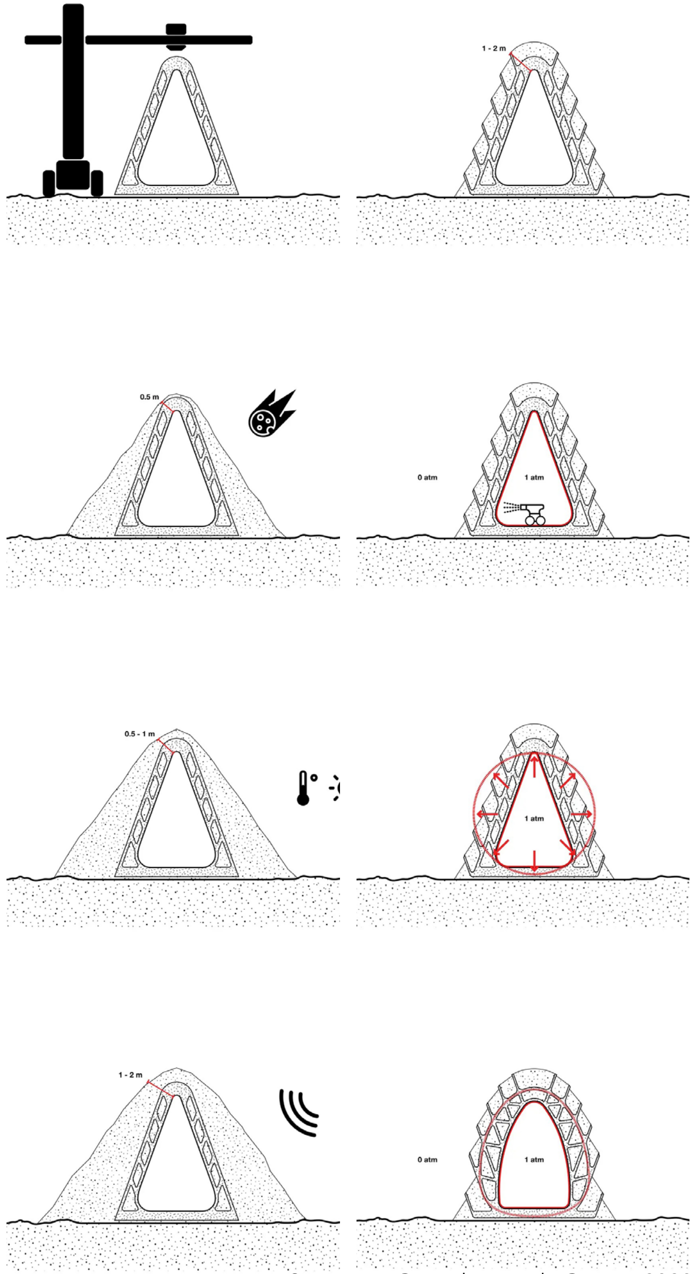


Image Source: BIG Bjarke Ingels Group, 2020

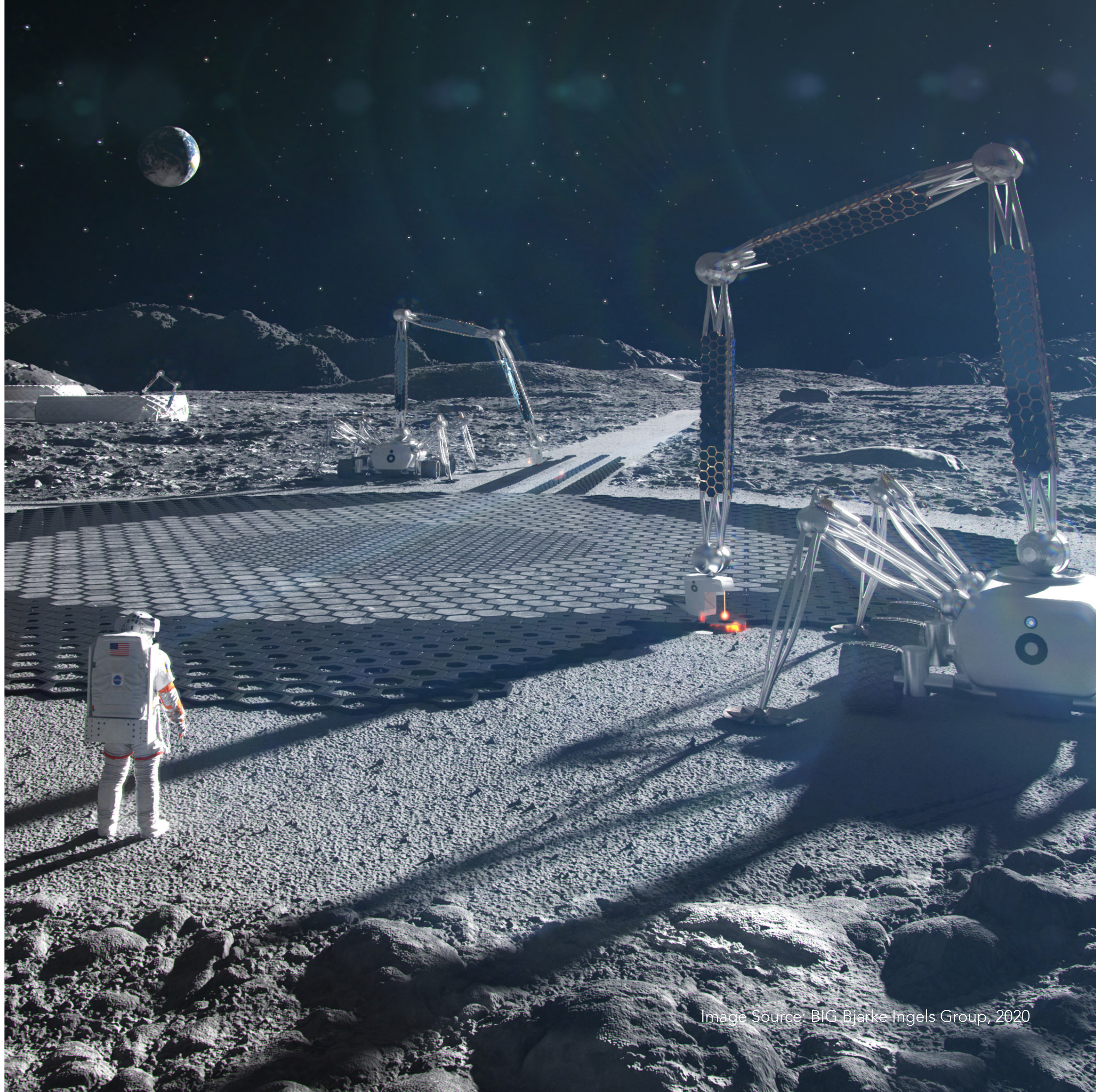


Image Source: BIG Bjarke Ingels Group, 2020

Reference Project 1

Project Olympus by ICON

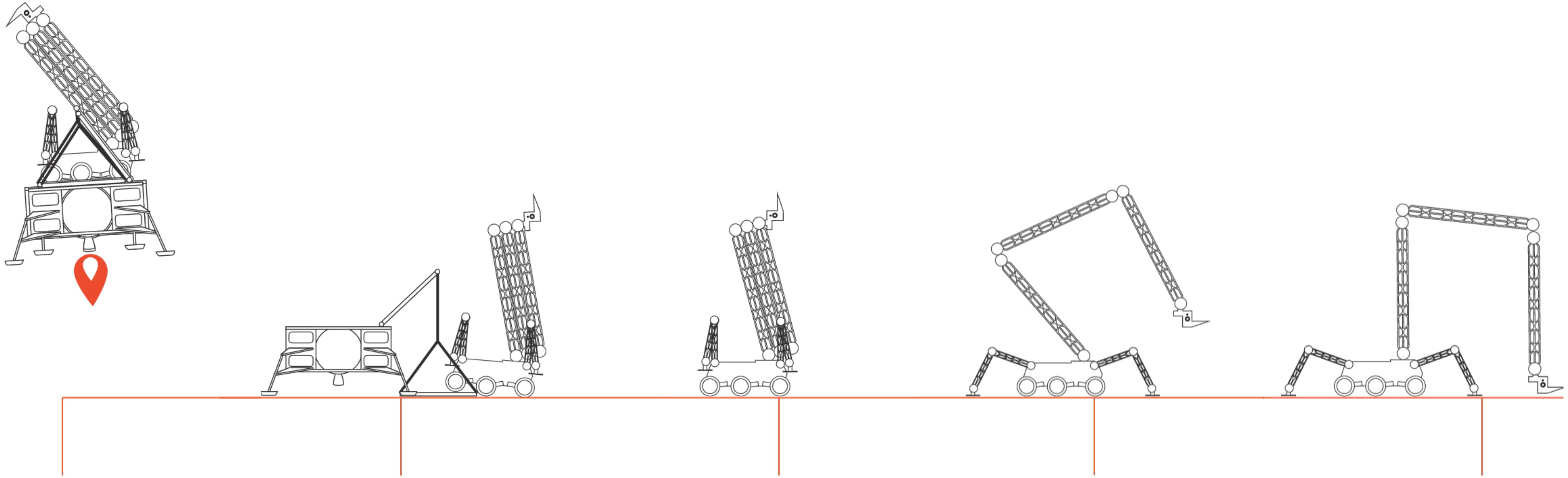
Image Source: BIG Bjarke Ingels Group, 2020

By utilizing 3D printing techniques, they aim to build structures and habitats directly on the Moon, minimizing the need for transporting heavy construction materials from Earth.

The utilization of in-situ resources not only reduces the cost and logistical challenges of lunar missions but also contributes to the sustainability of the outpost. By extracting and processing the regolith, various construction materials can be produced, creating a closed-loop system where resources are recycled and reused.

Furthermore, the Olympus project emphasizes the importance of collaboration and international partnerships. ICON recognizes that the establishment of a lunar outpost requires the combined efforts and expertise of various stakeholders, including government agencies, private companies, and research institutions. By fostering collaboration, sharing knowledge, and pooling resources, the project aims to create a unified approach towards lunar exploration and settlement.

As we delved deeper into the details of the project, we saw the vision of a self-sustaining outpost on the Moon, constructed with innovative 3D printing technology and powered by renewable energy sources, it offers a glimpse into the future of human presence in space.



01
Olympus lands on the luunar surface via commercial lander.

02
The lander off loads Olympus to thr Moon’s surface.

03
Olympus drives itself to its selected build site.

04
On arrival at the build site, Olympus deploys and prepares to build.

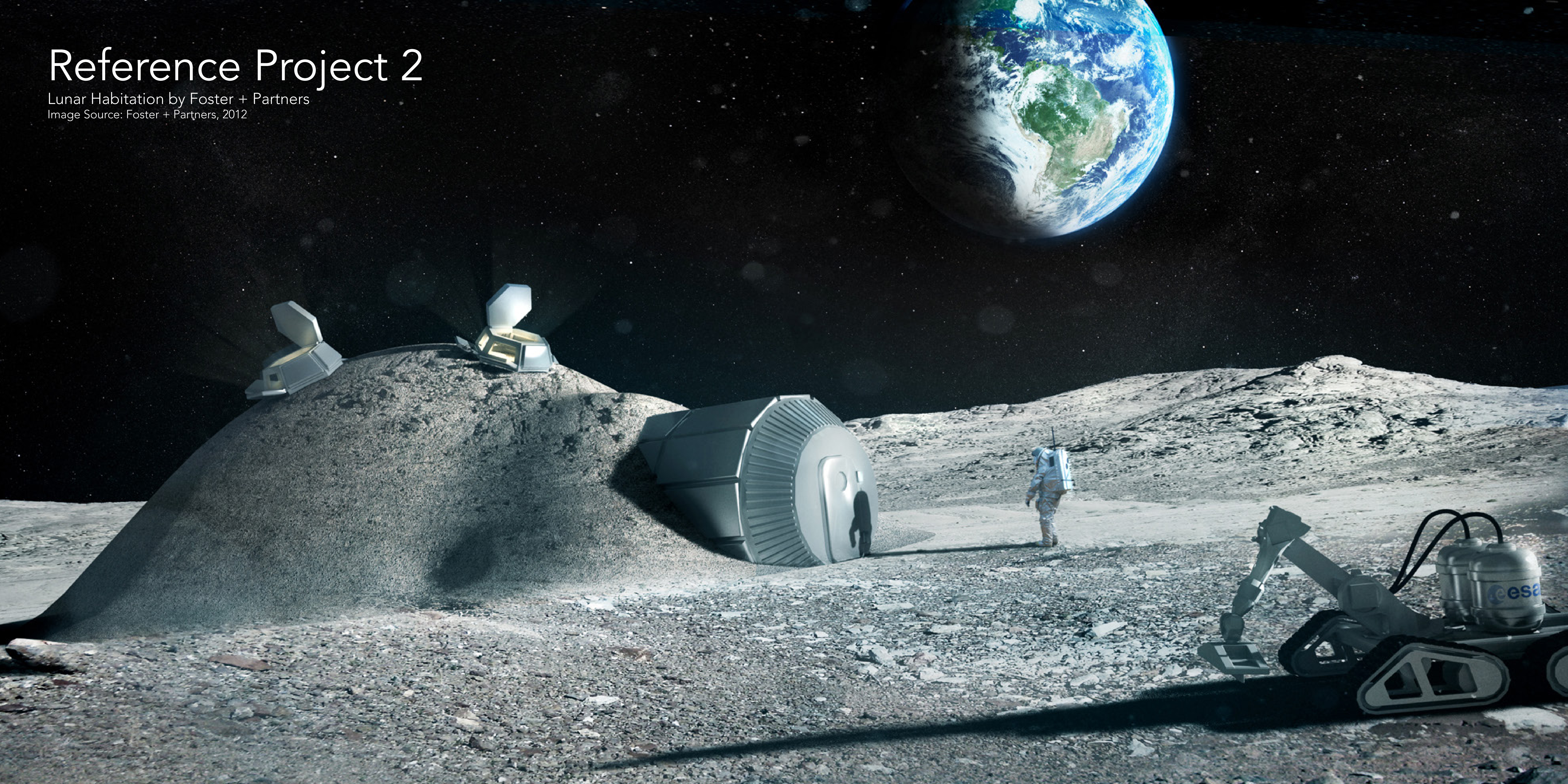
05
Olympus processes lunar regolith into a building material to print structures.

Image Source: ICON, 2020

Reference Project 2

Lunar Habitation by Foster + Partners

Image Source: Foster + Partners, 2012



In our research of space architecture and construction techniques for lunar habitats, we encountered an impressive project led by Foster + Partners in collaboration with the European Space Agency. This initiative revolves around the utilization of 3D printing technology for the construction of lunar habitations, addressing the logistical challenges of transporting materials to the Moon. It also delves into the innovative use of lunar regolith as a primary building material.

The core concept involves the design of a lunar base capable of accommodating four individuals, providing protection against meteorites, radiation, and extreme temperature fluctuations. The base is unfolded from a cylindrical module that can be transported by a space rocket. An inflatable dome extends from one end of the cylinder, serving as a structural framework for construction. Layers of regolith are then systematically printed over the dome's surface by a robot-operated 3D printer to create a protective shell. To optimize strength while minimizing the printed material, the shell is designed to have pockets to house loose regolith that will be filled by small autonomous robots. This innovative approach highlights the potential of 3D printing to mimic natural biological systems.

The Lunar Habitation project is supported by practical experimentation. Simulated lunar soil was employed to create a 1.5-ton mockup, and 3D printing tests were conducted at a smaller scale within a vacuum chamber to replicate lunar conditions. The chosen site for the lunar base is the Moon's South Pole, where near-perpetual sunlight on the horizon offers unique advantages.

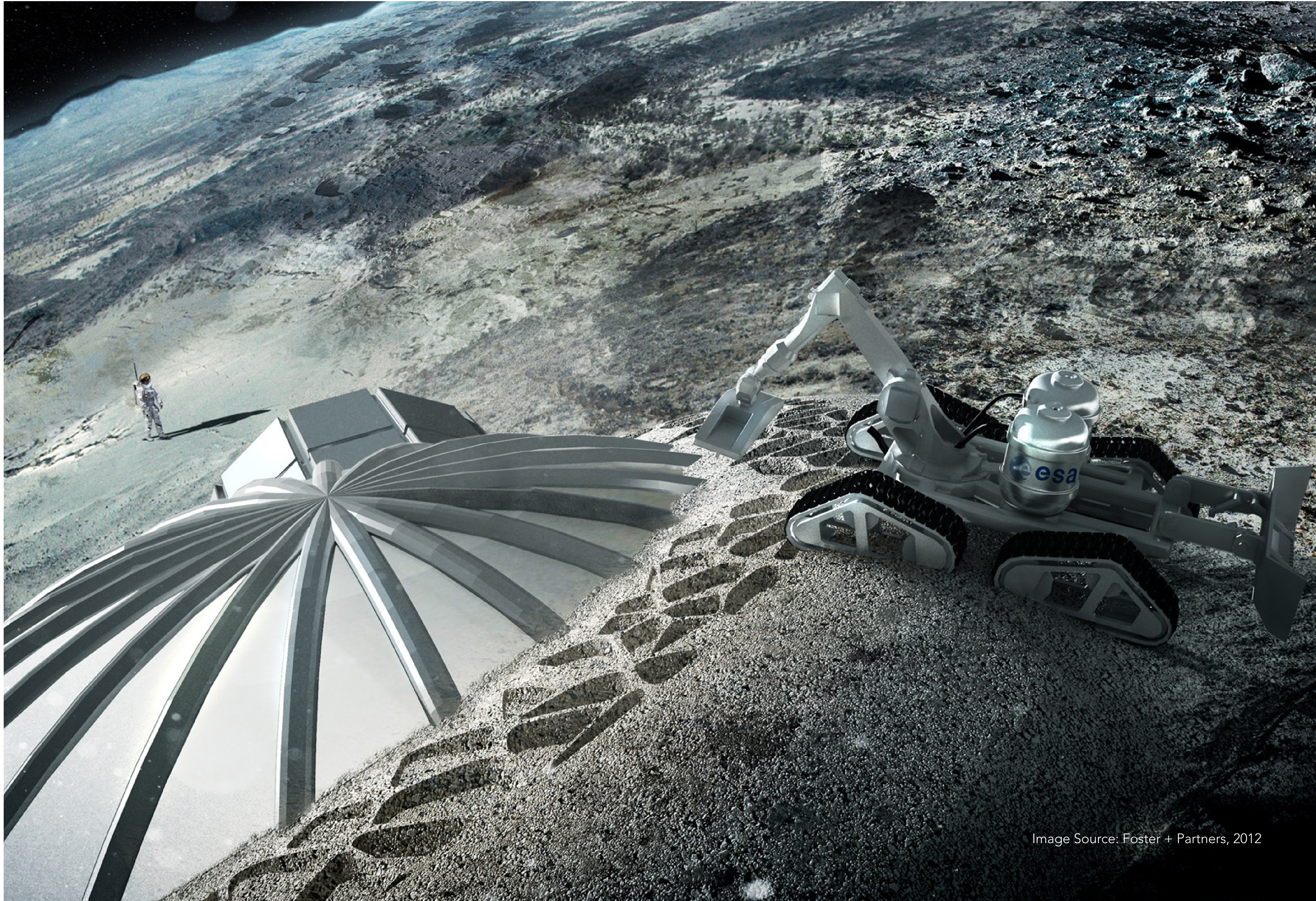


Image Source: Foster + Partners, 2012

This project embodies a compelling vision of establishing a self-sustaining human habitat on the lunar surface. It seamlessly integrates architecture and technology to provide a blueprint for a potential lunar civilization. Notably, it is a testament to human ingenuity, pushing the boundaries of what can be achieved and expanding our horizons beyond Earth.

Central to the Lunar Habitation project is a profound commitment to environmental sustainability. The habitat design harmonizes with the lunar landscape, utilizing local resources and cutting-edge technologies to minimize ecological impact. This approach not only ensures the preservation of the lunar environment but also offers valuable insights into sustainable living beyond Earth.

The design of the lunar habitat itself exemplifies functionality, aesthetics, and adaptability. Foster + Partners envisions a modular structure capable of easy deployment and expansion to meet the evolving needs of the lunar community. The architectural design blends seamlessly with the lunar surroundings while providing a secure and habitable environment.

To achieve the ambitious goal of lunar habitation, Foster + Partners leverages its expertise in advanced construction techniques and materials. The choice of using lunar regolith as a building material reduces the need for material transport from Earth. Additionally, lunar regolith offers radiation shielding and thermal insulation.

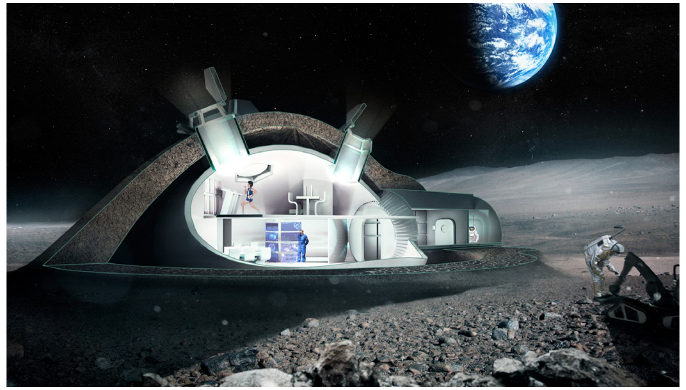


Image Source: Foster + Partners, 2012

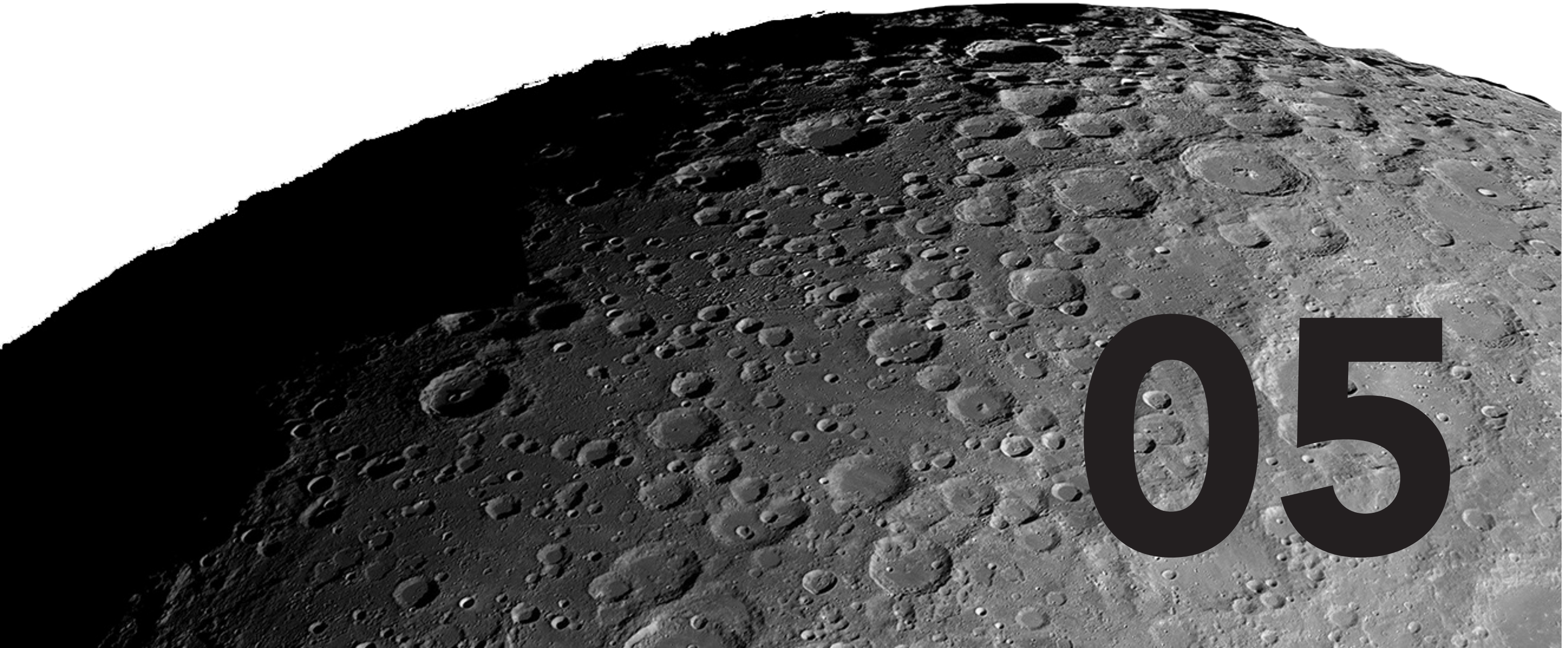
Image Source: Foster + Partners, 2012

Recognizing the importance of community and human connection in the lunar outpost, the Lunar Habitation project incorporates social spaces, recreational areas, and shared facilities. This design fosters collaboration and cohesion among residents, transforming the habitat into a sanctuary for scientific discovery and human exploration.

Despite its immense promise, the Lunar Habitation project faces formidable challenges due to the harsh lunar environment, including extreme temperatures, low gravity, and radiation exposure. Foster + Partners collaborates with scientific and engineering experts to develop robust solutions for the safety and well-being of lunar inhabitants.

Image Source: Foster + Partners, 2012

Site Decision 1: Lava Tube



Lava Tube Selection
Orijin of Lava Tubes

Geologists have proposed that lunar lava tubes share similarities with their terrestrial counterparts in terms of formation. However, the lunar environment, characterized by lower gravity and the absence of an atmosphere, suggests that lunar lava tubes are likely much larger in size (Sauro et al., 2020). Studies conducted on Earth's lava tubes indicate that the majority of them are hollow, and if lunar lava tubes form similarly, it is expected that they too would be hollow.

The formation process of a lava tube typically involves the development of a continuous crust on an active basaltic lava flow. In some cases, an open lava channel can develop a hardened rock crust that gradually extends from the sides and eventually meets in the middle, creating a roof. Even with the formation of a roof, the lava tube still maintains a flow of lava within it. While there is a possibility that the cooling lava could solidify and block the tube, it is important to note that most lava tubes on Earth do not experience such blockage.

As the flow of lava diminishes over time, the level of liquid within the tube decreases, resulting in an empty space between the top of the flow and the tube's roof (Theinat et al., 2019). This empty space creates an open pathway within the lava tube, allowing for the exploration and potential utilization of these spaces for

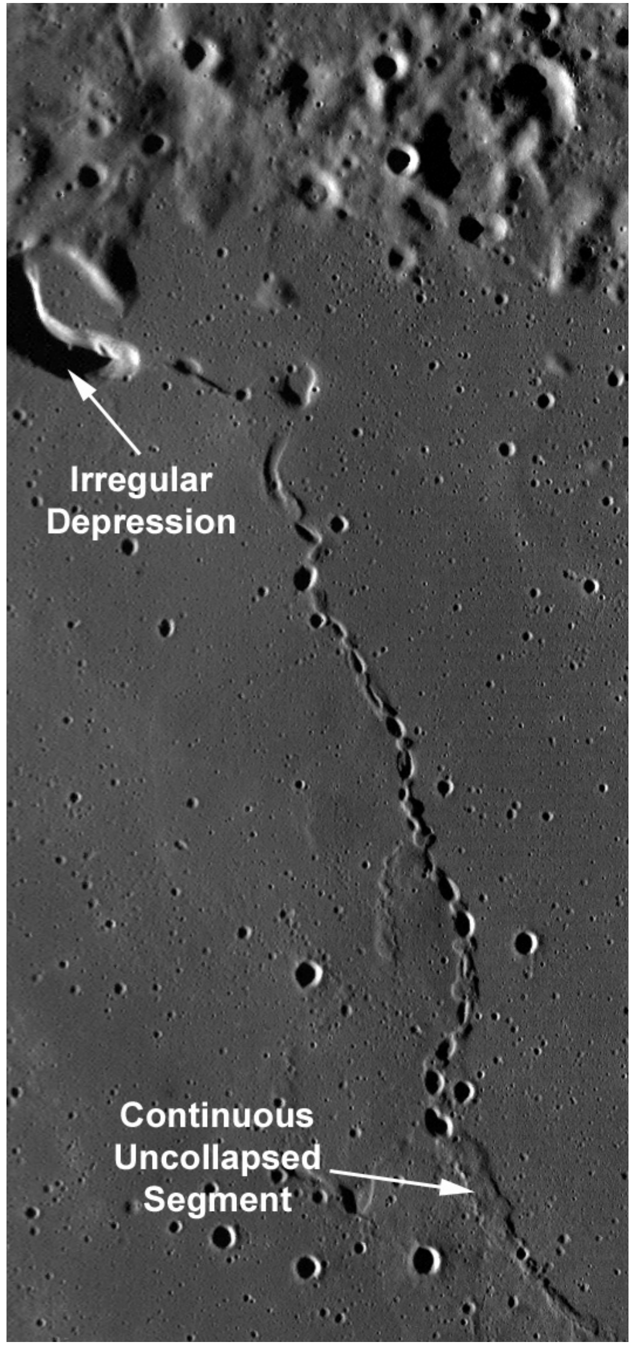


Image Source: https://triennale.org

human settlements.

The lunar lava tube, a natural formation created by volcanic activity, is a fascinating geological feature found on the Moon's surface. These subterranean tunnels hold great potential for lunar construction, offering a range of advantages that align perfectly with our vision for the touristic resort.

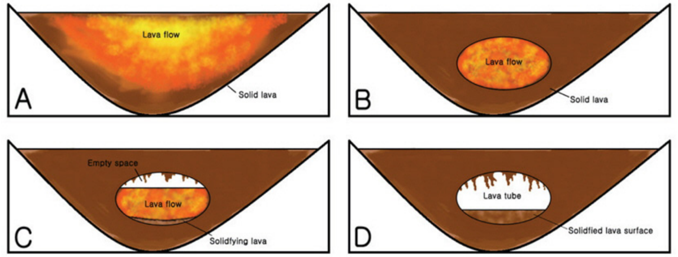
Advantages of Lunar Lava Tubes

1. Protection from radiation

Protection from radiation is a critical consideration for any long-term human presence beyond Earth, and lunar lava tubes offer a compelling solution in this regard.

This thick layer of rock acts as a strong barrier against radiation. Cosmic radiation, which consists of high-energy particles originating from outside our solar system, is largely absorbed and weakened by the rock layers. This shielding property significantly reduces the radiation exposure of astronauts and minimizes the risk of acute radiation sickness and long-term health effects that can result from exposure to intense solar radiation within the lava tube, protecting them from the harmful effects of cosmic radiation.

Solar flares which are characterized by intense releases of radiation originating from the Sun, present another noteworthy challenge for lunar exploration by humans.



"Pit crater formation mechanism. Lava tube entrance be created, while the collapse of the weak part of the ceiling."
Image Soruce: Journal of Astronomy and Space Sciences Volume 31, Issue2, p131~140, 15 June 2014

Lava tubes also provide a safeguard against solar flares.

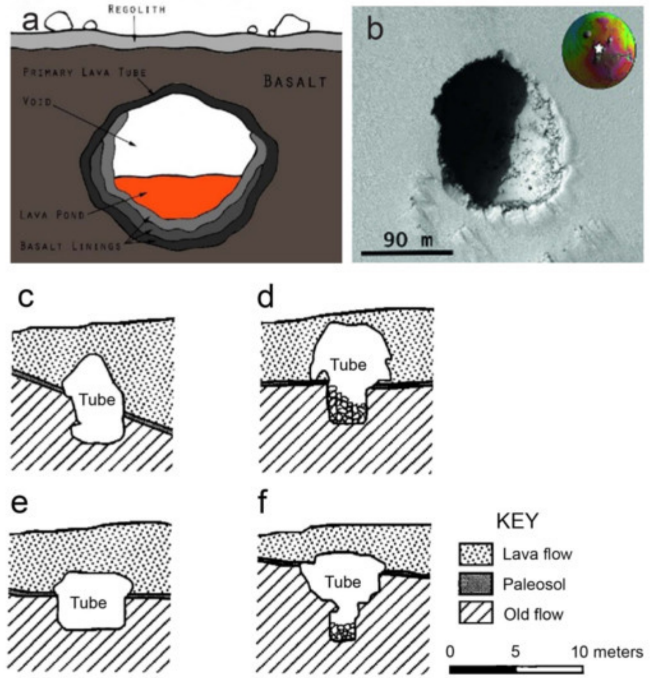
It is important to note that further research and engineering efforts are required to fully understand the extent of radiation shielding provided by lunar lava tubes and to develop appropriate measures to enhance safety within these environments.

However, the initial findings and inherent characteristics of the lava tubes make them a promising choice for mitigating the radiation challenges faced in lunar exploration and establishing sustainable habitats on the Moon.

2. Thermal stability

Thermal stability is a critical factor for establishing human habitats beyond Earth, given the extreme temperature variations on the lunar surface. Lunar lava tubes provide a unique solution to these challenges by leveraging their inherent thermal properties.

The lunar environment exhibits dramatic temperature shifts, from intense heat during the day to freezing cold at night, posing significant obstacles to every aspect of the settlement. Research and simulations indicate that lunar lava tubes maintain stable thermal conditions, making them suitable for human habitation.

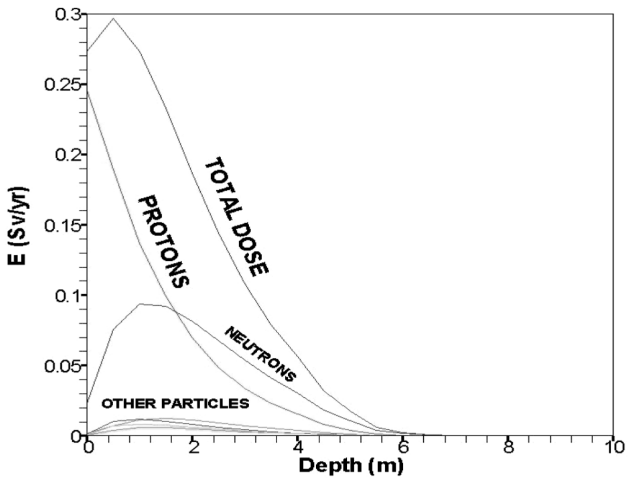


"(a) Transverse section of a lava tube [18]. (b) Possible gigantic lava tube skylight with a diameter of about 180 m captured by HiRISE imaging."
Image Soruce: NASA/JPL–Caltech/UArizona). (c–f) Cross–sections of Ainahou Ranch lava tube.

The thick layer of solid rock surrounding the tubes acts as insulation, shielding the interior from surface temperature fluctuations. This insulation creates a consistent temperature within the lava tube, providing a hospitable environment.

Harnessing these thermal properties significantly reduces the energy and resource requirements for maintaining a comfortable living environment in lunar habitats. Temperature estimates range from around -20 degrees Celsius to slightly above freezing, depending on factors like tube depth and proximity to heat sources within the moon.

Moreover, the stable thermal environment within the lava tubes supports various activities and equipment that require specific temperature conditions. Scientific experiments and manufacturing processes can succeed in this controlled environment, optimizing research and production activities and enhancing the overall productivity of lunar settlements.



"The radiation safety of lunar lava tubes environments has been demonstrated in the graph which shows the dramatic decrease of the GCR (Glactic Cosmic Rays) in accordance with depth. Results for Effective Dose (E) inside a lava tube (OTHER PARTICLES - i.e. all kinds of particles other than Protons and Neutrons transported by the FLUKA code, namely electrons, positrons, photons, pions, muons, kaons, deuterons, etc.)"
Image Source: NASA (Article titled "Lunar Lava Tube Radiation Safety Analysis"

3. Structural stability

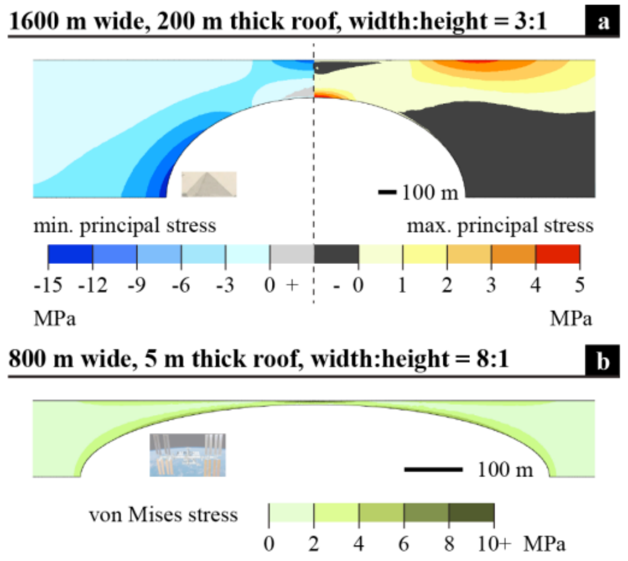
Structural stability is a crucial aspect to consider when designing habitats for long-term human presence on the Moon, and lunar lava tubes offer inherent stability that makes them well-suited for lunar construction. Lava tubes are geological formations formed by volcanic activity, where molten lava flows beneath the lunar surface and solidifies over time, resulting in the creation of hollow tunnels with durable walls and ceilings.

One advantage of the lava tubes' structural stability is their ability to withstand the low gravity on the Moon. Lunar gravity is only about one-sixth of the Earth's gravity, and this reduced gravitational force places different stress on structures compared to those experienced on Earth. The inherent stability of lava tubes ensures that they can withstand gravitational stresses without compromising their integrity.

Furthermore, the potential for seismic activity on the Moon is another consideration for structural stability. While the Moon experiences fewer seismic events compared to Earth, it is not completely devoid of tectonic activity. Lava tubes, with their solid rock construction, are believed to have the ability to withstand seismic events better than surface habitats, as the surrounding rock provides a natural buffer against ground shaking (Blair et al., 2017).

4. Reduced construction requirements

Building within a preexisting lava tube offers a significant advantage in terms of reduced construction requirements. The natural walls and ceilings of the lava tube serve as a ready-made framework for habitation, resulting in substantial savings



"Stress results from our models; compressive stresses are negative. a) A large, deeply buried tube found to be stable if thermal stresses are not included, similar in scale to tubes inferred from analysis of GRAIL* data. b) A tube with a thin roof approximating layer thicknesses seen in lunar skylights, which is near or past failure over a region ~60 m wide, similar to observed skylight diameters."
Image Source: From Chappaz, L., et al. (2014), AIAA Space 2014 Conf. and Expo

**GRAIL: The Gravity Recovery and Interior Laboratory, an American lunar science mission in NASA's Discovery Program, employed precise gravitational field mapping of the Moon to ascertain the interior structure of the body.*

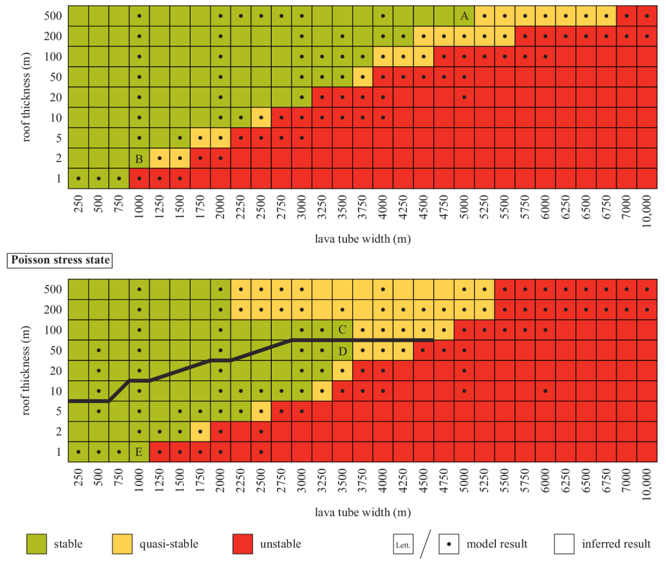
in terms of construction materials, time, energy, and resources that would otherwise be required to construct a habitat from scratch.

The presence of a preexisting framework also simplifies the overall construction process. The need for constructing thick walls to protect from radiation is no longer needed thus reducing construction time and effort. Also this eliminates the necessity for constructing new load-bearing structures and allows for a more efficient use of resources.

Additionally, the reduced construction requirements offer benefits in terms of logistics and transportation. Transporting construction materials from Earth to the Moon is a complex and costly endeavor. By leveraging the natural framework of the lava tube, the need for transporting large quantities of construction materials is significantly reduced, resulting in substantial savings in launch mass and associated costs.

5. Regolith shielding

Regolith shielding is an important advantage offered by lava tubes in lunar habitats. The loose lunar regolith, which is a soil-like material covering the Moon's surface, presents challenges for surface structures due to its abrasive nature and the potential for damaging equipment. However, by



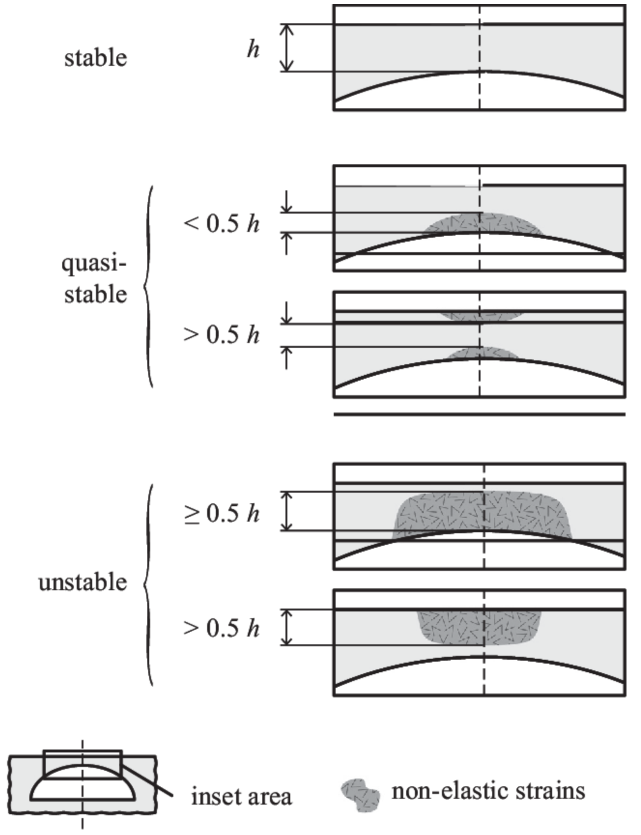
"Lava tube stability results from this study for an assumed lithostatic (top) and Poisson (bottom) state of stress in the material comprising the lava tube and its surroundings, and for a variety of combinations of lava tube width and roof thickness. A lava tube is deemed stable when there are no plastic strains present in the roof, quasi-stable when plastic strains are present in < 50% of the roof's thickness, and unstable when plastic strains are found over ≥50% of the roof's thickness. The bold line in (b) indicates a division between two modes of failure in the Poisson models, with models below that line (and all models in the lithostatic stress state case) failing in contraction, and models above that line failing in extension due to downwards flexure of the roof."
Image Source: Blair, D.M., Chappaz, L.P., Sood, R., Milbury, C., Bobet, A., Melosh, H.J., Howell, K.C., & Freed, A.M. (2017). The structural stability of lunar lava tubes. Icarus, 282, 47-55.

utilizing lava tubes, astronauts can effectively avoid direct contact with the regolith, reducing the damage on equipment and minimizing the risk of lunar dust contamination inside the habitat.

The regolith on the lunar surface consists of fine grains of dust and small rocks that have been broken down over millions of years by micrometeorite impacts . This abrasive material can pose a threat to the integrity of surface structures and equipment (James & Kahn-Mayberry, 2009). It can potentially lead to mechanical harm, and even blockage of sensitive instruments. Moreover, lunar dust has electrostatic properties and can stick to surfaces, making it difficult to clean and potentially interfering with the proper functioning of equipment.

By locating the habitats within lava tubes, we can create a barrier between the regolith and the living spaces, research facilities, and equipment. The solid rock walls and ceilings of the lava tube serve as a protective shield, preventing direct contact with the regolith. This shielding effect reduces the risk of damage to equipment and extends the lifespan of critical components, ultimately contributing to the long-term sustainability of lunar missions.

Moreover, the use of lava tubes minimizes the risk of lunar dust contamination inside the habitat. Lunar dust particles are extremely fine and have jagged edges, making



"Model outcome designations. We deem a tube "stable" (top) when there are no non-elastic strains in the lava tube's roof; "quasi-stable" when there are nonelastic strains in less than half of the roof's total thickness (middle); and "unstable" when non-elastic strains are present in more than half of the roof's thickness (bottom). In the latter two cases, we do not distinguish based on the location of the non-elastic strains, instead considering only their total prevalence in the roof. Illustration roughly to scale."
Image Source: Blair, D.M., Chappaz, L.P., Sood, R., Milbury, C., Bobet, A., Melosh, H.J., Howell, K.C., & Freed, A.M. (2017). The structural stability of lunar lava tubes. Icarus, 282, 47-55.

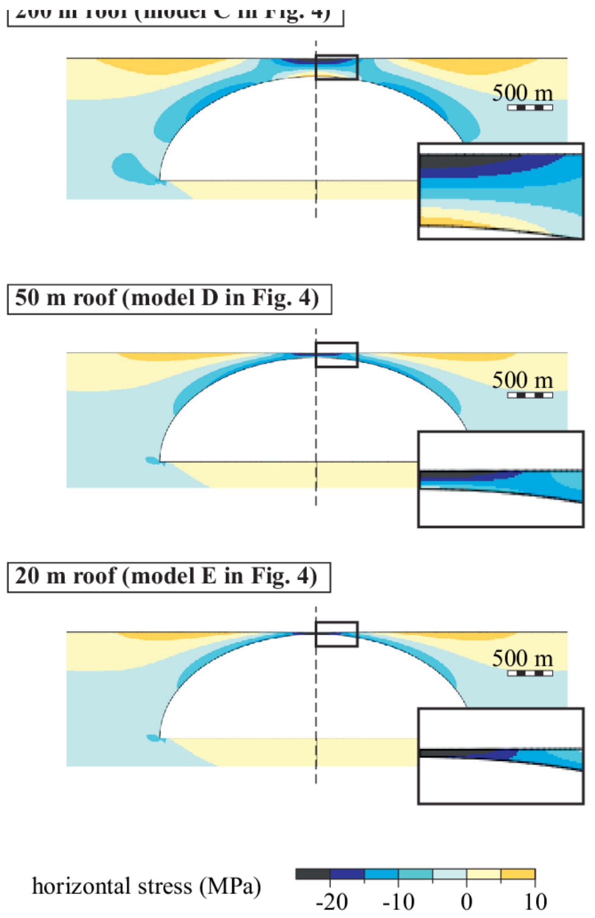
them potentially hazardous if inhaled or ingested by astronauts. These particles can cause respiratory issues and pose a risk to human health. By avoiding direct contact with the regolith, the intrusion of lunar dust into the living spaces and research areas can be significantly reduced, ensuring a cleaner and healthier environment for the lunar inhabitants.

6. Psychological benefits

During our visit to Triennale di Milano, there was a part dedicated to psychological effect of being in the vastness of outer space. This visit made us think about the psychological benefits of lava tubes in lunar habitats which are significant. The enclosed and cave-like environment offers a unique setting that can have positive effects on the well-being and mental health of astronauts.

This environment simulates a sense of protection, which can contribute to their overall psychological well-being during long-duration space missions.

The human mind is influenced by the physical environment, and being in an enclosed space can evoke feelings of security and comfort. Lava tubes, with their natural walls and ceilings, create a closer and more enclosed living space compared to open-surface habitats. This sense of enclosure can help reduce the feeling of



"Models of a 3500 m wide tube with an initial Poisson stress state, showing how varying roof thickness results in different final stress states, failure modes, and stability outcomes. The model with a 200 m roof (model C here and in Fig. 3) fails in extension at the apex of the tube; with a 50 m roof (model D) is stable and shows uniformly compressional horizontal stresses; and with a 20 m roof (model E) fails in compression from the surface downwards. Color contours show the horizontal stress in the model, with positive stress corresponding to tension. Inset boxes show the central portion of the roof magnified for clarity, and the vertical dashed lines represent the plane of symmetry. Shown to scale."
Image Source: Blair, D.M., Chappaz, L.P., Sood, R., Milbury, C., Bobet, A., Melosh, H.J., Howell, K.C., & Freed, A.M. (2017). The structural stability of lunar lava tubes. Icarus, 282, 47-55.

isolation and provide a sense of belonging and safety.

Research conducted in similar environments, such as Antarctic research stations or underwater habitats, has shown that living in confined spaces can have both positive and negative psychological impacts. However, studies have also indicated that a sense of privacy, and the ability to create personal spaces within confined environments can significantly improve psychological well-being.

In conclusion, the advantages of lunar lava tubes in terms of radiation protection, thermal stability, structural integrity, reduced construction requirements, regolith shielding, and psychological well-being make them an excellent choice for positioning a lunar touristic resort. By leveraging the natural benefits of these formations, we can create a safe, comfortable, and scientifically rich environment for tourists to experience the wonders of the Moon.

An Overview

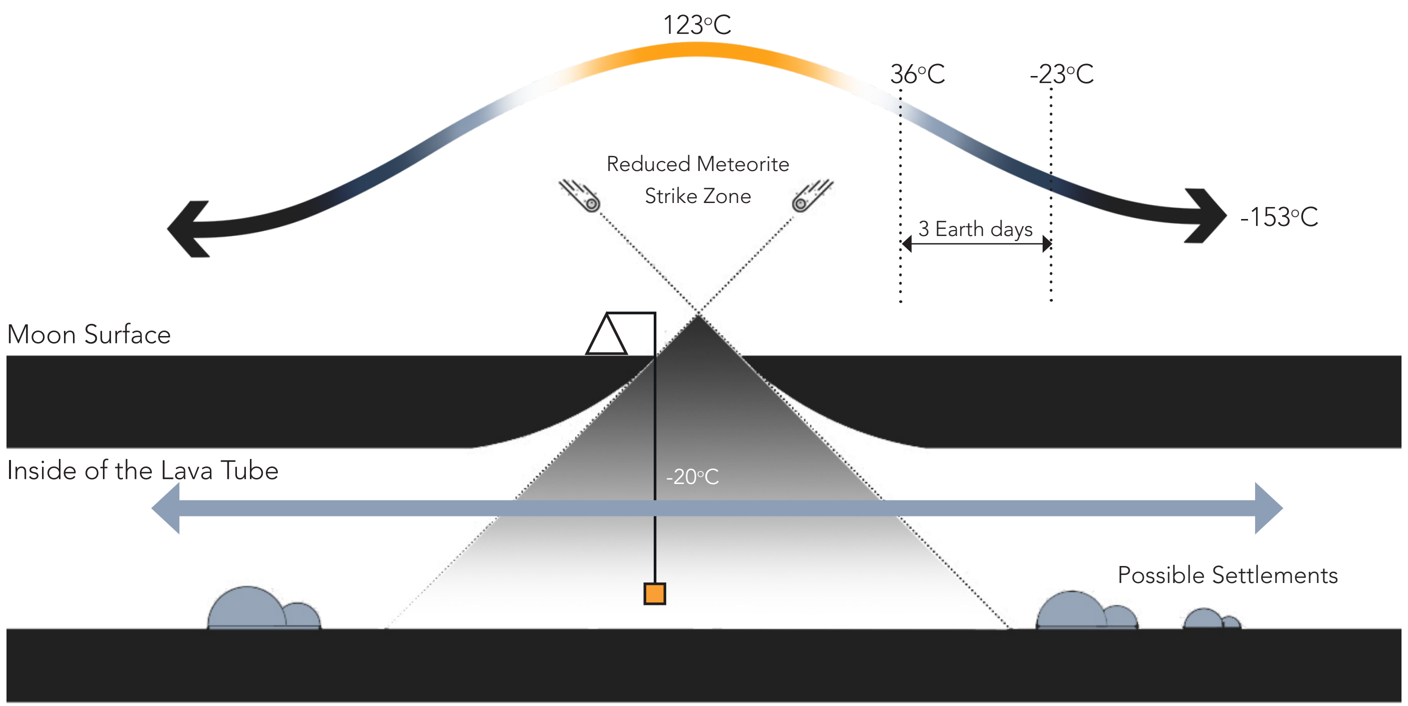
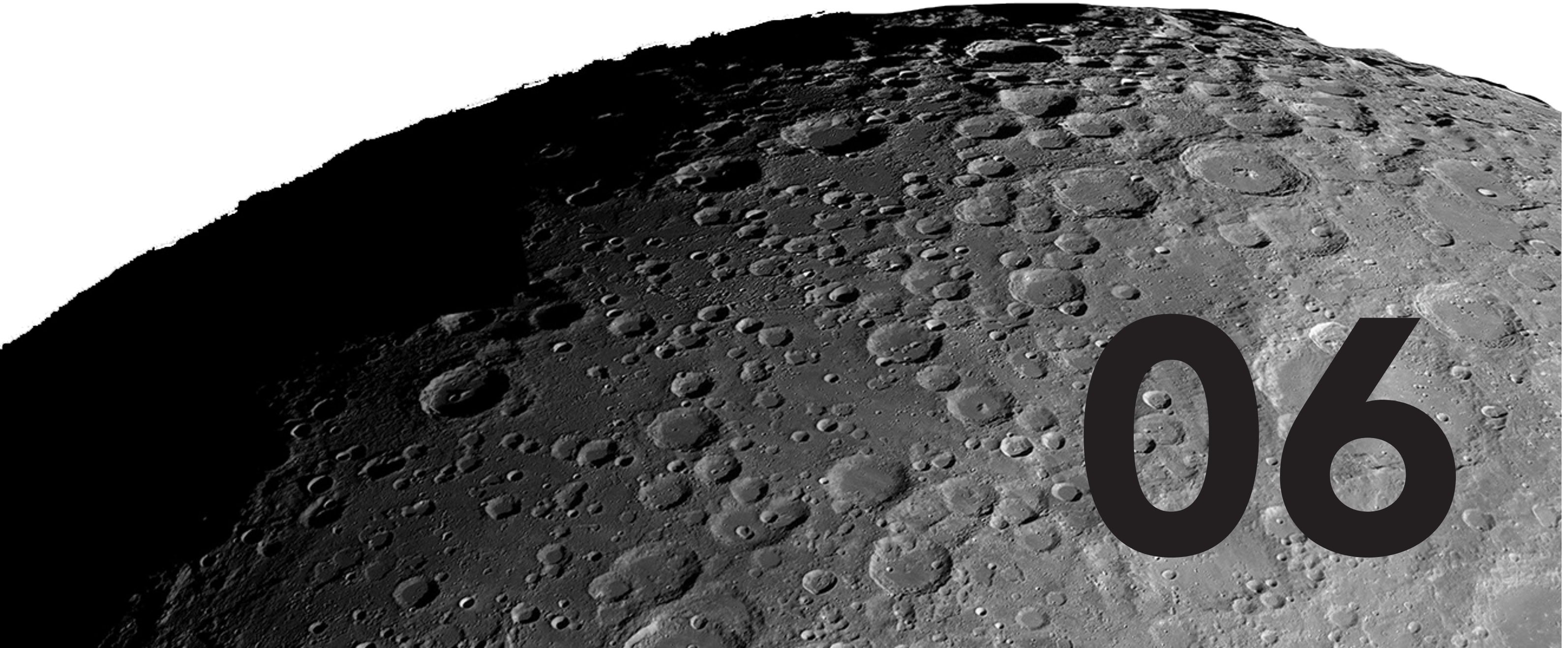


Diagram by E. Kırmızıyeşil, E. N. Yavuz, November 2022

Design Scenario 1

During our design process, we developped several design scenarios. Our initial intent was to design a preliminary project based on the existing data that we have, primarily aimed at starting a discussion during the upcoming seminar with Professor Durbiano. This signifies a dynamic shift from the original outline, highlighting the value of investigation in shaping the direction of our project.



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Design Scenario 1 with Phase version 1

Tourist Resort in lava tube

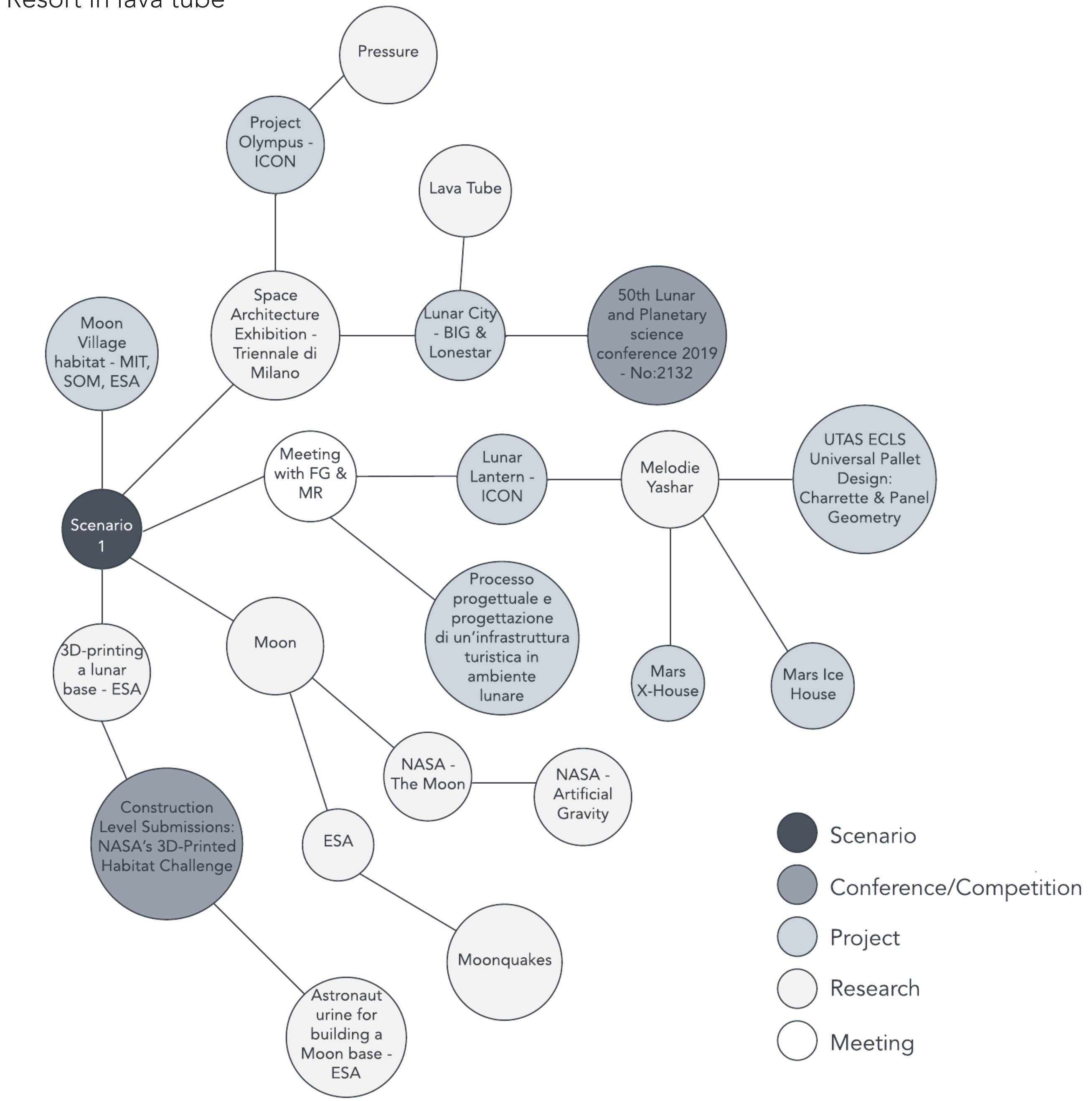


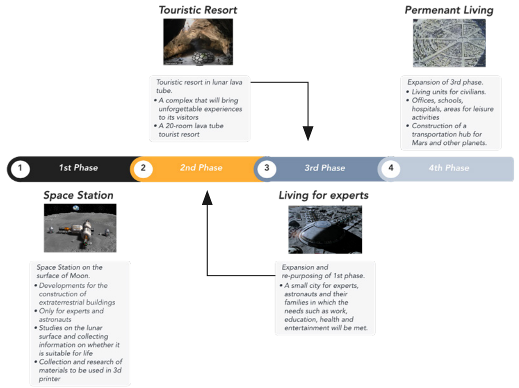
Diagram by E. Kırmızıyeşil, E. N. Yavuz, November 2022

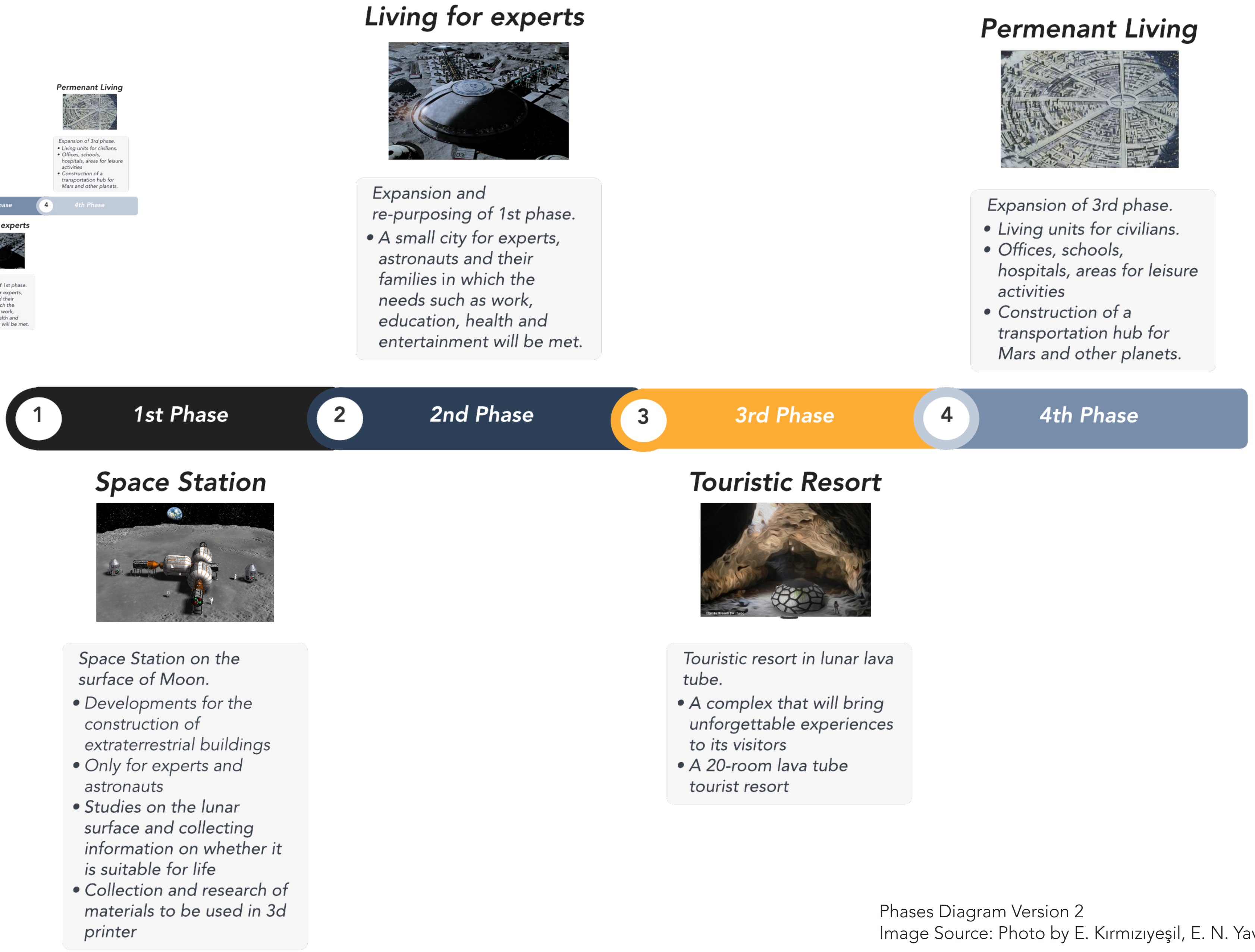
Moon Habitation Phases Version 2

An important decision was made during our recent meeting with Marta Rossi and Federica Joe Gardella. This meeting resulted in slight adjustments to the timeline of the previous phases, influenced by our research of NASA's Artemis program. The knowledge acquired through this research significantly contributed to shaping our perspective on the future of lunar architecture.

As we advanced in the planning of our project, we realized that our initial plan of constructing a tourist resort on the lunar surface without a comprehensive space station was not a practical approach. It became clear to us that a solid foundation, in the form of a functional and fully operational space station, was necessary before entering the field of lunar tourism. Therefore, we made the decision to swap the second and third phases of the project, ensuring a more logical progression in our phases.

Phase 2: Living for Experts (2029-2034)
The second phase of our lunar architecture project now takes precedence. This phase focuses on building a habitat for space station workers and astronauts. The vision remains unchanged: to create a self-sustaining ecosystem that expands over time, fostering a thriving lunar community.
This shift in the timeline allows us to lay a solid foundation for the phases to come. By first establishing a functional habitat, we can make sure that we have the required infrastructure and systems in place to guarantee the long-term success of our lunar missions.





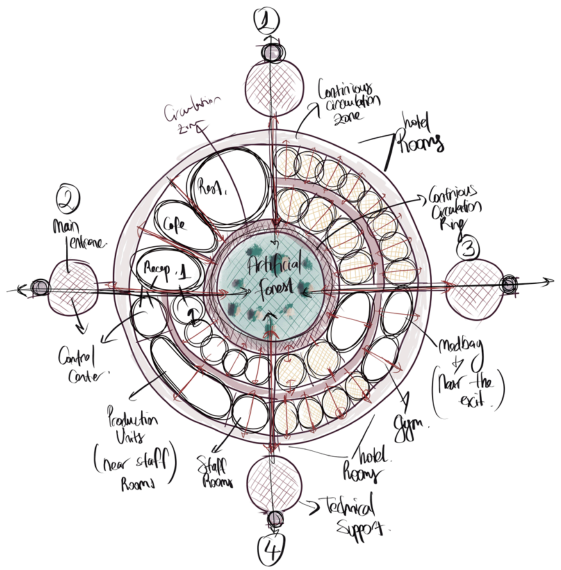
Phases Diagram Version 2
Image Source: Photo by E. Kırmızıyeşil, E. N. Yavuz, 2022

*it indicates which phase design we have decided to work on.

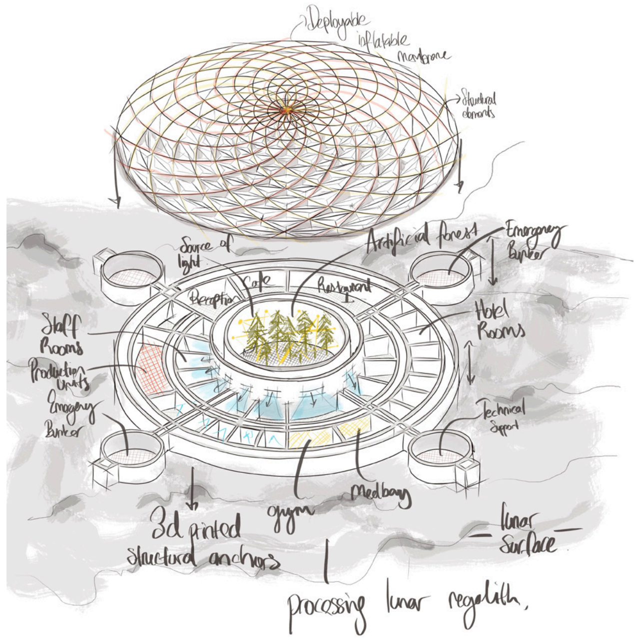
After our detailed research on the Lava tube, we started the design of the tourist resort project. Since there is not enough geographic data on the lava tubes on the Moon yet, we created a 3d model based on the estimated lava tube sizes. Referring to the design process in reference project Olympus, we determined the shape as a circle. Circle shape is the most suitable shape considering the pressure difference. After this part, which will be 3d printed, we designed the dome with the Inflatable structure, which was also used in the Lunar Habitation project of Foster and Partners. the use of inflatable structures for lunar settlements offers a lightweight, deployable, and versatile solution that can provide a safe and habitable environment on the Moon.

So we decided on the shape, we determined the spaces that should be in a touristic resort. Then, we listed the areas that should be in space architecture and prepared a basic spatial distrubition diagram. Space architecture is supposed to contain many technical spaces. While identifying these technical areas, we took references from Foster and Partners' Lunar Habitation project. As it can be seen in the plan, we decided to design four exit/entrance areas with airlocks and technical rooms. For emergency, we designed a outer circle which is directly connected to each space.

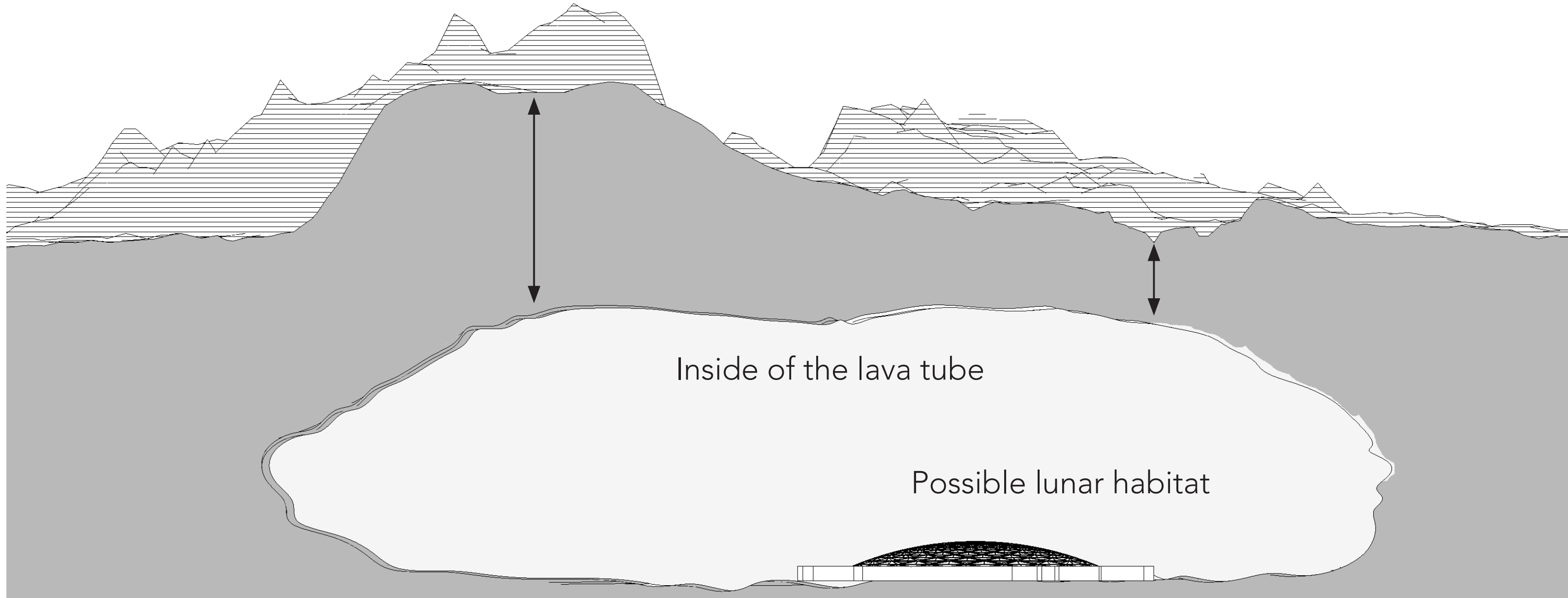
Emphasizing the significance, it becomes evident that the model and the design choices were conceived with the explicit purpose of extent of our capacity to innovate within the confines of our current, albeit restricted, understanding of space architecture. This endeavor served as a pivotal juncture, enabling us to fathom the possibilities inherent within the extent of our existing knowledge. As the thesis progressed, this exploration assumed an even greater importance, acting as a dynamic compass guiding the evolution of the project itself. The nature of this process allowed us to witness how the project transformed, adapting and refining itself along the trajectory of its development.



Sketch by E. Kırmızıyeşil, E. N. Yavuz, December 2022



Sketch by E. Kırmızıyeşil, E. N. Yavuz, December 2022

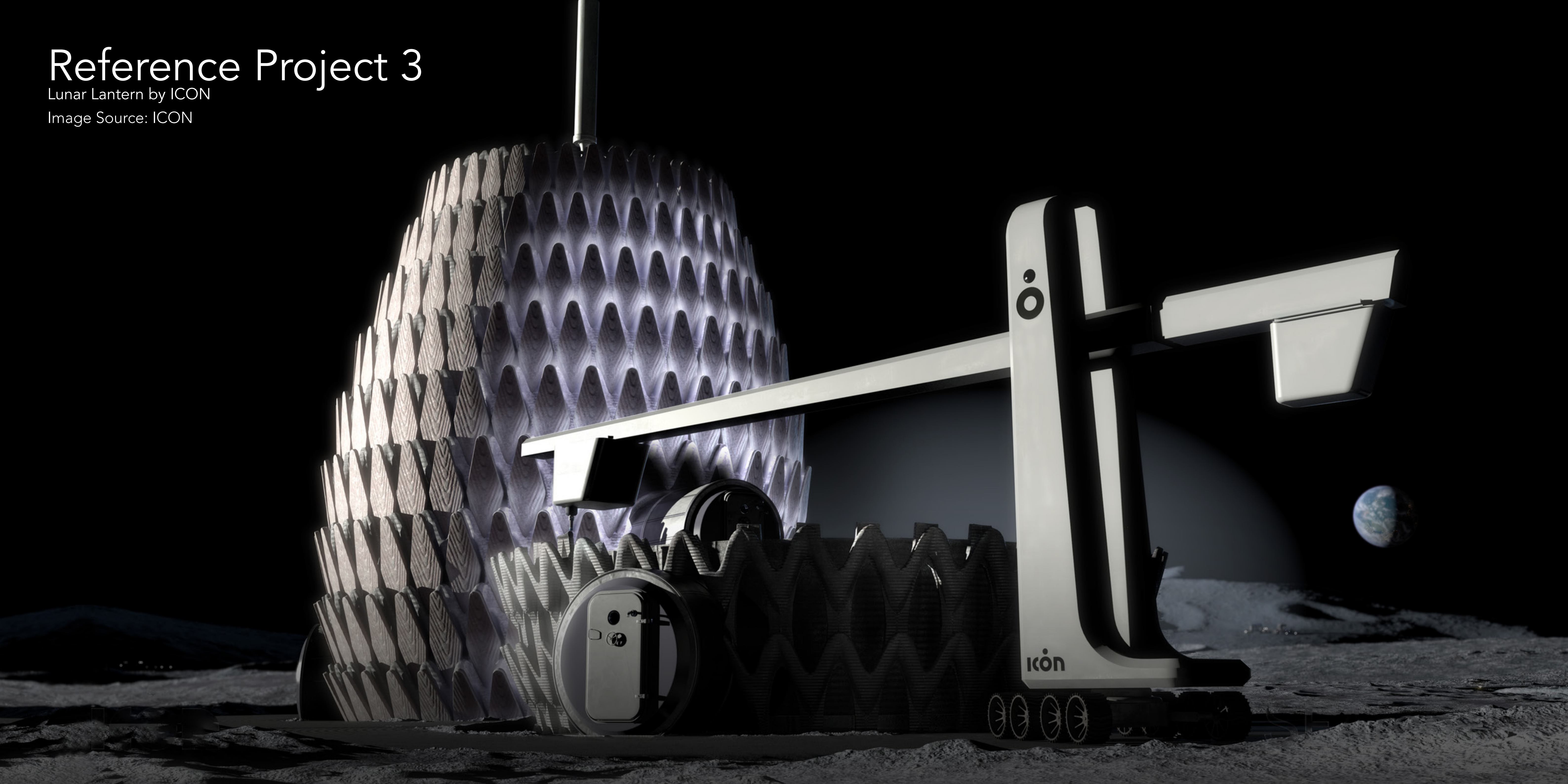


Drawing by E. Kırmızıyeşil, E. N. Yavuz, December 2022

Reference Project 3

Lunar Lantern by ICON

Image Source: ICON



During our weekly meeting, Marta Rossi recommended us to take a look at the Lunar Lantern project.

The project designed by ICON as part of NASA's Moon-to-Mars Planetary Autonomous Construction Technologies (MMPACT) program back in 2020. It involves a collaboration between ICON and SEArch+ to design various construction elements required for a lunar settlement. These designs covers aspects like setting up structures on the lunar surface, the order in which construction should occur, and structural considerations. Most importantly, these designs were developed in consultation with ICON's engineers and NASA's collaborators to ensure they were feasible within hardware and material limitations. This collaboration illustrates the connection between architectural planning and engineering requirements.

The resulting habitat, called the "Lunar Lantern" due to its dual-layer protective structure, prioritizes principles related to human safety and comfort to ensure the well-being of future lunar inhabitants. The project, as a whole, aims to create durable, self-sustaining structures on the lunar surface, using advanced 3D-printing technologies.

The Lunar Lantern Project caught our attention due to its blend of artistic creativity and practical design choices. Its primary goal is to design a set of sculptures, known as "lanterns," that serve as both sources of inspiration and cultural symbols.

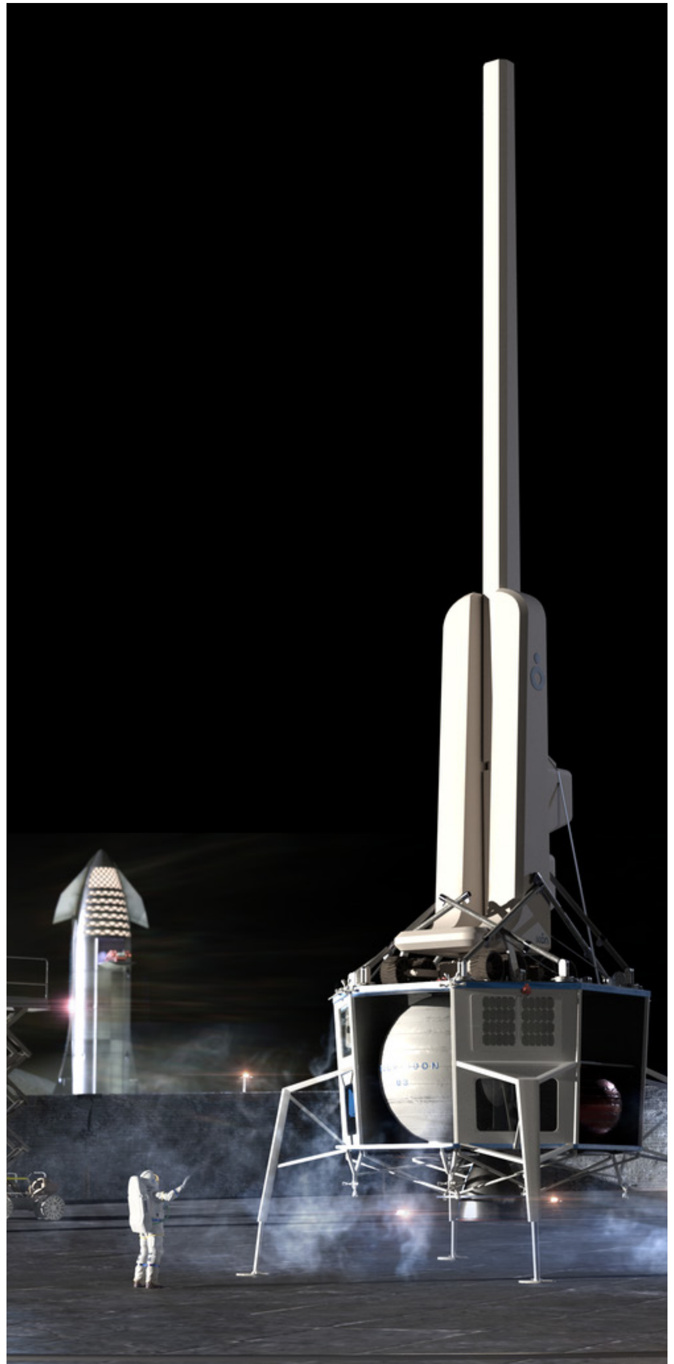
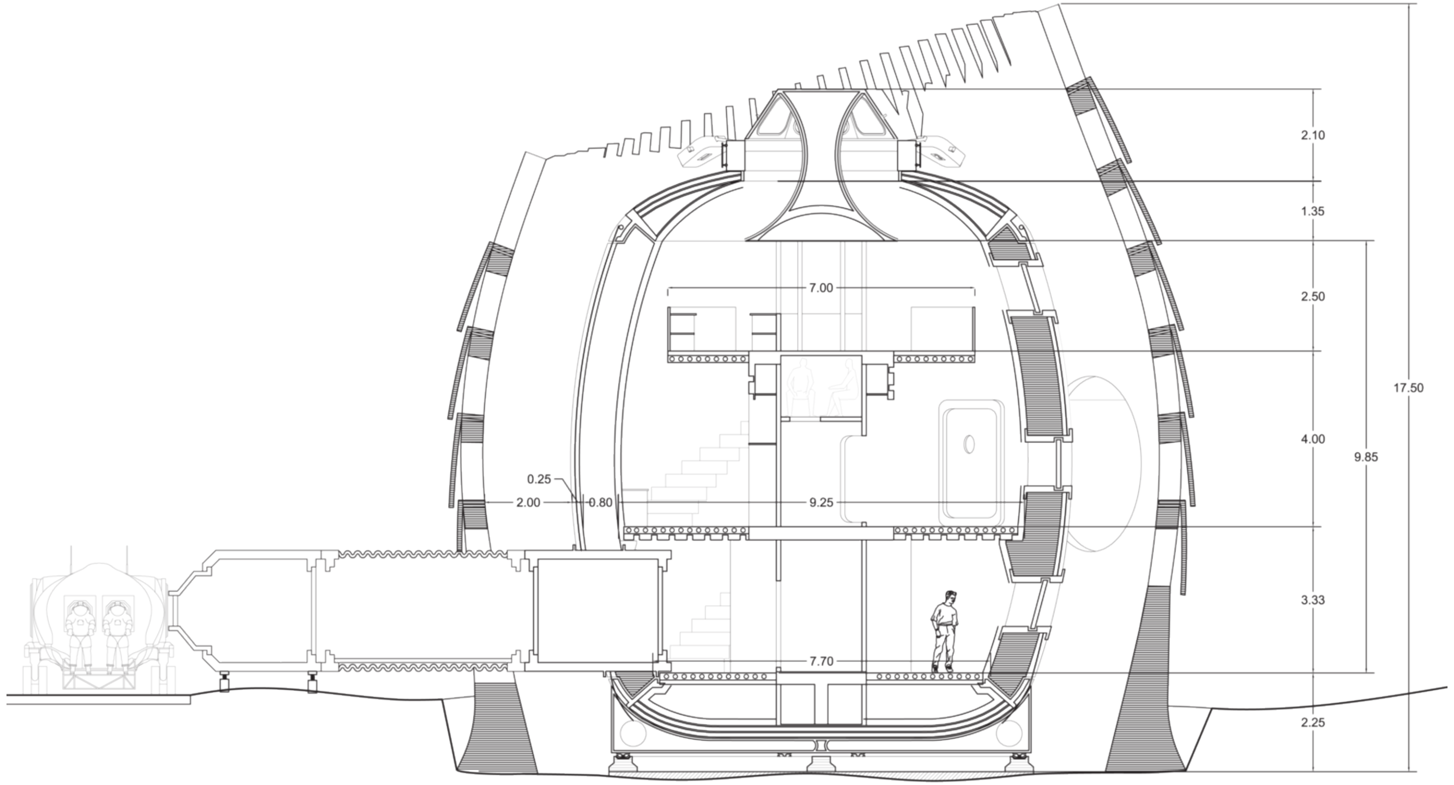


Image source ICON



"The Lunar Lantern, ICON in partnership with SEArch+, NASA."
Image source: ICON

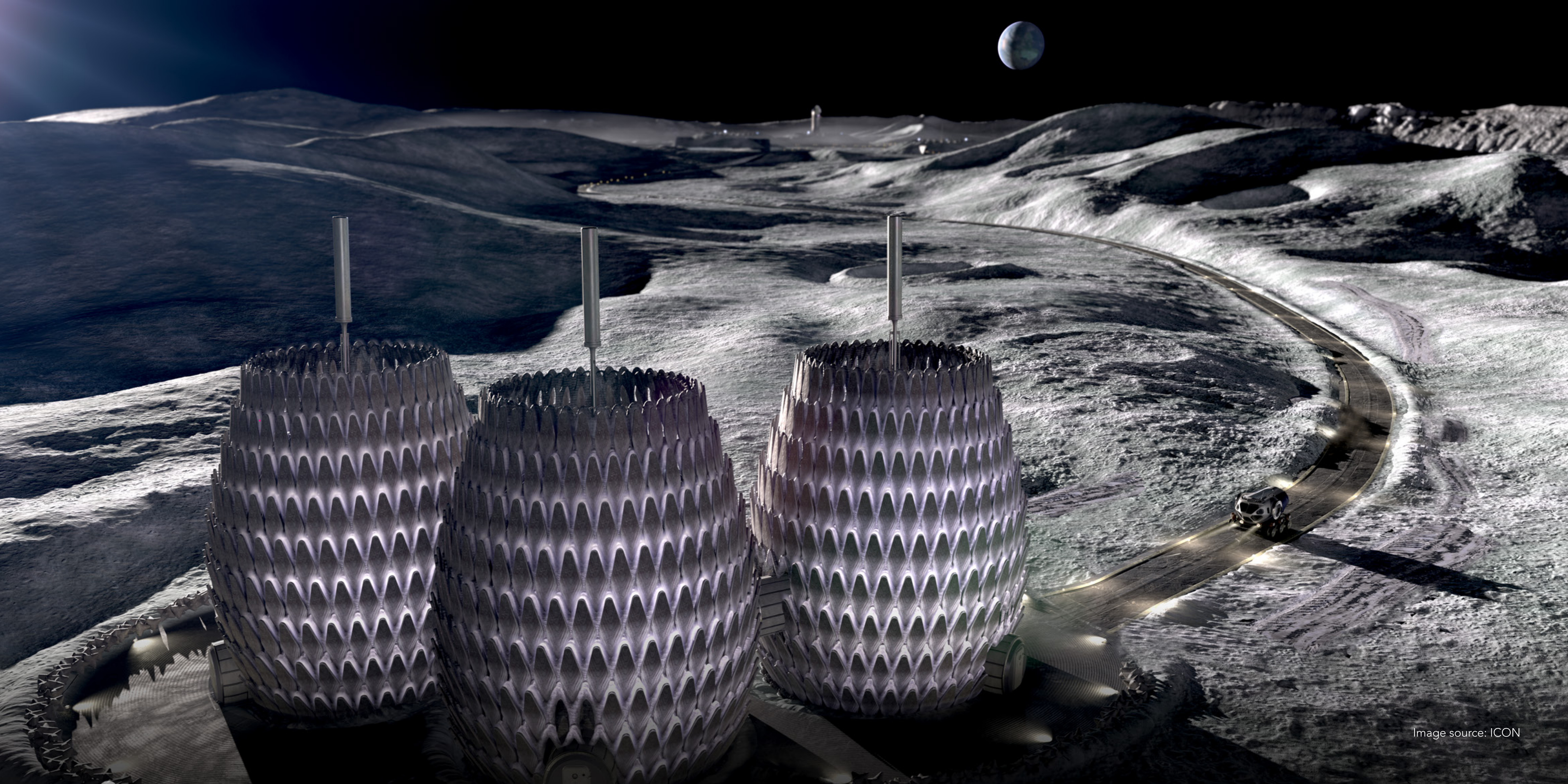


Image source: ICON

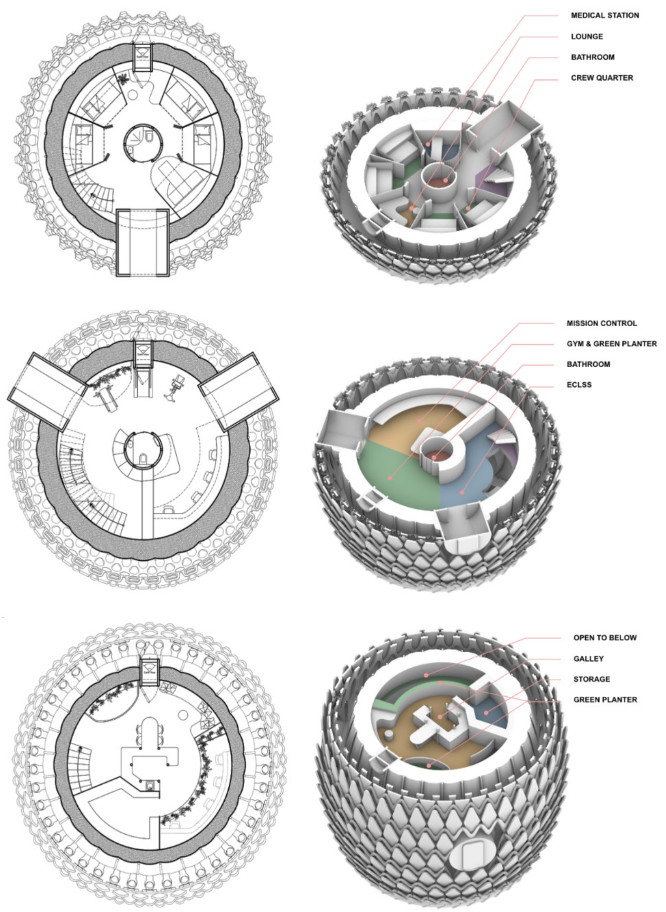
At its core, this initiative celebrates the diversity of human culture. ICON envisions a collaborative effort with artists from various parts of the world, bringing together different artistic traditions and visions to create an international celebration of our shared cultural heritage. Through this collaboration, the Lunar Lantern Project aims to showcase the richness and diversity of human experience.

While the Lunar Lantern Project has artistic and cultural aspects, it also has practical benefits. Besides their visual appeal, the illuminated lanterns will serve as landmarks and guides for future lunar missions and exploration efforts, aiding in navigation and enhancing our understanding of the lunar landscape.

To turn this visionary idea into reality, ICON plans to leverage its expertise in advanced manufacturing and 3D printing technologies. These innovative techniques will allow for precise, efficient, and durable construction of the lunar lanterns, ensuring they can withstand the challenges of the lunar environment.

While the Lunar Lantern Project primarily focuses on art and culture, it is closely tied to broader lunar exploration goals. These sculptures symbolize humanity's commitment to exploration and discovery, sparking curiosity and inspiring future generations to explore beyond our planet.

As we delve into the details of the Lunar Lantern Project, we are impressed by the blend of art, culture, and space exploration it represents. This combination offers a unique perspective,

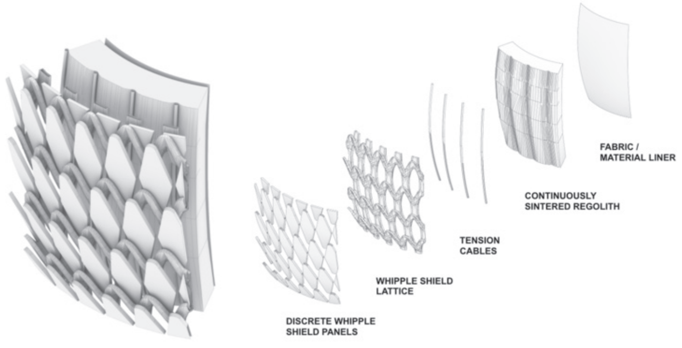


Floor plans of a module
Image source: ICON

reminding us that while scientific progress and technological innovation are essential, art and creativity also should play a crucial role in our designs.

However, it is important to acknowledge the challenges this project may face. The technical complexities involved in designing and building illuminated sculptures that can withstand the lunar environment, along with the logistical challenges of transporting them to the Moon, present significant obstacles that must be overcome.

Nevertheless, the Lunar Lantern Project showcases the harmonious integration of human creativity and scientific exploration, highlighting the potential that arises from interdisciplinary collaboration. It opens up new possibilities for artistic expression, cultural exchange, and exploration.



Whipple Shield design
Image source: ICON

Reference Project 4

Moon Village by ESA & MIT & SOM

Image Source: ESA & MIT & SOM

While researching lunar settlement projects, we came across the ‘Moon Village’ initiative, a collaborative endeavor involving the European Space Agency (ESA), the Massachusetts Institute of Technology (MIT), and Skidmore, Owings & Merrill (SOM). This ambitious project has garnered attention from both scientific and architectural communities.

The Moon Village, crafted through joint efforts by ESA, MIT, and SOM, seeks to establish a permanent human presence on the lunar surface. It reflects humanity’s commitment to advancing space exploration, fostering international collaboration, and setting the foundation for a sustainable lunar society.

At its core, the Moon Village aims to create a lunar base for scientific research, technological innovation, and human habitation. Unlike earlier missions, which were brief visits, this project is dedicated to establishing a lasting lunar presence, encouraging sustained human exploration and permanence beyond Earth.

Central to the Moon Village concept is global cooperation. ESA, MIT, and SOM envision a collective effort involving nations, organizations, and individuals worldwide to collaboratively construct and operate the lunar outpost. This approach highlights the shared objective of expanding humanity’s presence in space.

Architectural design plays an important role in realizing the Moon Village’s vision. SOM, renowned for its architectural expertise, applies

Image Source: ESA & MIT & SOM

innovative design principles to create a lunar habitat that harmonizes with the lunar environment. The design emphasizes sustainability, efficiency, and adaptability, considering the lunar landscape’s unique challenges.

Furthermore, the Moon Village aims for self-sufficiency by utilizing lunar resources and advanced technologies to meet the needs of its inhabitants. Collaborative efforts between ESA, MIT, and SOM have led to inventive solutions, such as 3D printing using lunar regolith, for constructing habitats and infrastructure. This approach reduces dependence on Earth for construction materials and explores the potential of using local resources for long-term lunar habitation.

Beyond its scientific and technological aspects, the Moon Village emphasizes community-building and enhancing residents’ well-being. It envisions a social and cultural environment with shared spaces, recreational facilities, and opportunities for collaborative activities, promoting friendship and connection among its residents.

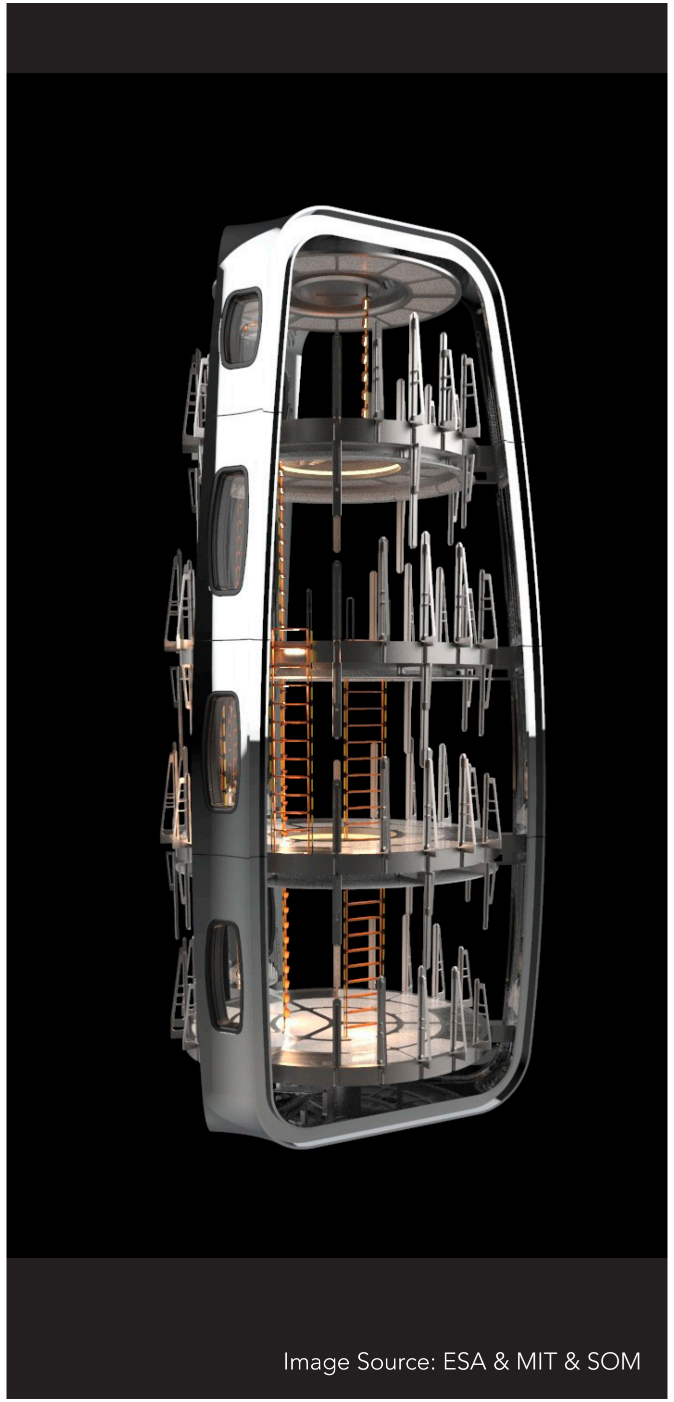


Image Source: ESA & MIT & SOM

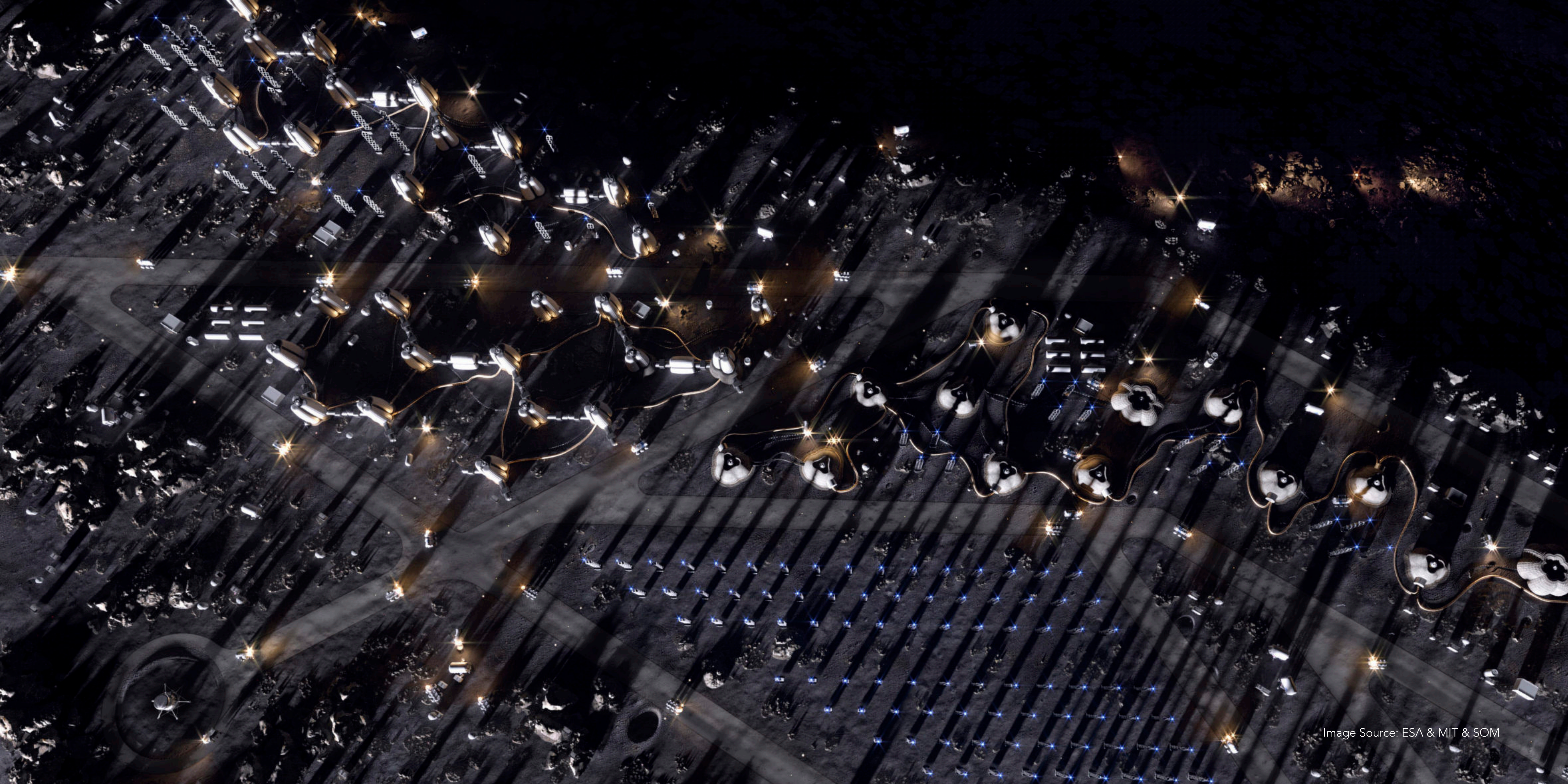
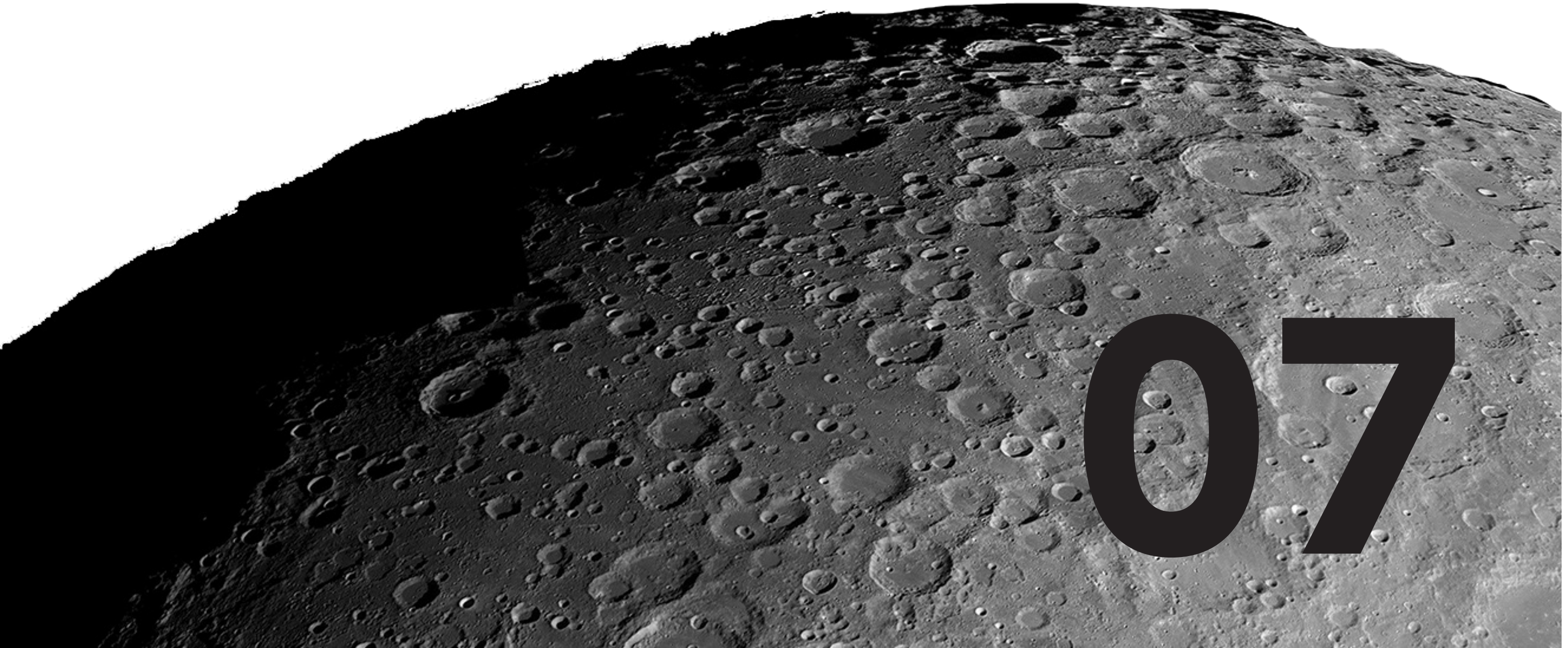


Image Source: ESA & MIT & SOM

Site decision 2: Amundsen



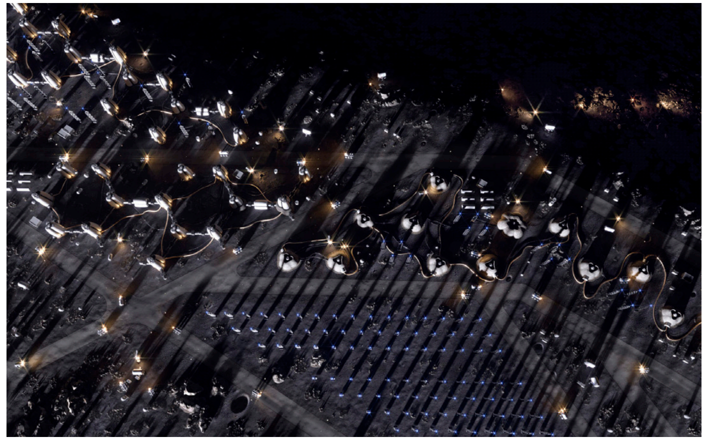
After deciding on the project site in a lunar lava tube, we decided to analyze the potential disadvantages of construction in a lava tube, since the reference projects we examined in detail in the previous chapters such as; Lunar Lantern, Project Olympus, Moon Village, are all on the lunar surface.

While construction in lunar lava tubes offers certain advantages, there are also several disadvantages associated with it. Here are some notable disadvantages that we found:

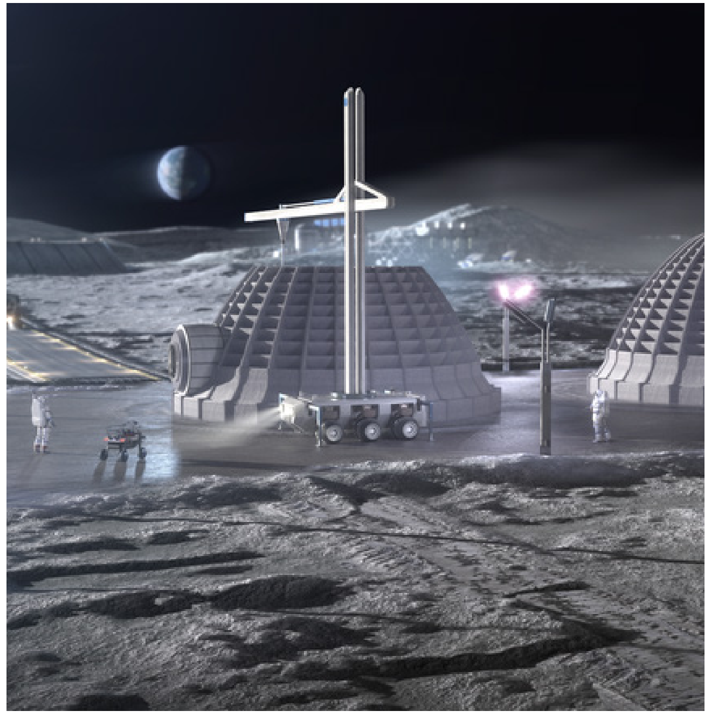
Limited Availability: Lunar lava tubes are not uniformly distributed across the Moon's surface. Their presence is largely concentrated in specific regions. This limited availability can restrict the options for constructing habitats or facilities in desired locations (Sibille, Saeed, Bouledroua, & O'Connor, 2020).

Accessibility Challenges: Lunar lava tubes are located underground, which poses significant challenges in terms of access and transportation. Excavating and establishing entry points to reach the tubes can be technically complex and resource-intensive, requiring specialized equipment and considerable effort (Hura & Zamani, 2019).

Structural Instability: Although we explained in the previous chapter how stable the lava tubes are, we found out that there are also discussions about the instability that can happen due to natural phenomena which can be dangerous for the lunar settlement.



"Moon Village by ESA & MIT & SOM, Master plan established on Lunar Surface."
Image Source: SOM



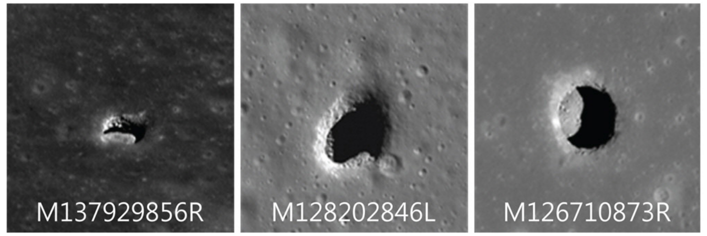
"Lunar Lantern by ICON, View of 3D printing process on Lunar Surface. "
Image Source: ICON

Over time, the stability of the lava tube ceilings and walls can be compromised due to various factors such as seismic activity, thermal stress, and geological processes. This instability can pose risks to the integrity of constructed structures within the lava tubes.

Geological Uncertainties: Our understanding of lunar lava tubes is still limited, and there are uncertainties regarding their dimensions, stability, and composition. Conducting thorough surveys and assessments is necessary to determine the feasibility and safety of construction in specific lava tubes. The geological complexity of the Moon presents challenges in predicting potential hazards, which can impact construction projects (Blair, Alemán, & Caruso, 2013).

Limited Space and Constraints: Lunar lava tubes, while offering the potential for large enclosed spaces, still have inherent limitations in terms of available usable area. The irregular shapes and dimensions of the tubes may restrict the size and configuration of structures that can be built within them. This constraint could limit the scalability and versatility of construction projects on the Moon (Povinelli et al., 2019).

Infrastructure Requirements: Establishing a construction site in a lunar lava tube would require substantial infrastructure development. This includes creating a suitable life-support system, power supply, communication networks, and transportation mechanisms to and from the site.



"Lunar large scale pit craters. Marius hills(left), Mare Ingenii(-center), Mare Tranquillitatis(right)."
Image Source: Journal of Astronomy and Space Sciences Volume 31, Issue2, p131~140, 15 June 2014 Lunar Pit Craters Presumed to be the Entrances of Lava Caves by Analogy to the Earth Lava Tube Pits,

Location	Marius Hills	Mare Ingenii	Mare Tranquillitatis
Latitude	14.09°N	35.95°S	8.33°N
Longitude	55.77°W	166.05°E	33.22°E
Diameter	65 m	120 m	100 m
Depth	36 m	60 m	100 m

"Lunar large scale pit crater information."

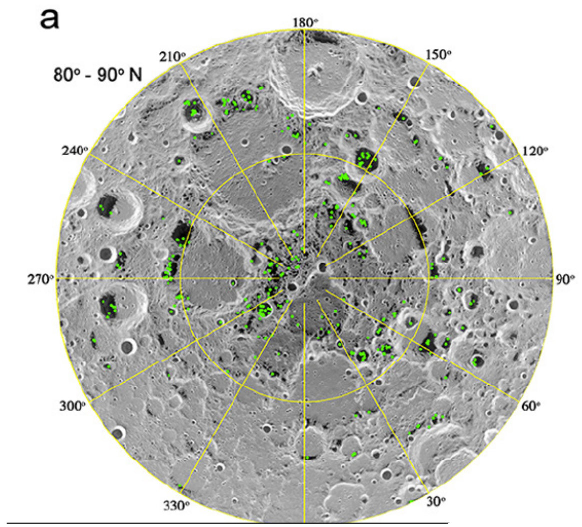
Image Source: Journal of Astronomy and Space Sciences Volume 31, Issue2, p131~140, 15 June 2014 Lunar Pit Craters Presumed to be the Entrances of Lava Caves by Analogy to the Earth Lava Tube Pits,

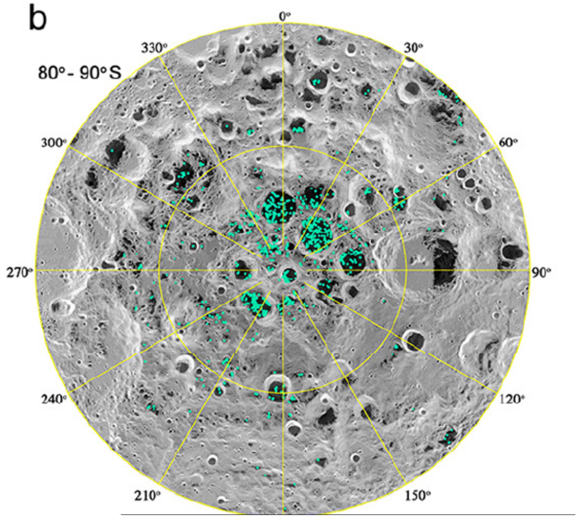
Building and maintaining such infrastructure would involve significant resources and logistical challenges (Hura et al., 2017).

Cost and Complexity: Construction in lunar lava tubes would be a technologically demanding and cost-intensive endeavor. The development of specialized equipment, tools, and construction techniques suitable for the lunar environment would require significant investment. Also, the complexity of operating in a remote and harsh lunar environment adds to the overall cost and logistical complexity of construction projects (Hura et al., 2017).

Due to the disadvantages mentioned above, we decided to design the settlement on the lunar surface.

After making this decision, we decided to research which pole of the Moon is more suitable for a settlement. We realized that there are many factors to consider such as PSR, topography, and water sources which will be explained in detail in the next pages.

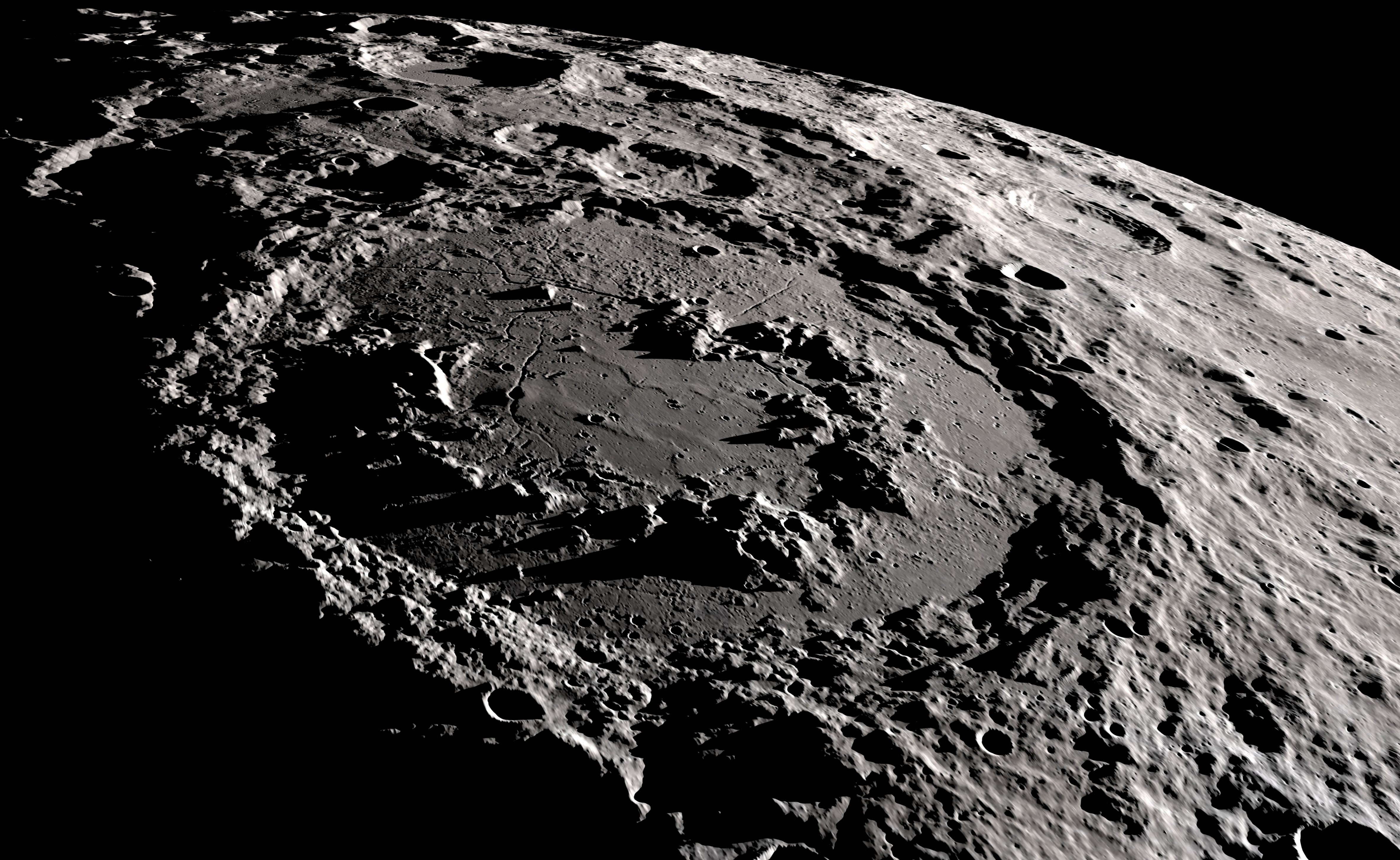




"Topographic map of lunar poles shows PSR."
Image Source: Shuai Li, Brown University

“Orbital perspective of the lunar south pole as viewed looking from the North and over the lunar farside surface. The south polar region is a heavily cratered terrain, with dramatic topography, rather than the relatively flat lava flow surface that characterized the Apollo 11 landing site. The South Pole, at the top of the image, is on the rim of the 21-km-diameter Shackleton Crater, which is not easily discerned from shadows in this oblique perspective.”

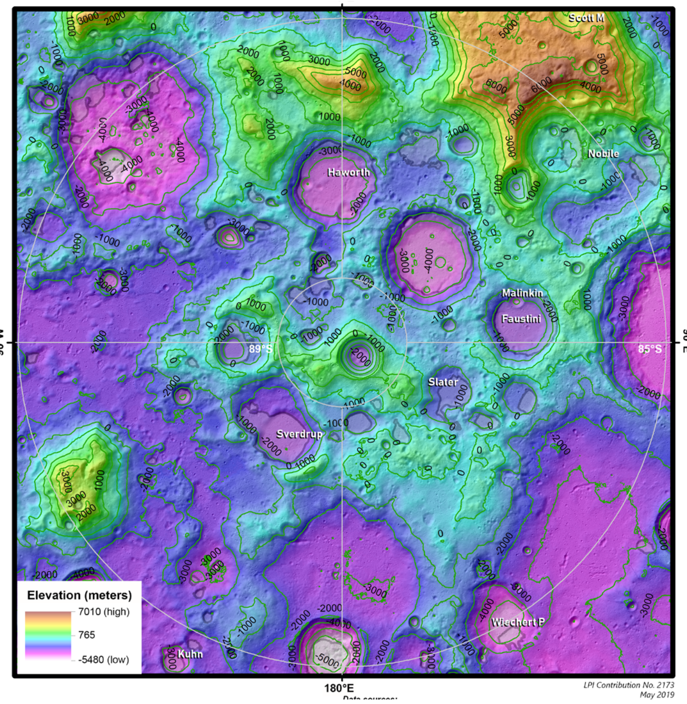
Image Source: NASA GSFC Scientific Visualization Studio.



Why the South Pole?

1. Sunlight: The South Pole has regions known as peaks of eternal light, which are areas that receive nearly continuous sunlight. These areas are located on the rims of some craters near the lunar poles. Continuous sunlight is advantageous for several reasons. First, it provides a reliable and constant energy source for power generation using solar panels. This energy can be used to operate equipment, power life support systems, and scientific instruments. Second, consistent sunlight allows for more efficient utilization of solar power, as there are no prolonged periods of darkness that would require energy storage or alternative power sources (Calle & Sotin, 2006).

2. Resources: The South Pole is believed to have abundant water ice deposits in permanently shadowed regions of its craters. These regions receive almost no direct sunlight, which means constant low temperatures that allow water molecules to freeze and accumulate as ice (Li et al., 2020). Water is an invaluable resource for human presence on the Moon. It can be melted and filtered to use for drinking, and growing plants in controlled environments, and also water molecules can be split into its atoms to be used as a source of oxygen and hydrogen for breathing and rocket propellant production (Duke & Brinton, 2006). Having access to local water resources reduces the need for transporting water from Earth, which is costly and resource-intensive.



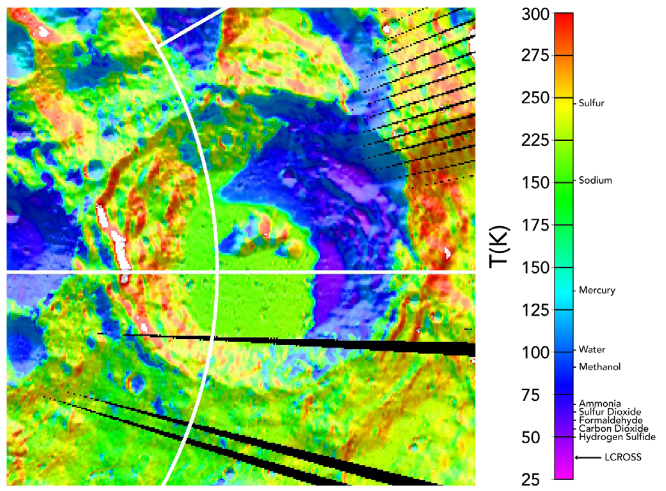
"This map is based on data released by the Lunar Reconnaissance Orbiter Lunar Orbiter Laser Altimeter (LOLA). The map is centered on the south pole and shows the LOLA 20-m elevation product between 85°S and the pole (NASA Goddard Space Flight Center; Smith et al., 2010; Smith et al., 2017). The elevation data are overlain on a derived hillshade with solar azimuth 45°W and solar elevation 45°. Permanently shaded Regions (PSRs) larger than 10 km2 digitized by Arizona State University and determined by Mazarico et al. (2011) are shown as gray outlines. 1000-m elevation contours (relative to global radius) are shown as green lines with elevations marked. Polar stereographic projection is used with scale true at the pole. Selected feature names are included on the map."

Image source: Stopar J. and Meyer H. (2019) Topography and Permanently Shaded Regions (PSRs) 85°S to Pole of the Moon, Lunar and Planetary Institute Regional Planetary Image Facility, LPI Contribution 2173,

3. Accessibility: The South Pole of the Moon offers several advantages in terms of accessibility. Firstly, it has relatively flat terrains compared to the North Pole, which simplifies construction and infrastructure development. This reduces the need for extensive site preparation and leveling, making it easier to establish structures and installations. Secondly, the presence of water ice in nearby craters means that the resources required for sustaining a lunar base are readily available in the vicinity (Foing & Almeida, 2015). This reduces the distance needed to transport and extract resources, making logistics and operations more efficient.

4. Communication: The South Pole has better line-of-sight communication with Earth compared to the North Pole. Because the Moon's rotation is such that it always keeps the same face toward Earth, maintaining a direct line of communication is crucial for real-time communication and data transmission. The South Pole's location provides better visibility of Earth-based communication antennas, enabling faster and more reliable communication between lunar missions and Earth (Deutsch & Javadian, 2017). This is particularly important for scientific research, remote operations, and maintaining the overall coordination and safety of lunar activities.

5. Potential for extended stays: The combination of favorable sunlight conditions, availability of resources like water ice, and relatively hospitable terrain make the South Pole a suitable location for establishing a long-duration lunar



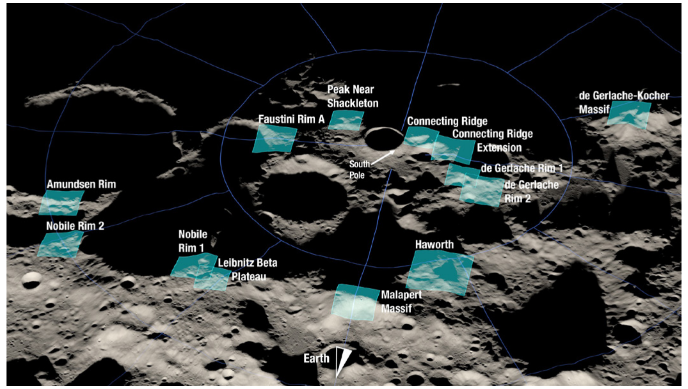
"This temperature map from the Diviner instrument on the Lunar Reconnaissance Orbiter shows the locations of Amundsen crater that are potential cold traps for water ice as well as a range of other icy compounds commonly observed in comets. Image source: NASA/GSFC/UCLA |"

base. The presence of continuous sunlight enables sustained power generation, while the presence of water ice allows for self-sufficiency in terms of water and potentially fuel production. The relatively flat terrain and proximity to resources make it easier to construct and maintain the necessary infrastructure for a sustainable lunar outpost. This could serve as a hub for further exploration and utilization of lunar resources, supporting extended stays and expanding human presence on the Moon.

6. Artemis Mission: As we will be explaining in detail in the next chapters (Page 90), we decided to integrate the project with Artemis missions. The potential landing sites of the Artemis program are located at the South Pole. For this reason, it seems more appropriate to choose the location of the project at the South Pole.

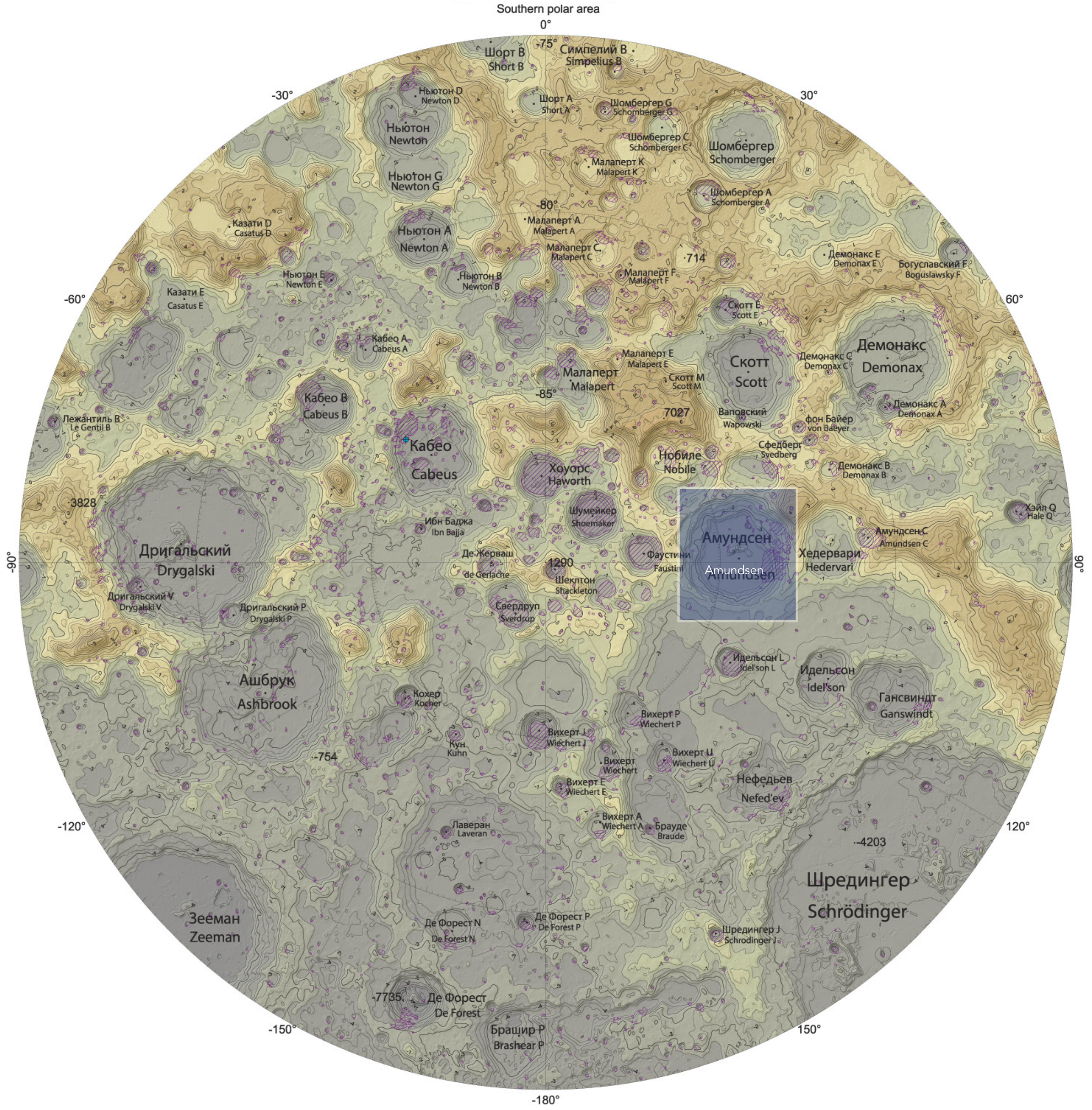
However, the North Pole also has areas with permanently shadowed regions and potential water ice deposits so it is important to note that both poles have their own unique characteristics and advantages. Future missions and research will provide more detailed information, enabling a better understanding of both poles and their suitability for lunar construction.

Finally, after the research we have done, we came to the conclusion that the South Pole of the Moon is more suitable for lunar construction in terms of sunlight, resources, accessibility, communication, vicinity to Earth, potential for long-term stays, and integrability with Artemis Program.



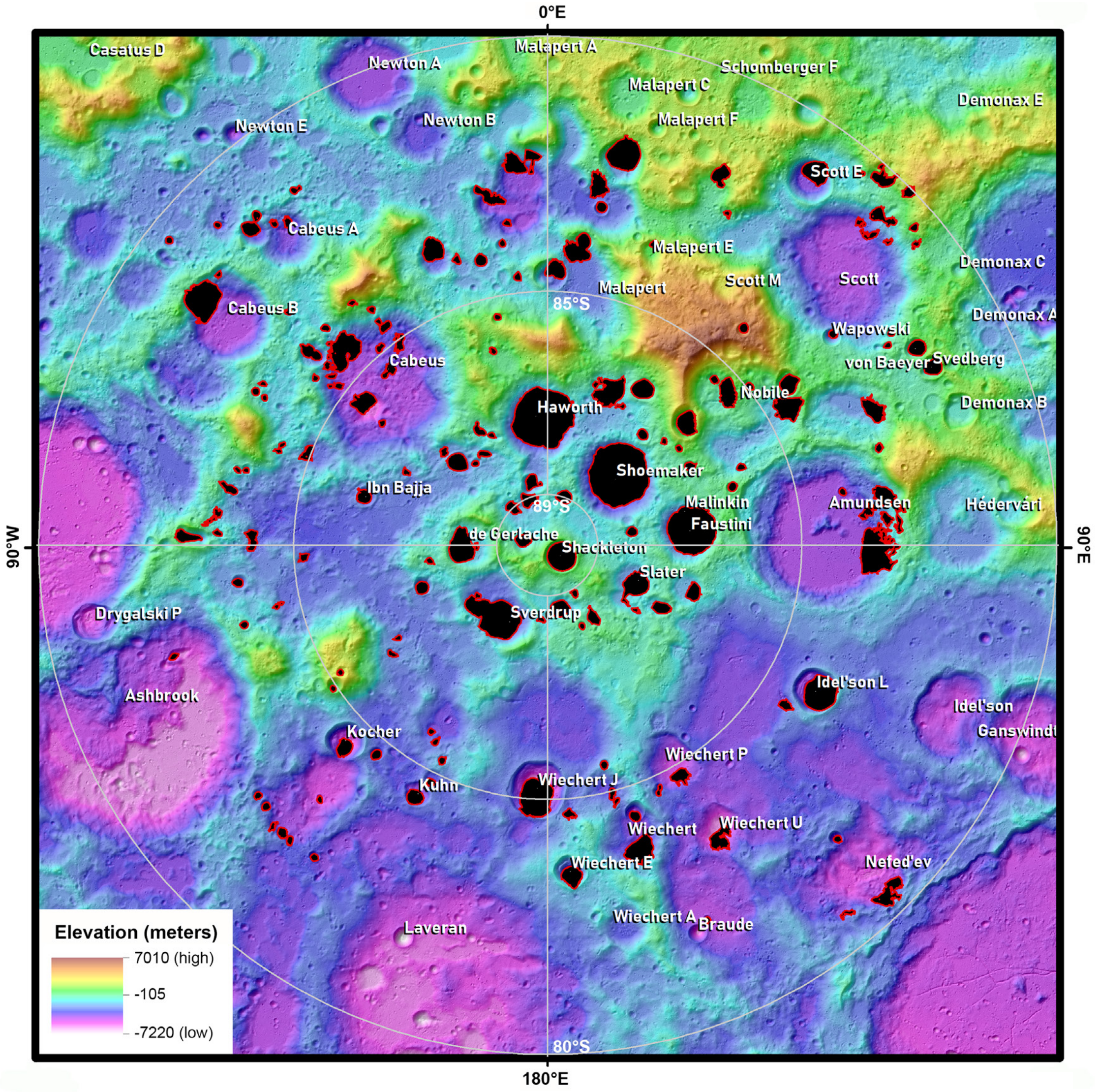
"The lunar south polar region has been a target of exploration since the late 1990s when the Lunar Prospector (LP) spacecraft imaged illuminated summits and topographically low permanently shadowed regions (PSRs), including the PSR within Shackleton crater at the lunar south pole. At the end of the LP mission, the spacecraft was intentionally crashed into the PSR within Shoemaker crater on July 31, 1999. That impactor concept was employed again by the Chandraya'an 1 mission, which carried a 35 kg payload called the Moon Impact Probe (MIP). That probe hit the surface November 14, 2008. When the Lunar Reconnaissance Orbiter was launched, there was an opportunity to carry a second vehicle. Thus, the Lunar Crater Observation and Sensing Satellite (LCROSS) was launched. In this experiment, a 2000 kg Centaur upper stage was crashed into the surface, followed by a trailing spacecraft (s/c) designed to measure any excavated volatile material. Both vehicles hit the surface within Cabeus crater October 9, 2009. The debris from those spacecraft will certainly be encountered by future explorers to the lunar south polar region."

Image source: LPI/CLSE (David A. Kring)

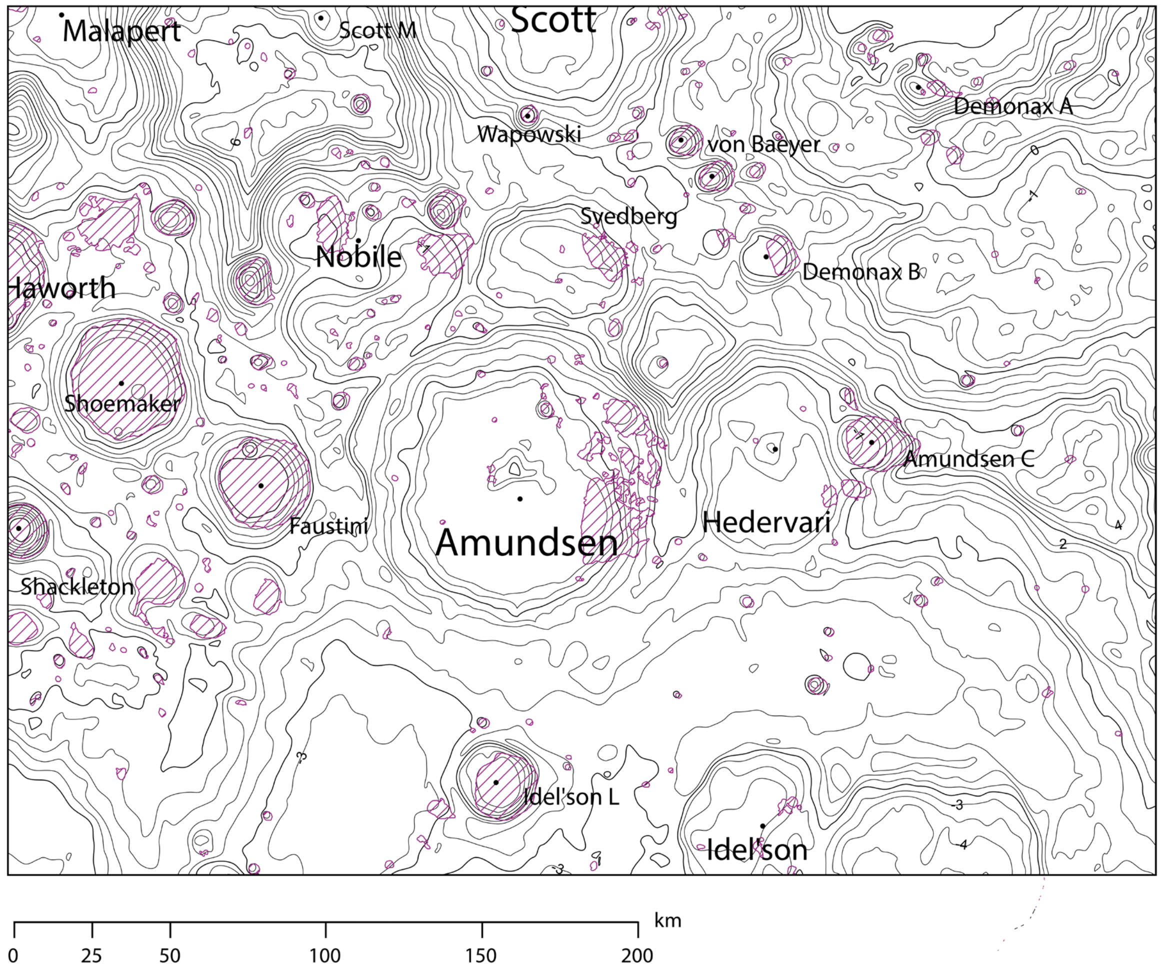


"Topographic maps provided courtesy of Moscow State University of Geodesy and Cartography (MIIGAiK). The maps include the lunar polar regions to 75°. The maps are based on Lunar Reconnaissance Orbiter Lunar Orbiter Laser Altimeter (LOLA) and SELENE (Kaguya) data, and include feature names. Polar stereographic projection is used with scale true at the pole. Relief of features and supplementary maps of proposed Luna 25 landing sites in Boguslawsky crater are also included."
Image source: Kokhanov A. A., Rodionova Zh. F., and Karachevtseva I. P. (2016) Hypsometric Map of the Lunar Polar Areas, Moscow State University of Geodesy and Cartography (MIIGAiK).

Topography and Permanently Shaded Regions (PSRs) of the Moon's South Pole (80°S to Pole)



"This map is based on data released by the Lunar Reconnaissance Orbiter Lunar Orbiter Laser Altimeter (LOLA). The map is centered on the south pole and shows the LOLA 20-m elevation product between 80°S and the pole (NASA Goddard Space Flight Center; Smith et al., 2010; Smith et al., 2017). The elevation data are overlain on a derived hillshade with solar azimuth 45°W and solar elevation 45°. Permanently shaded regions (PSRs) larger than 10 km2 digitized by Arizona State University and determined by Mazarico et al. (2011) are shown as red outlines with black fill. Polar stereographic projection is used with scale true at the pole. Feature names are included on the map."
Image source: Stopar J. and Meyer H. (2019) Topography and Permanently Shaded Regions (PSRs) of the Moon's South Pole (80°S to Pole), Lunar and Planetary Institute Regional Planetary Image Facility, LPI Contribution 2170.



Cartographer: Kokhanov A.A.
Editors: Rodionova Zh. F., Karachevtseva I.P.
Published with support of
Russian Science Foundation (project №14-22-00197)

Legend

· Craters

—1— Contours in 0.5 km

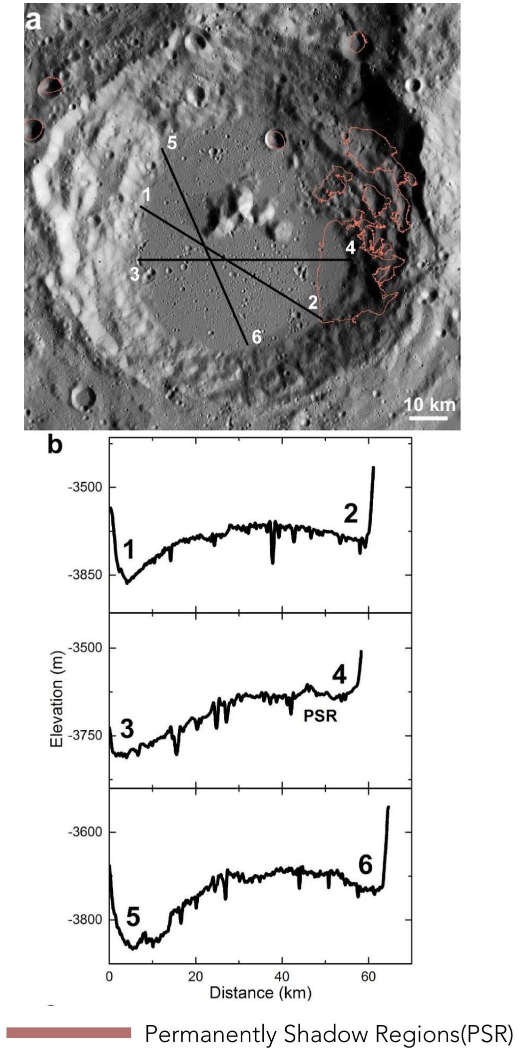
Permanently shadowed areas

Amundsen Crater is a large impact crater located near the South Pole of the Moon. It has been identified as a potential site for future lunar activities, including construction and resource utilization. Here are some key points regarding Amundsen Crater and its significance for lunar construction:

Location and Size: Amundsen Crater is located near the lunar south pole, it has a potential for building a settlement due to its permanently shadowed regions. It has a diameter of approximately 100 kilometers and a depth of about 4 kilometers. The presence of permanently shadowed areas is of particular interest for potential lunar construction due to the possibility of water ice deposits (Fa et al., 2021).

Permanently Shadowed Regions: The PSRs also offer protection from extreme temperature variations on the Moon's surface (Nozette et al., 1996).

Water Ice Deposits: One of the primary reasons for considering Amundsen Crater for lunar construction is the presence of water ice in the permanently shadowed regions. Water is a crucial resource for establishing a lunar base and sustaining human presence on the Moon, as it can be used for drinking, growing plants, and electrolysis to produce oxygen and hydrogen for fuel. Extracting and utilizing water from these ice deposits would be a key component of any lunar construction activities in the area. Water can be processed and used for life support systems, as well as radiation shielding when combined with regolith (Spudis et al., 1998).

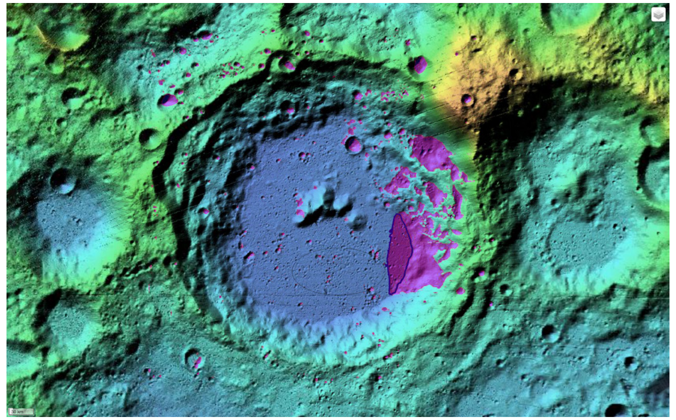


"a) LRO-WAC and LOLA blended image of Amundsen crater with PSR regions overlaid. b) The topographic profiles taken along three sides suggest possible uplift within the crater. The PSR present on the eastern side of the crater floor is partially located within this uplifted region."
Image source: 53rd Lunar and Planetary Science Conference (2022)

Radiation Shielding: The crater's topography, including its rims, provides natural shielding from cosmic and solar radiation, which is critical for the safety of lunar inhabitants (Cucinotta et al., 2005).

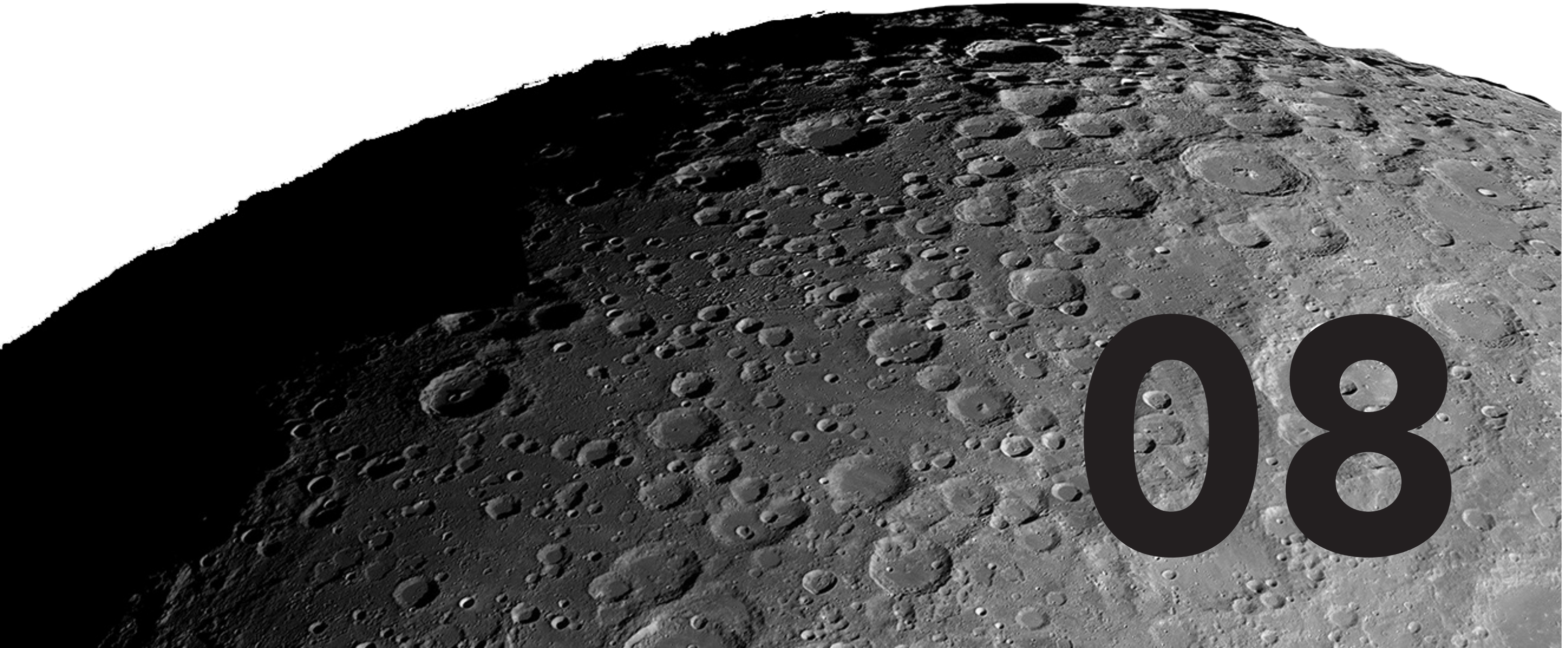
Scientific Exploration: In addition to its potential for construction, Amundsen Crater also holds scientific value. The permanently shadowed regions are believed to have preserved ancient materials, including potential volatiles and organic compounds (Mazarico et al., 2014). Studying these resources can provide insights into the history of the Moon and the solar system.

To conclude, Amundsen Crater has significant potential for lunar construction. The Artemis program led by NASA and other international space agencies aims to return humans to the Moon, and future missions will likely assess various lunar sites for their suitability for construction and resource utilization.



"Topography Stalite Image of Amundsen Crater shows the permenantly shadowed regions."
Image Source: https://ceias.nau.edu/capstone/projects/CS/2020/CartoCosmos-S20/demo/index.html

Document Mapping



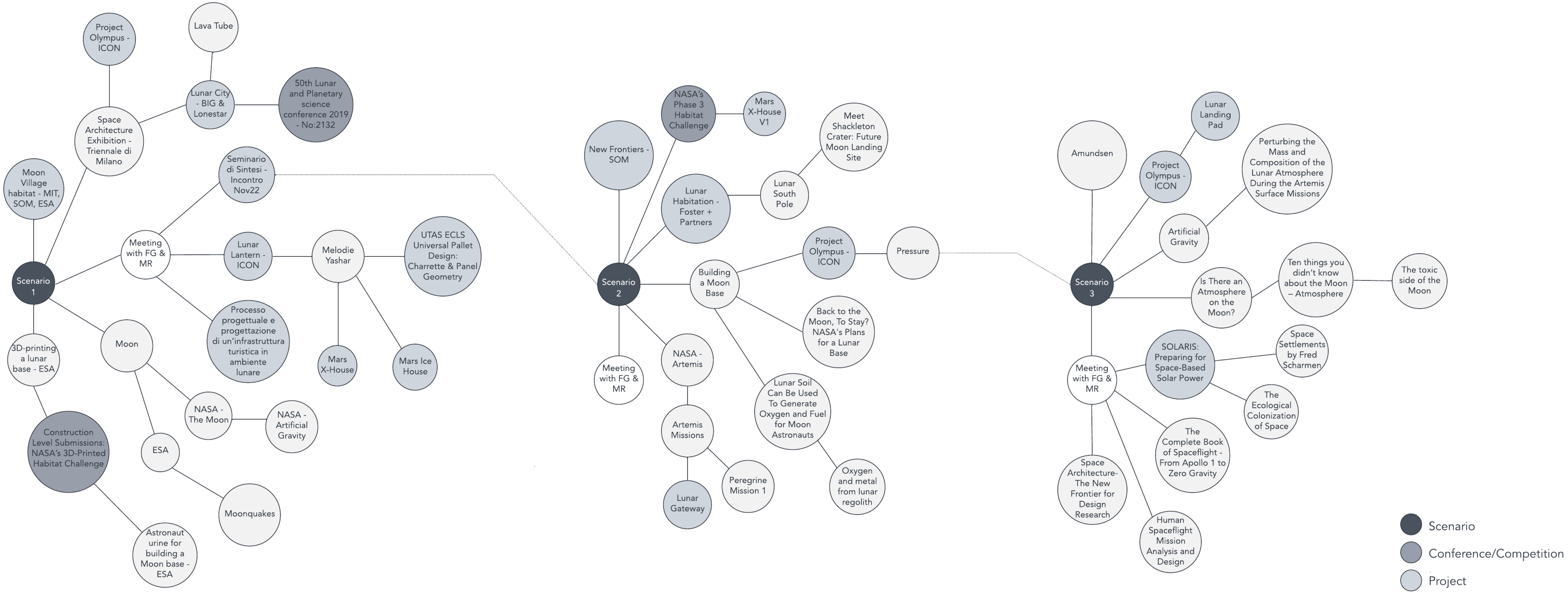
Our design process results from thoughtful consideration of each significant step in creating a lunar settlement. Understanding how our ideas evolved throughout our design's development is crucial for this project and provides a comprehensive overview.

On the next page, the diagram illustrates how we have documented our progress through three different scenarios. Within this diagram, we can see key discoveries that have influenced the direction of our design process. These include projects, articles, meetings, and seminars, which collectively guide our design work.

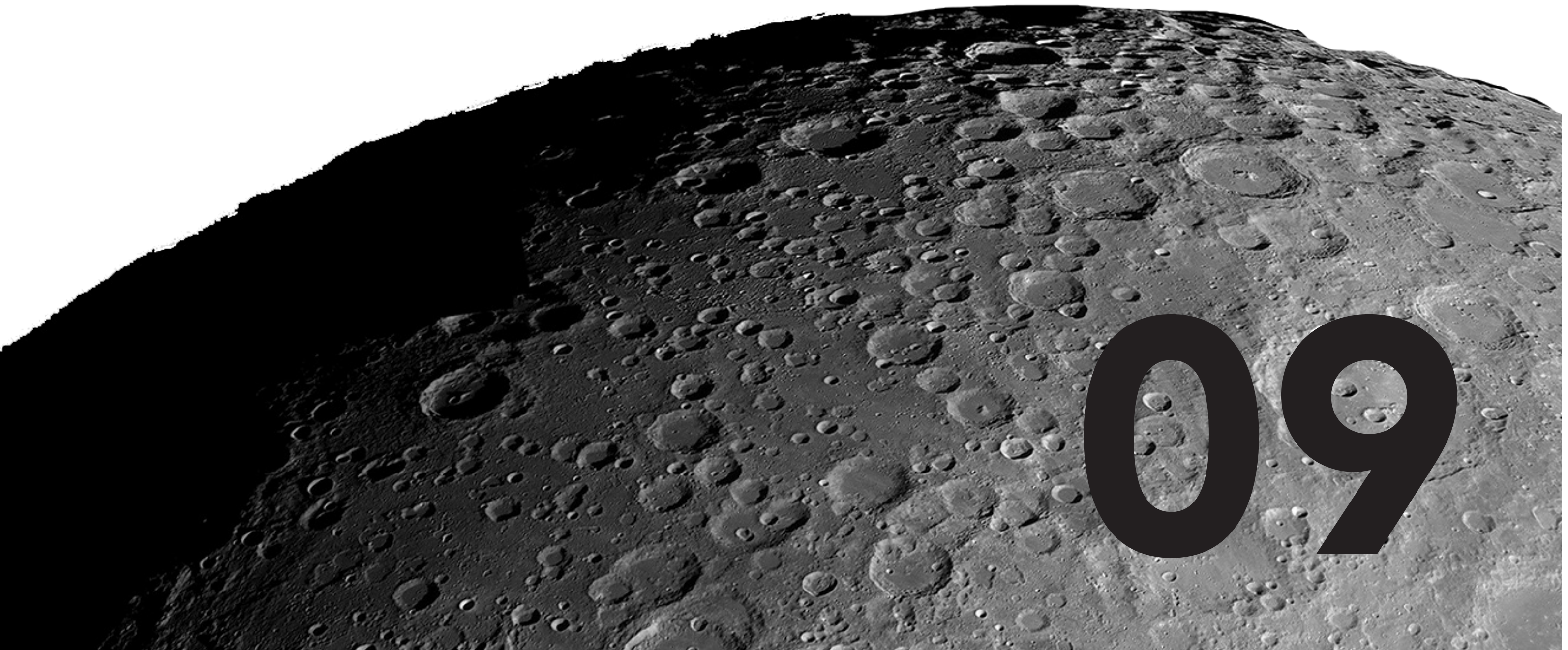
The diagram not only highlights essential elements of our design journey but also indicates crucial moments when we decided to transition between scenarios. For instance, we visually represented the shift from scenario one to scenario two, initiated during the "Seminario di Sintesi." This decision was influenced by valuable insights from our professors' feedback during the seminar. This connection illustrates the dynamic nature of the design process, where informed decisions are shaped by the guidance and evaluations received, ultimately defining the project's course.

Diagram of Document Mapping

Diagram by E. N. Yavuz & E. Kirmiziyesil, 2023



Design Scenario 2



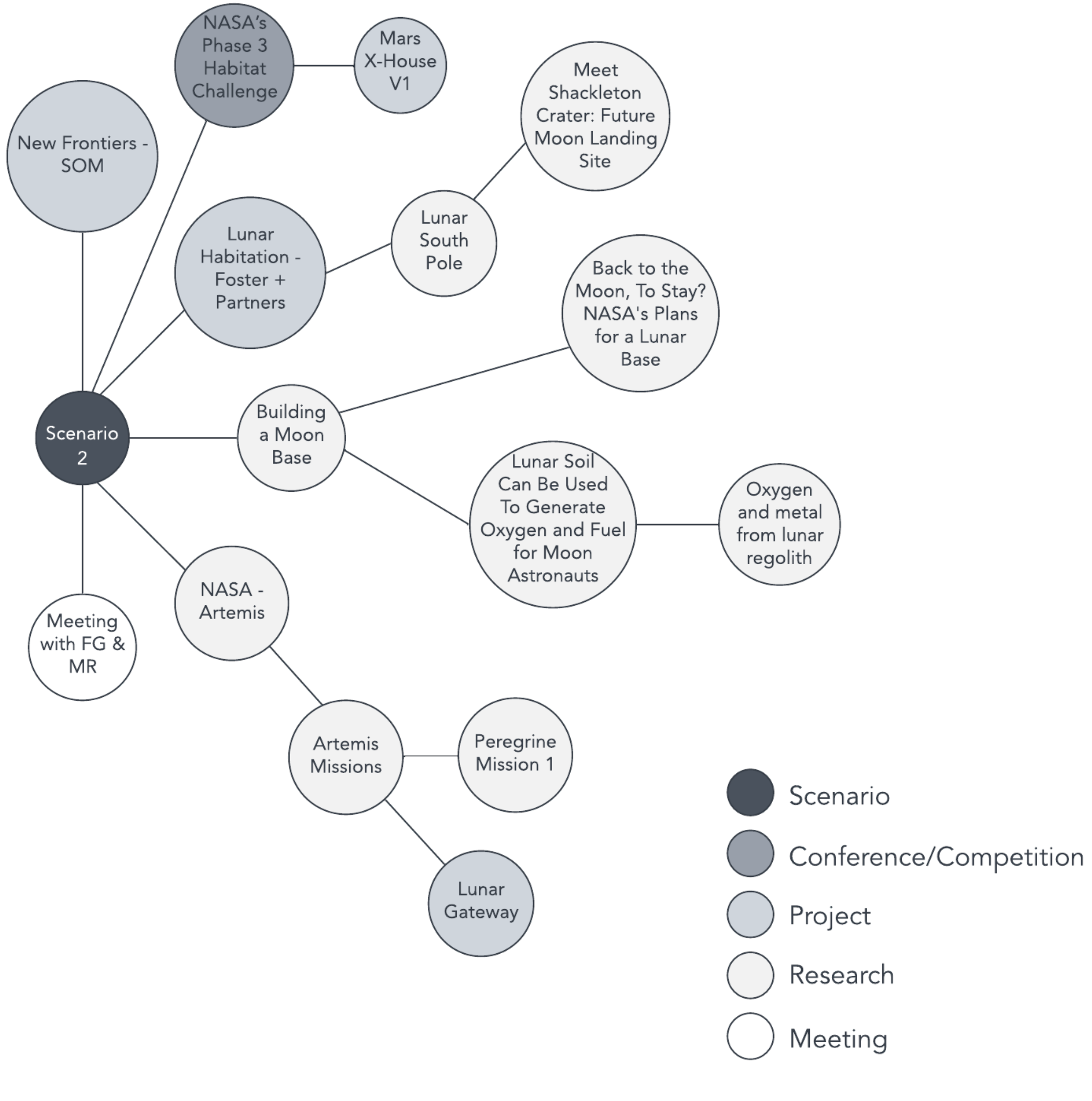


Diagram by E. N. Yavuz & E. Kirmiziyesil, 2023

Moon Habitation Phases Version 3

Artemis Program Integration

Reorganization of Timeline

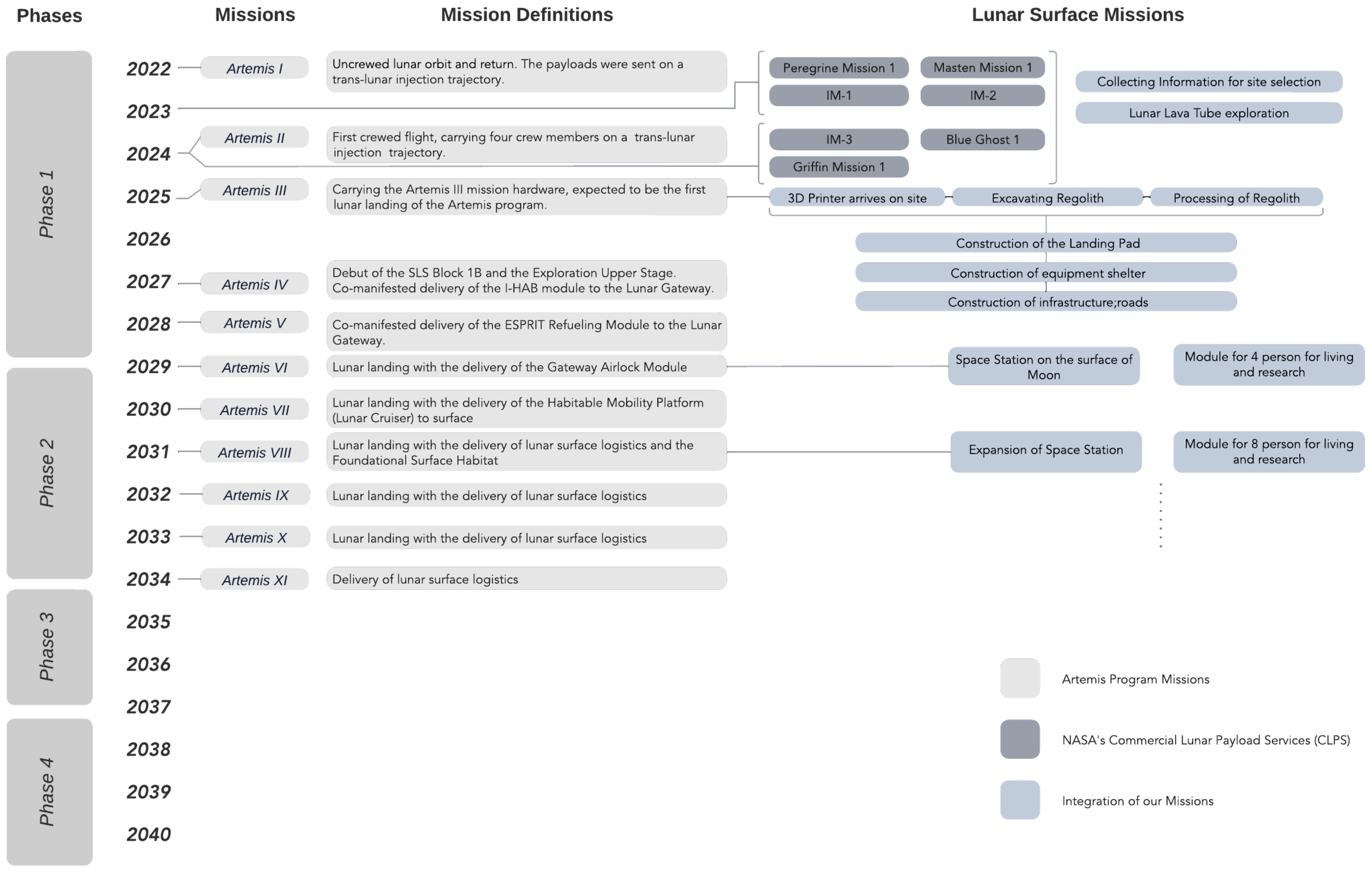
While determining the Moon habitation phases, we aimed to be integrated with the Artemis program. That is why we added the “Exploration” phase in addition to the other phases. At this stage, we created a process by considering the lunar surface missions aimed by the Artemis program. Also, considering the feedback we received at the seminar, we decided to continue the design process with the Moon station. Detailed explanations of the phases seen in the timeline are as follows:

Phase 1: Exploration (2022-2028)

During this initial phase, our focus is on gathering essential information and conducting extensive research. We aim to gain a deeper understanding of the lunar environment, including its geological features, resources, and potential challenges. The data collected will serve as a foundation for the subsequent phases, enabling us to make informed decisions and plan effectively.

Phase 2: Space Station (2029-2034)

In the second phase, our objective is to establish a temporary space base on the lunar surface. This base will serve as a stepping stone towards further exploration and development. By setting up a functioning outpost, we can conduct experiments, test technologies, and study the long-term effects of living in a lunar environment. It will provide valuable insights and pave the way for subsequent phases.



Created by E. N. Yavuz & E. Kirmiziyesil, 2023

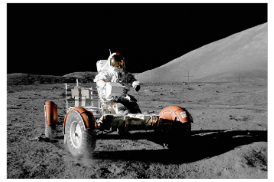
Phase 3: Living for Experts (2035-2045)
The third phase involves the creation of a habitat for space station workers and astronauts. This habitat will expand over time, accommodating a growing number of individuals. The focus will be on developing sustainable life-support systems, efficient resource management, and ensuring the well-being of the inhabitants. The knowledge gained from the previous phases will be crucial in constructing a reliable and self-sufficient lunar living environment.

Phase 4: Touristic Resort (2046-2055)
As the lunar infrastructure becomes more established, the fourth phase aims to introduce controlled tourism to the Moon. In this stage, a tourist resort will be constructed, providing a unique and awe-inspiring experience for a limited number of civilians. This controlled inflow of visitors will help refine the infrastructure and operational procedures while preparing for the next phase.

Phase 5: Permanent Living (2056 onwards)
The fifth and final phase presents an entirely new chapter in lunar colonization. With the foundation laid by the previous phases, we will transition from temporary stays to permanent life on the Moon. This phase will offer individuals the opportunity to reside on the lunar surface permanently, with all the necessary facilities and infrastructure in place. It will open up new horizons for human civilization, pushing the boundaries of exploration and providing a platform for scientific research and discovery.

1 1st Phase

Exploration

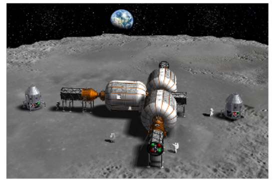


Collecting datas on the surface of Moon.

- *This phase will be carried out in an integrated manner with the Artemis program.*
- *Material and feasibility studies will be carried out on the lunar surface.*
- *It also includes getting the 3D printer to the lunar surface with Artemis 3 and building a construction pad.*

2 2nd Phase

Space Station



Space Station on the surface of Moon.

- *Developments for the construction of extraterrestrial buildings*
- *Only for experts and astronauts*
- *Studies on the lunar surface and collecting information on whether it is suitable for life*
- *Collection and research of materials to be used in 3d printer*

3 3rd Phase

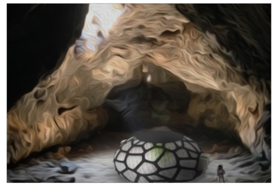
Living for experts

Expansion and re-purposing of 2nd phase.

- *A small city for experts, astronauts and their families in which the needs such as work, education, health and entertainment will be met.*

4 4th Phase

Touristic Resort

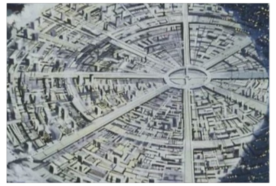


Touristic resort in lunar lava tube.

- *A complex that will bring unforgettable experiences to its visitors*
- *A 20-room lava tube tourist resort*

5 5th Phase

Permenant Living



Expansion of 3rd phase.

- *Living units for civilians.*
- *Offices, schools, hospitals, areas for leisure activities*
- *Construction of a transportation hub for Mars and other planets.*

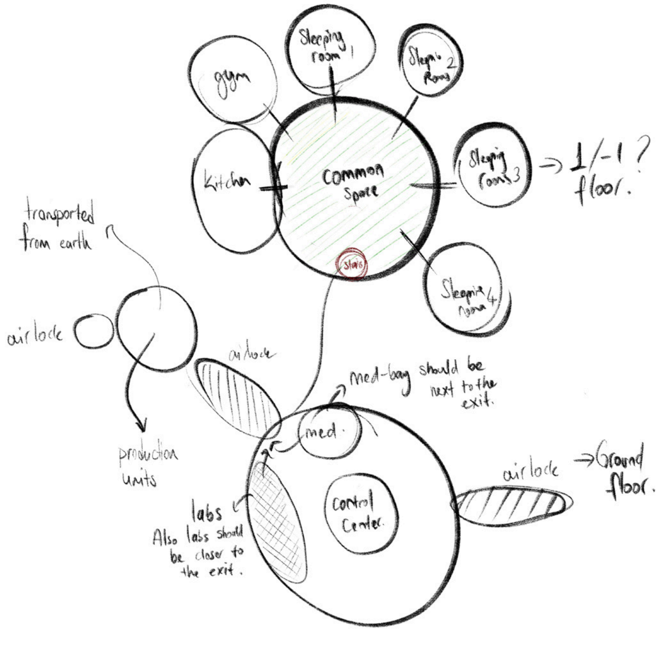
The realization of these phases will not only contribute to the advancement of space exploration but also hold the potential to shape the future of humanity.
Phases Diagram Version 3
Created by E. Kırmızıyeşil, E. N. Yavuz, 2023

Functions

As outlined in the phase diagram on the previous page, once the decision was made to pursue the development of the space station, our focus shifted towards researching the necessary functions and spaces that should be incorporated into this station. During this phase, we referred back to the projects we had previously studied. Additionally, we conducted an analysis to identify the various technical spaces essential for accommodating the demands of the lunar environment. We recognized the importance of compiling a list of these space types as a preliminary step before advancing to the project's design phase.

These required functions are:

- **Common living space:** This area must be used by staff and visitors, and it must be planned as a communal area that promotes interaction.
- **Private sleeping rooms:** Individual staff quarters that are simple but comfortable and designed for the Moon station's resident staff
- **Bathrooms**
- **Kitchen:** A space to provide a controlled and equipped environment for the preparation, cooking, and storage of food for astronauts.
- **Gym:** It will therefore be crucial to design an exercise area to go along with the current suits, which are made to ensure bone and muscle stimulation in order to limit the effects of the various gravitational conditions.
- **Airlocks:** In the lunar environment, people must pass through designated filter areas that are referred to as "Airlocks" in order to move from the interior (pressurized) areas of the Moon Station to the exterior (non-pressurized) lunar environment in complete safety without experiencing catastrophic pressure losses.
- **Technical rooms:** The function of technical rooms in a lunar base is to house and support the various technical and mechanical systems required for the operation and maintenance of the facility.
- **Control room:** It serves as the focal point for managing all operations and systems at the lunar base. Mission controllers in the control room supervise and plan various operations to maintain the base's efficiency.
- **Med-bay:** Medical bay to ensure astronauts' health and safety throughout their missions and to provide the resources and medical care needed to address any health issues that might arise in the challenging circumstances of space.
- **Laboratories:** Laboratories will be required to process data and examine samples for the variety of research that will be done at the base (geological analyses, analyses of lunar resources, surveys, etc.). To make it easier to transport samples into the station, these areas must be near areas of entry and exit.
- **Greenhouse:** The greenhouse is a multifunctional component of a space station, contributing to life support, and food production. It plays a crucial role in making space missions more sustainable and self-reliant while providing valuable research opportunities for future space exploration.



Sketch by E. N. Yavuz & E. Kirmiziyesil, 2023

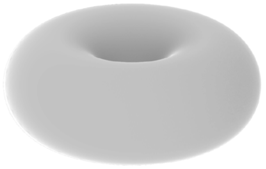
Design Process

We have chosen an optimized form that minimizes sharp angles and flat planes, aligning with the principles of 3D printing. This strategy provides the most effective solution for achieving both 3D print compatibility and pressurization.

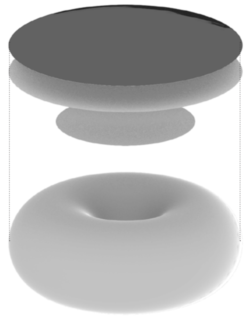
To address the structural continuity of the envelope, we have implemented a floating slab.

To minimize the amount of printed wall while maintaining the required level of protection, we have strategically utilized loose regolith within small pockets of the 3D printed layer.

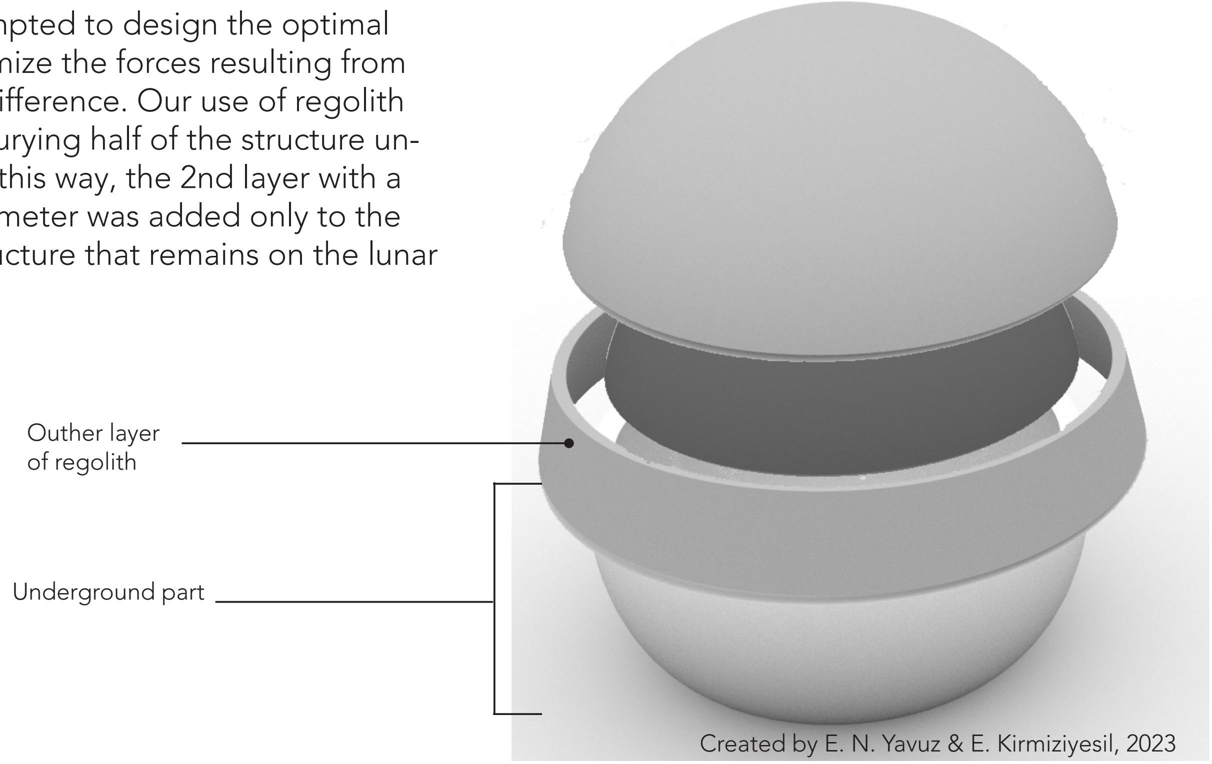
We have attempted to design the optimal shape to minimize the forces resulting from the pressure difference. Our use of regolith is limited by burying half of the structure underground. In this way, the 2nd layer with a thickness of 1 meter was added only to the part of the structure that remains on the lunar surface.

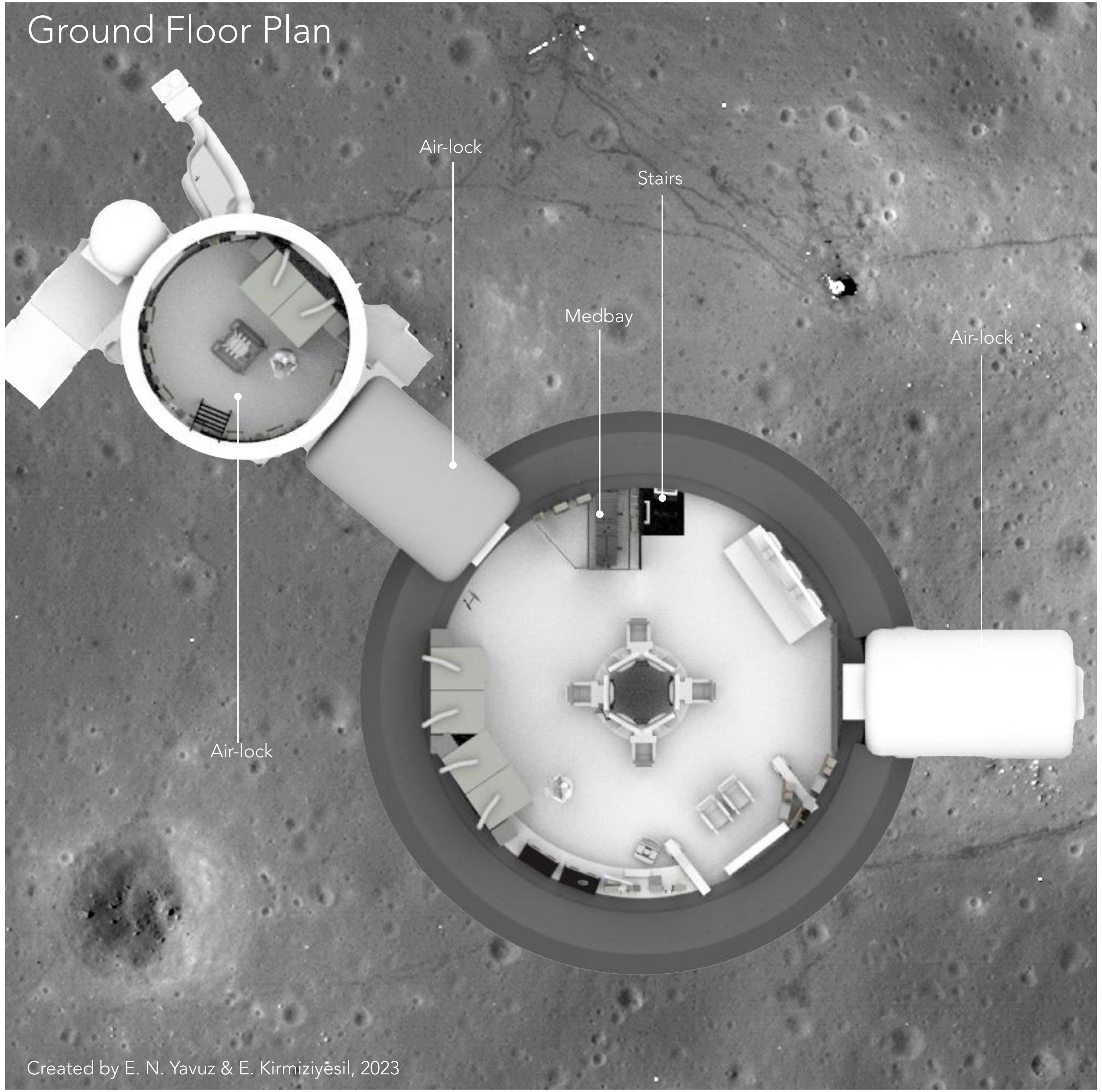


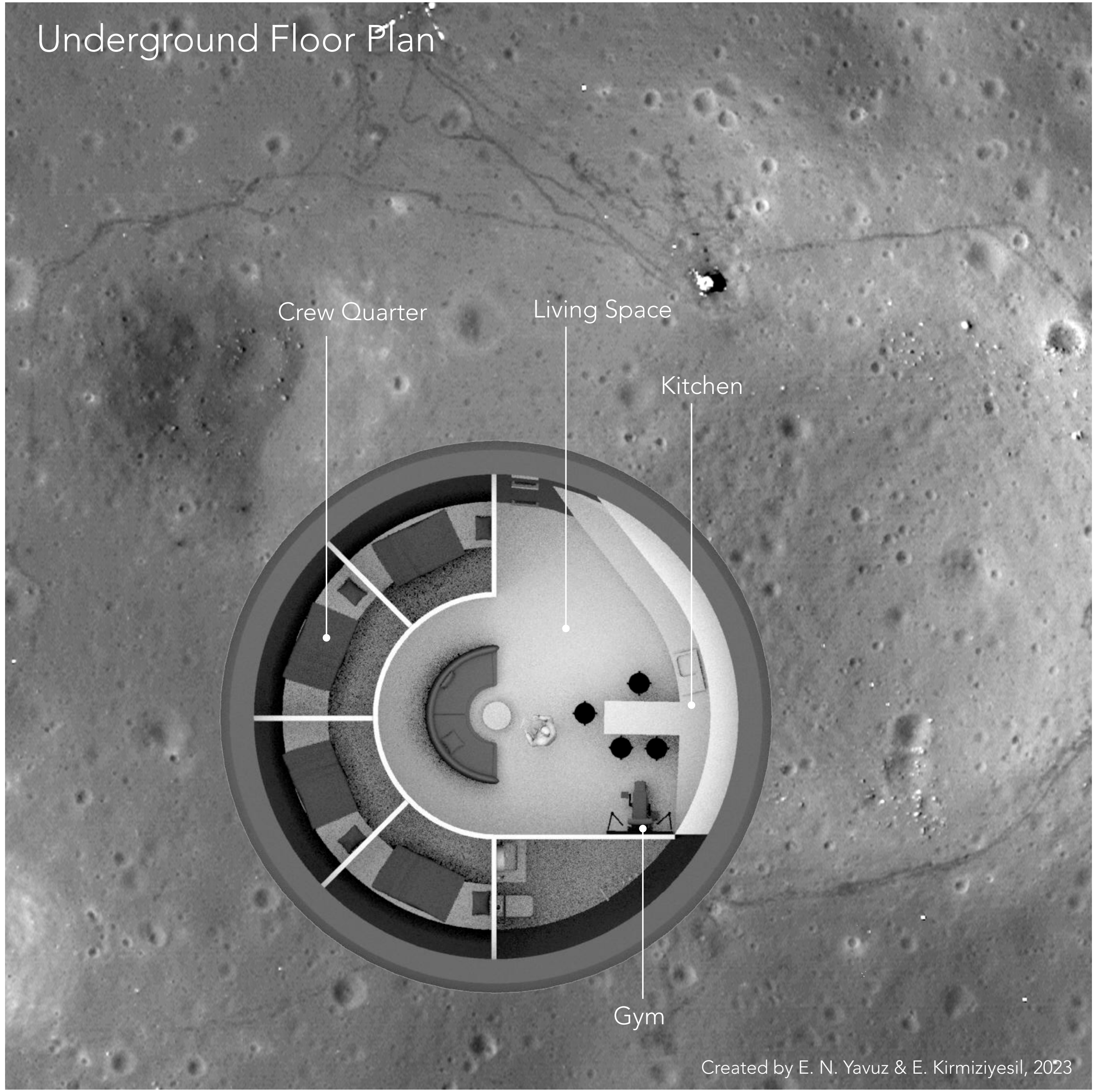
Initial Design

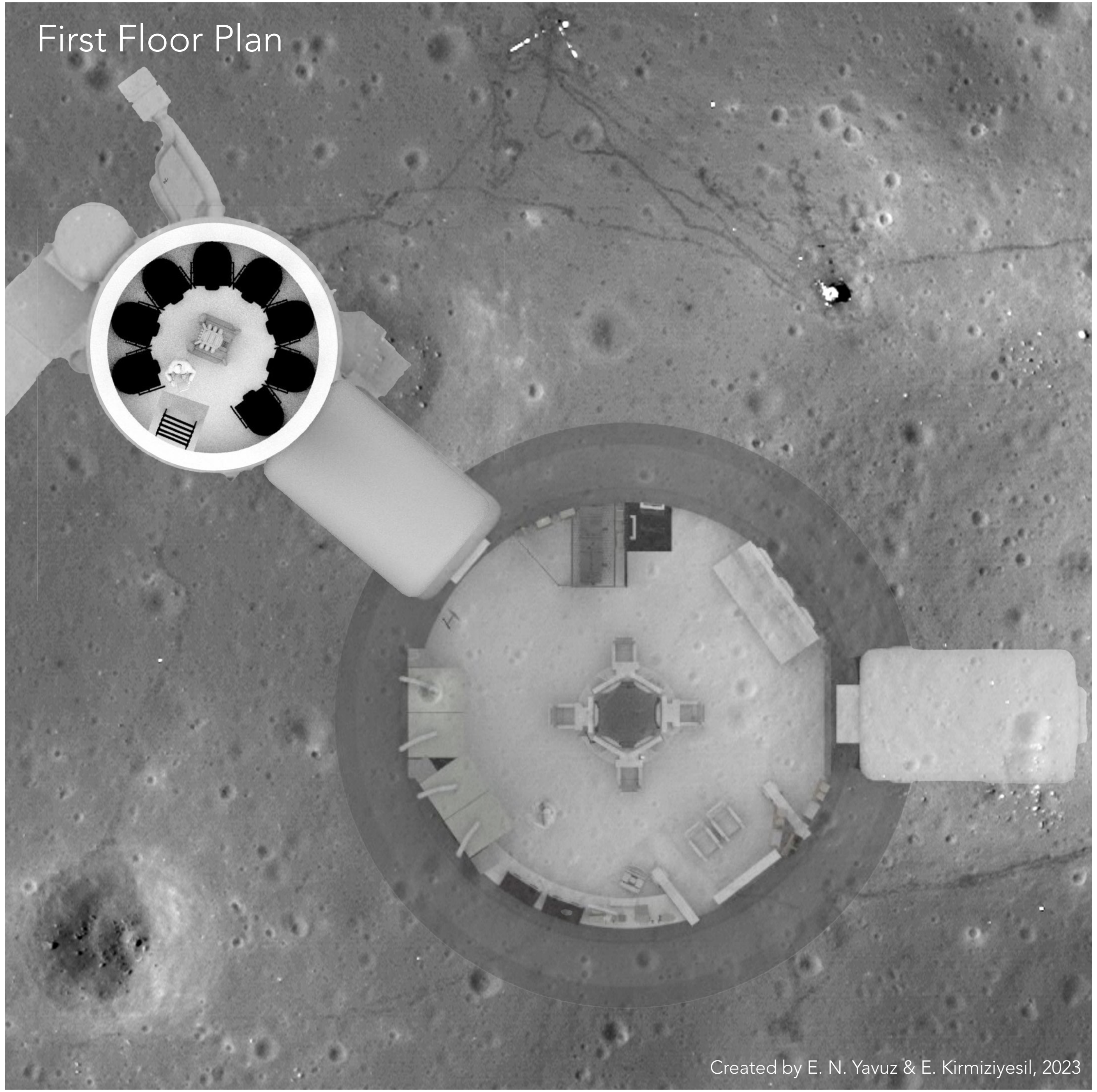


Closed shape to minimize the surface area



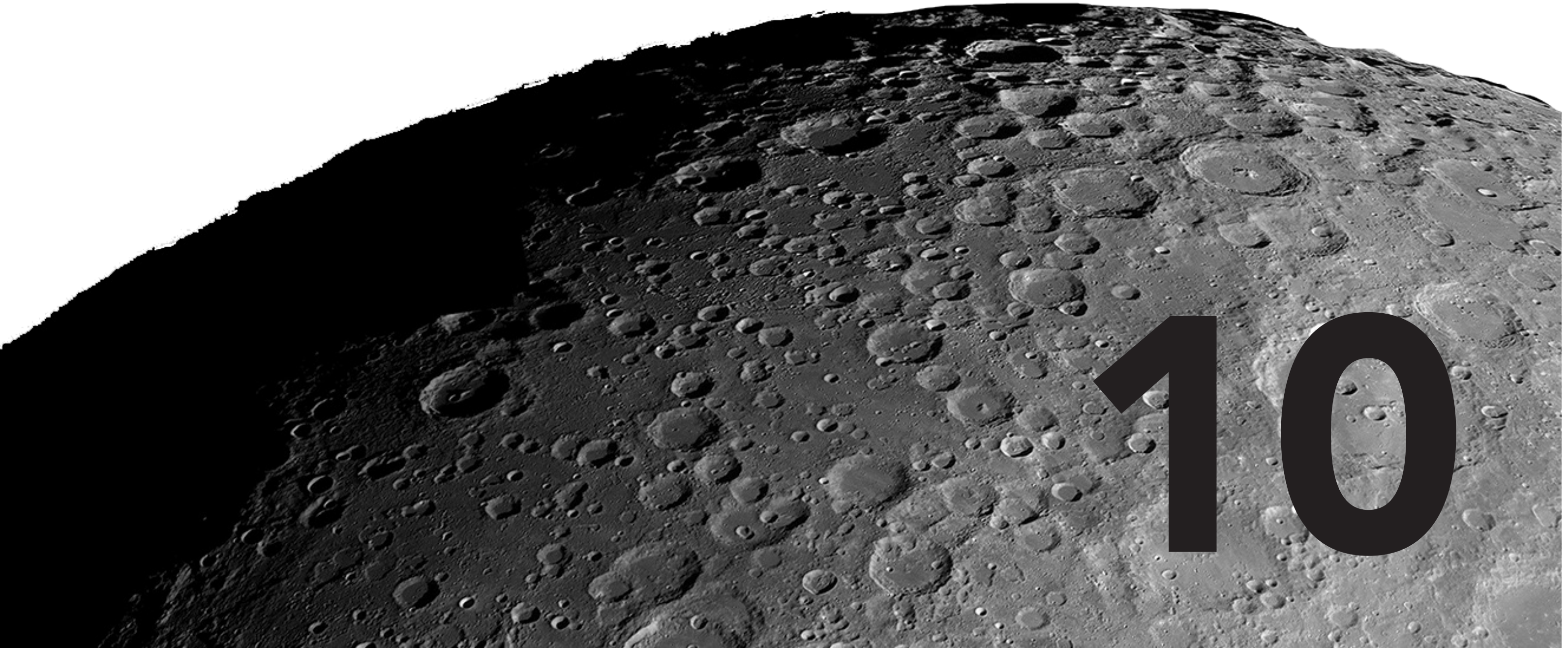


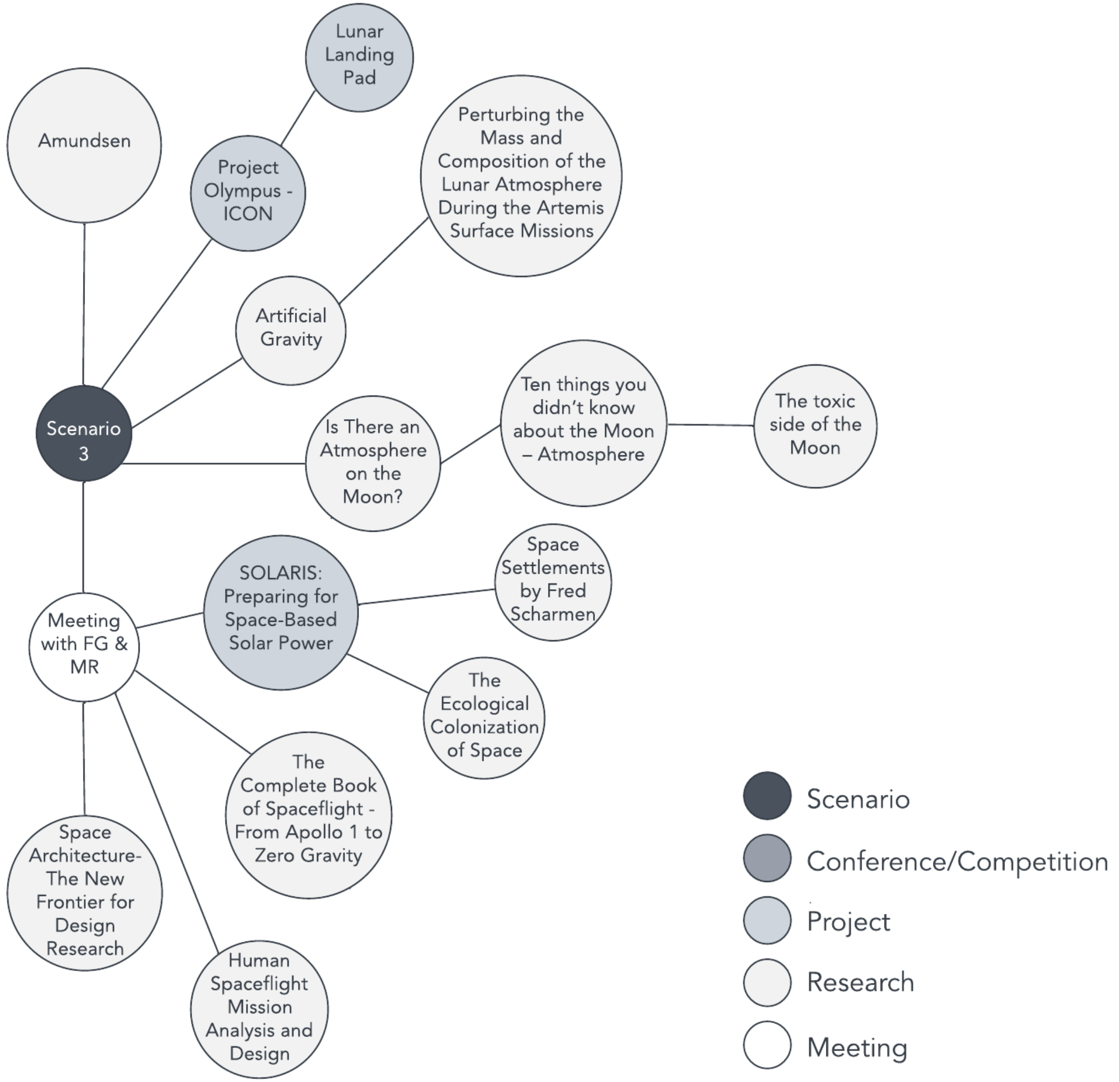

Underground Floor Plan
Crew Quarter
Living Space
Kitchen
Gym
Created by E. N. Yavuz & E. Kirmiziyesil, 2023


First Floor Plan
Created by E. N. Yavuz & E. Kirmiziyesil, 2023

Design Scenario 3

We have decided to change our design after reviewing our recent research. Recognizing the critical role of pressure in our lunar module design, we have opted for the most appropriate shape, a sphere. This choice ensures an even pressure distribution and the structural integrity of our modules.





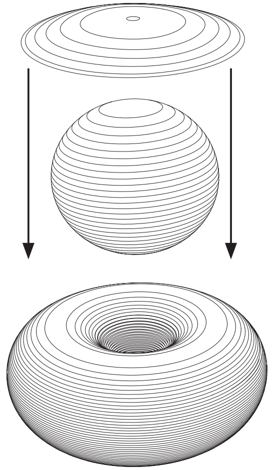
Created by E. N. Yavuz & E. Kirmiziyesil, 2023

Design Phases of 3rd Scenario

Changing the shape

This newly acquired knowledge led to a strategic reevaluation of our design strategy, which was now enlightened by the rules regulating pressured structures. As a result, the module's configuration underwent subtle yet purposeful alterations. We planned these modifications to address the significant pressure differences between the carefully controlled interior of the module and the lunar environment outside.

Our design modifications focused on achieving equilibrium between these opposing forces, taking into account the vacuum-like pressure conditions of the lunar expanse, which registers at 0 atm, in contrast to the requirement to maintain a stable internal pressure equivalent to Earth's standard atmospheric pressure of 1 atm. This equilibrium not only ensures the well-being and safety of the residents but also guarantees the structural integrity of the module itself.



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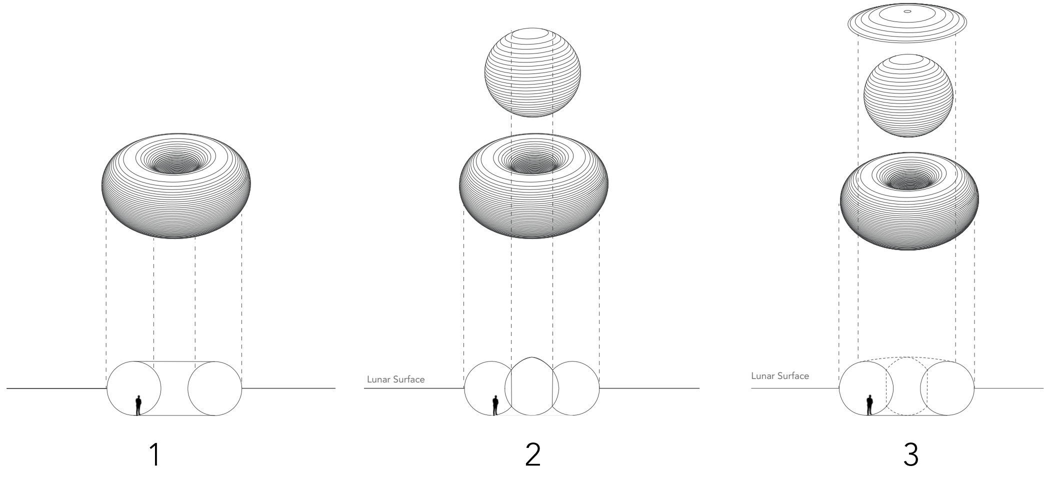
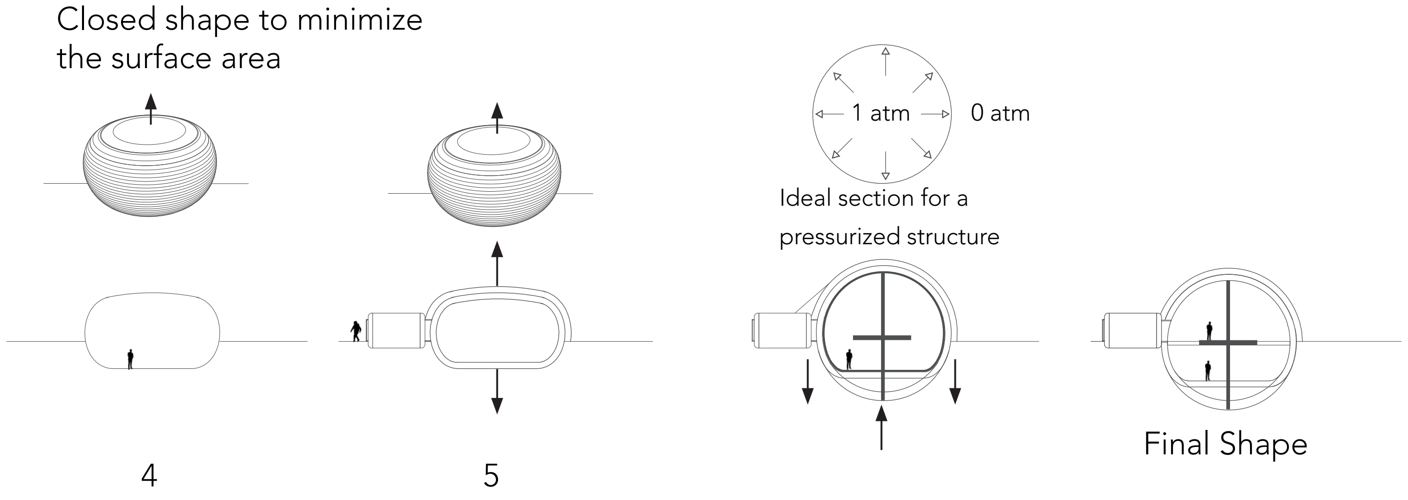


Recognizing the crucial role of pressure in the lunar environment and integrating pressurized structures into our design exemplify a meticulous and adaptable approach. This resourcefulness, employed to address the unique challenges of the lunar setting, highlights the significance of innovation in accomplishing successful space-oriented design endeavors.

To achieve both 3D printability and effective pressurization, we have optimized the module's shape, reducing hard corners and flat surfaces, all while adhering to the principles of 3D printing. Additionally, we have minimized the use of regolith by burying half of the module underground. In this way, the 2nd layer with a thickness of 1 meter was added only to the part of the structure remaining on the lunar surface.

We have also planned to apply a liquid elastomer membrane to the interior face of the 3D printed wall to ensure the print is airtight and can withstand the pressure difference.



Created by E. N. Yavuz & E. Kirmiziyesil, 2023

Reference Project 3

Lunar Lantern by ICON

After finalizing the selection of the outer shell design for our project, we embarked on an extensive search for appropriate design solutions to ensure the static stability of the building. In this pursuit, we closely examined the methodology employed by Project Lantern, which was thoroughly explored in the previous chapter. We discovered that their approach aligned harmoniously with our own design concept.

The project's construction journey begans with the establishment of a solid foundation on the lunar surface. This critical step involved the utilization of a highly advanced 3D printer, designed by the company. The foundation served as the groundwork for all subsequent construction phases.

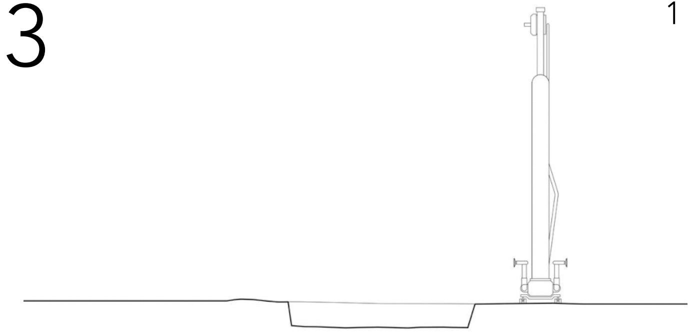
Following the successful foundation creation, the next step involves the meticulous positioning of a folded structure transported from Earth. This structure was strategically placed at the core of the Lunar Lantern's floor plan.

With the foundation and core structure in place, the 3D printing process for the outer walls of the Lunar Lantern initiates. This phase is executed cerefully, with the 3D printer gradually printing the structure. However, a notable challenge emerges when dealing with the complex shape of the structure's upper section. To overcome the challenge posed by the intricate shape of this section, a creative solution is devised. An openable structure, specifically designed to fit within the walls of the upper section, was introduced. This internally mounted structure could be opened with the assistance of a robotic system. This innovation enables precise placement, resolving the printing challenge effectively.

The construction of the Lunar Lantern project showcases the human ability to adapt and integrate in the face of unique challenges through the strategic use of advanced technologies, careful planning, and the integration of robotic assistance.

As we move forward in our project of a station on the Moon, the lessons learned from the Lunar Lantern project will contribute to our design.

1



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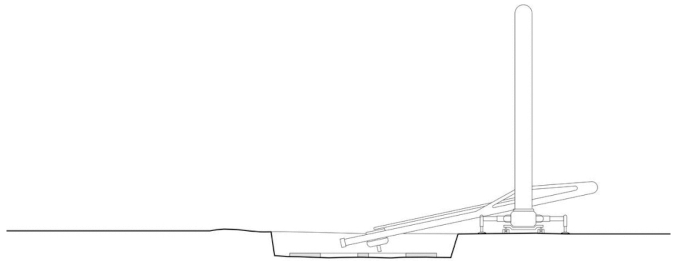

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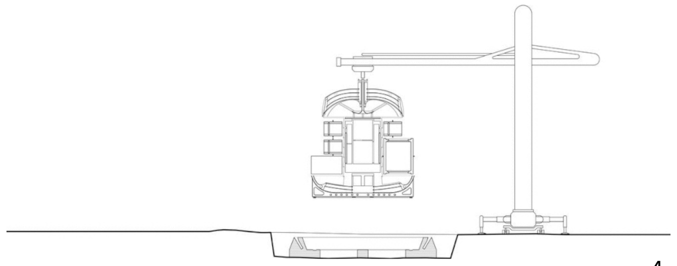

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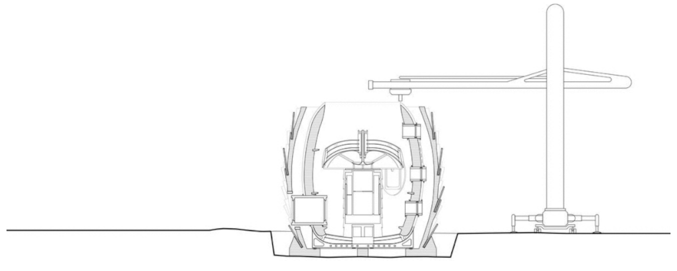

Image Source: ICON

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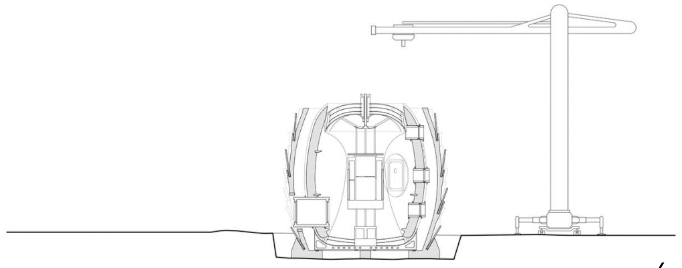

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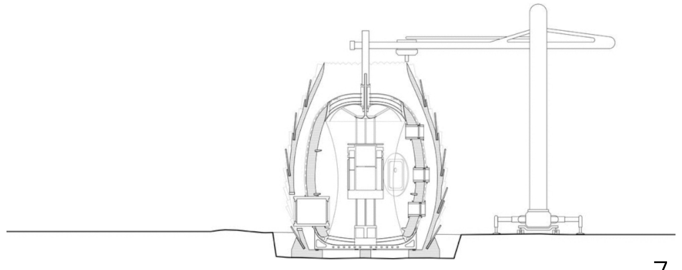

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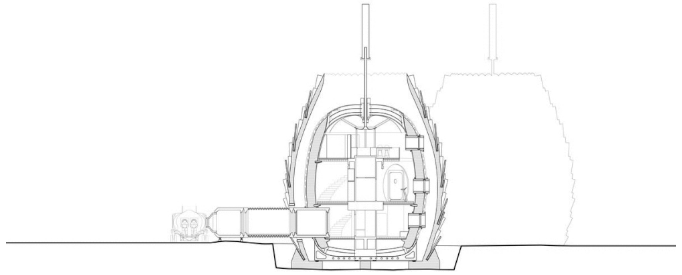


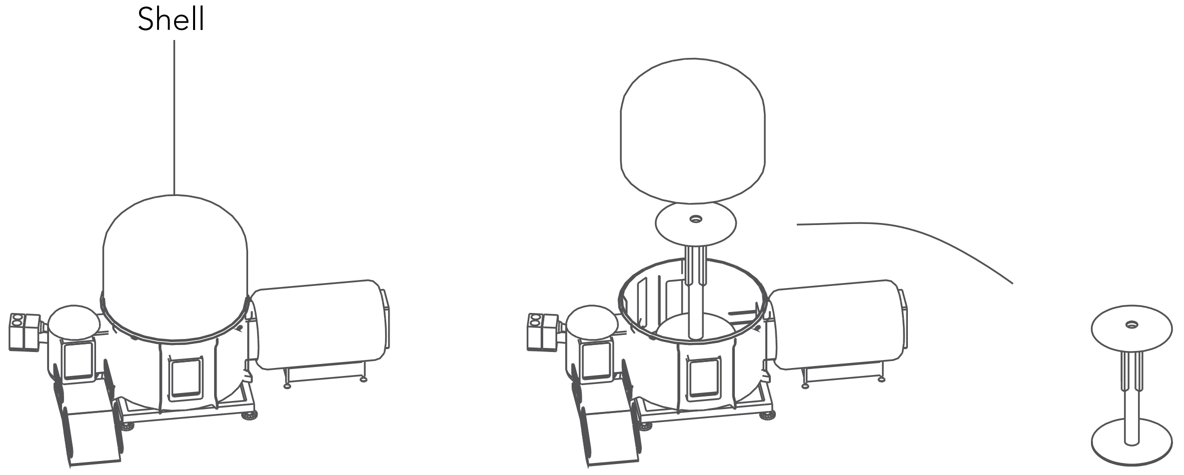
Image Source: ICON

Construction Phase of 3rd Scenario

The construction process begins when semi-autonomous 3D printers and excavators arrive on-site. Once the project location is determined, the first step is to process the regolith and dig a hole in the ground that is 5.4 meters deep. Next, 3D printers start printing the spherical foundation. Subsequently, a second delivery arrives, consisting of deployable aluminum structures, which are positioned within the crater to form the central structure of the settlement.

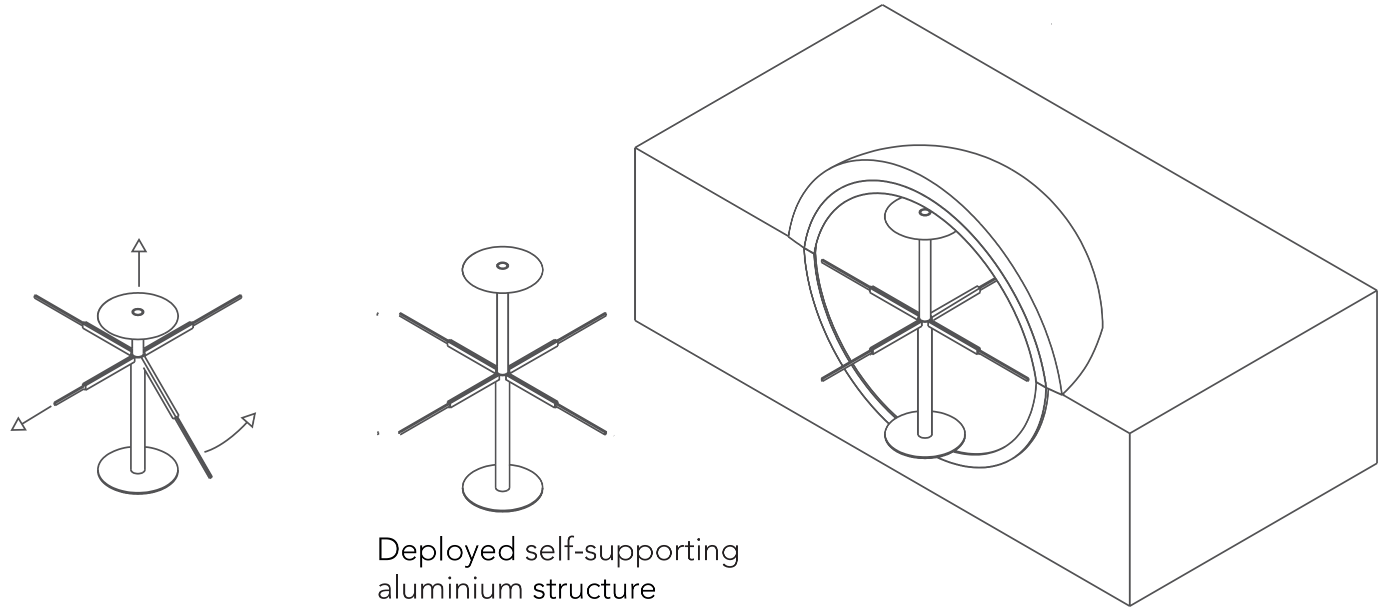
Due to the great distance from Earth and the resulting communication delays, the deployment and construction are intended to occur with little to no human involvement, depending instead on rules and objectives rather than precise instructions. For a project of this size, the system should be more adaptable to change, and the likelihood of unforeseen difficulties.

*HDU-DSH: The NASA Deep Space Habitat (DSH) is a two-story habitat unit with four ports and an approximate volume of around 112 cubic meters. The outer shell of the HDU-DSH can accommodate additional laboratory or living spaces once the 3D printer and deployable structure are delivered.



The HDU-DSH* Shell Unit

Pre-deployed self-supporting aluminium structure



Deployed self-supporting aluminium structure

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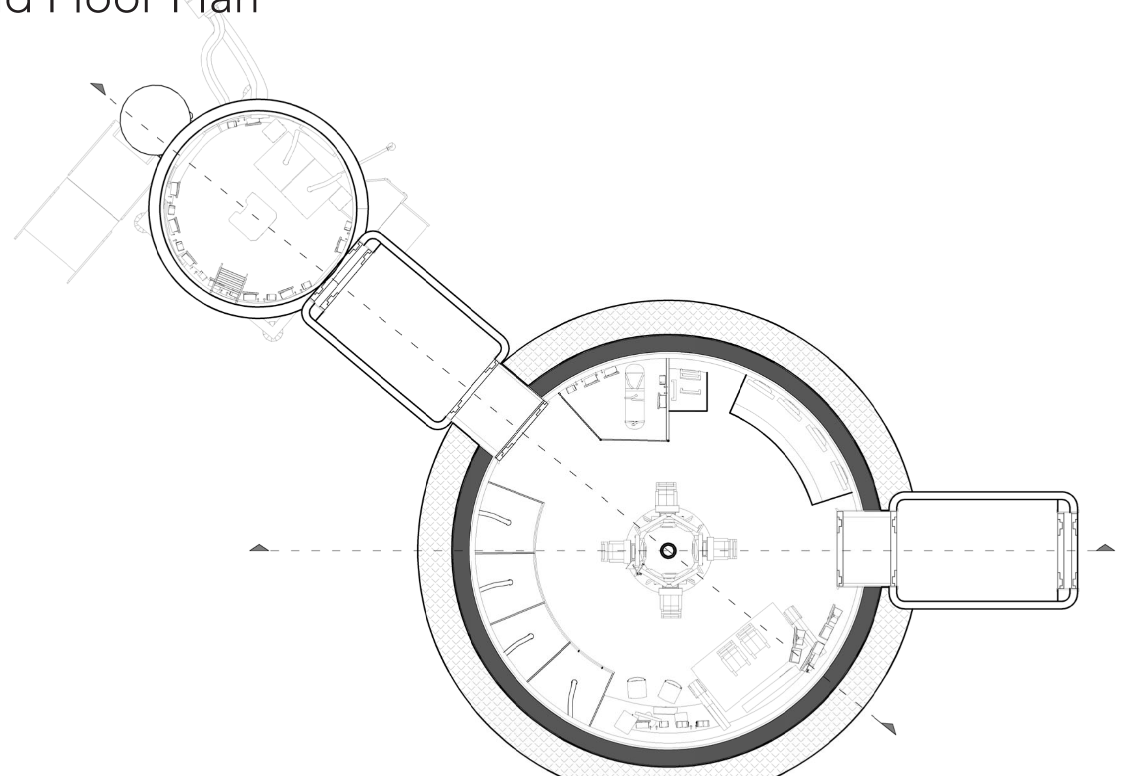
Ground Floor Plan



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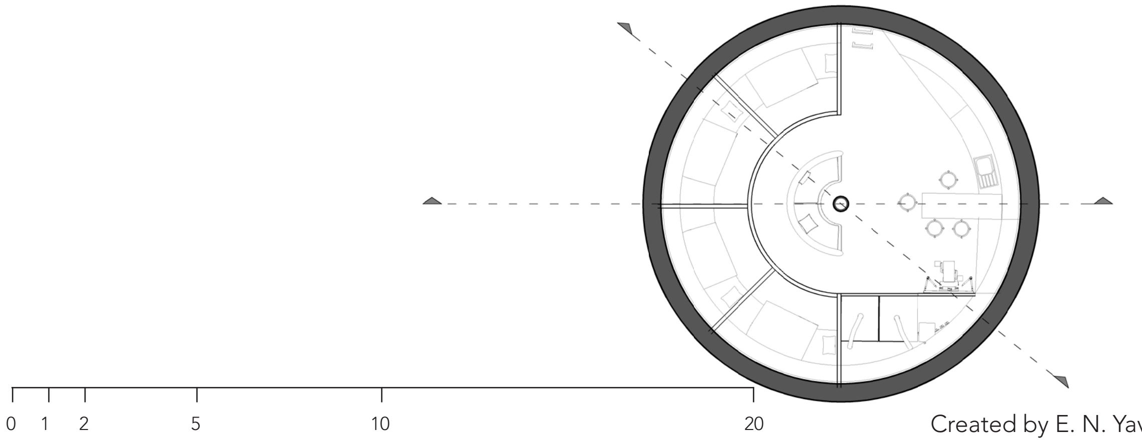
Underground Floor Plan



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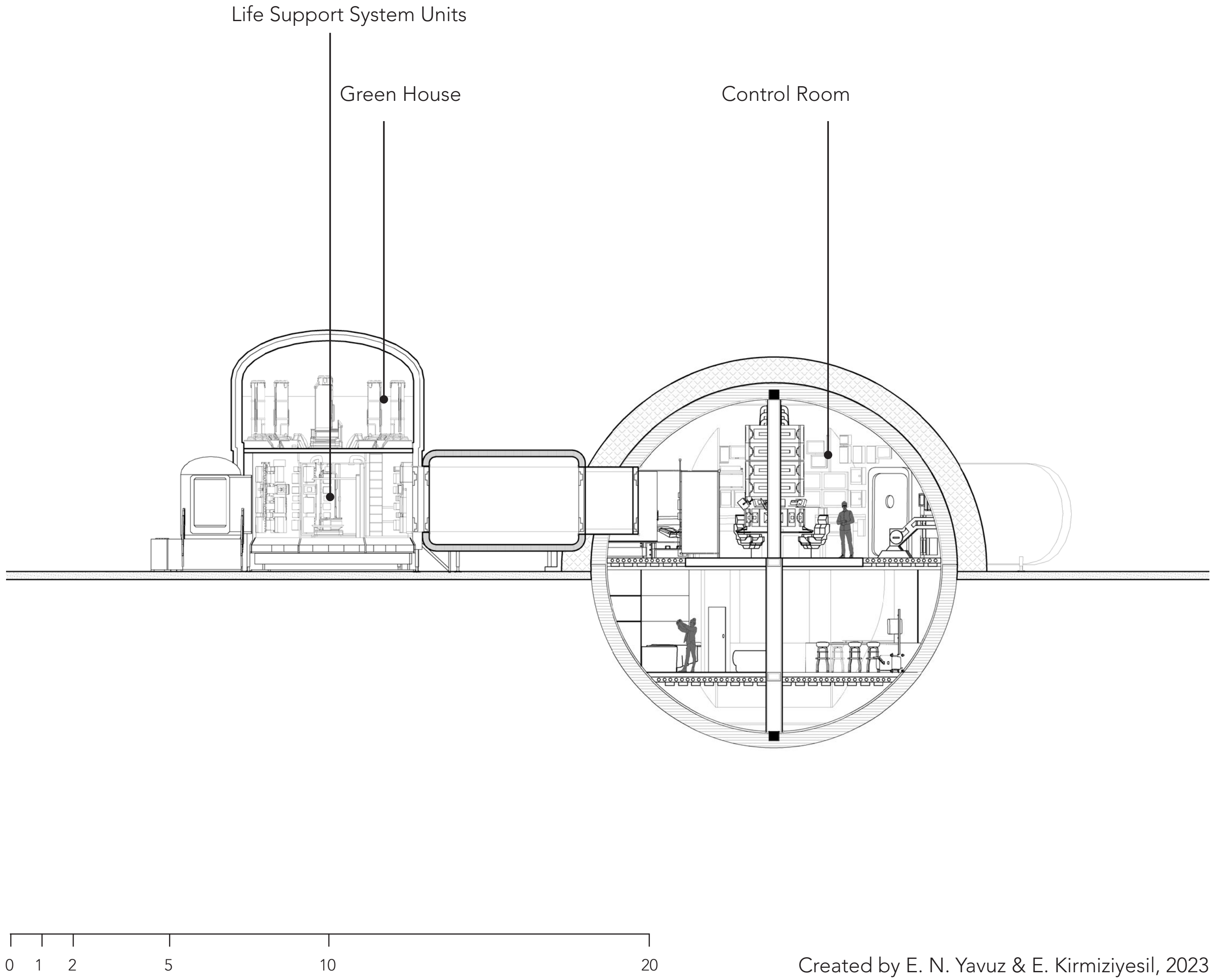
Section A-A′



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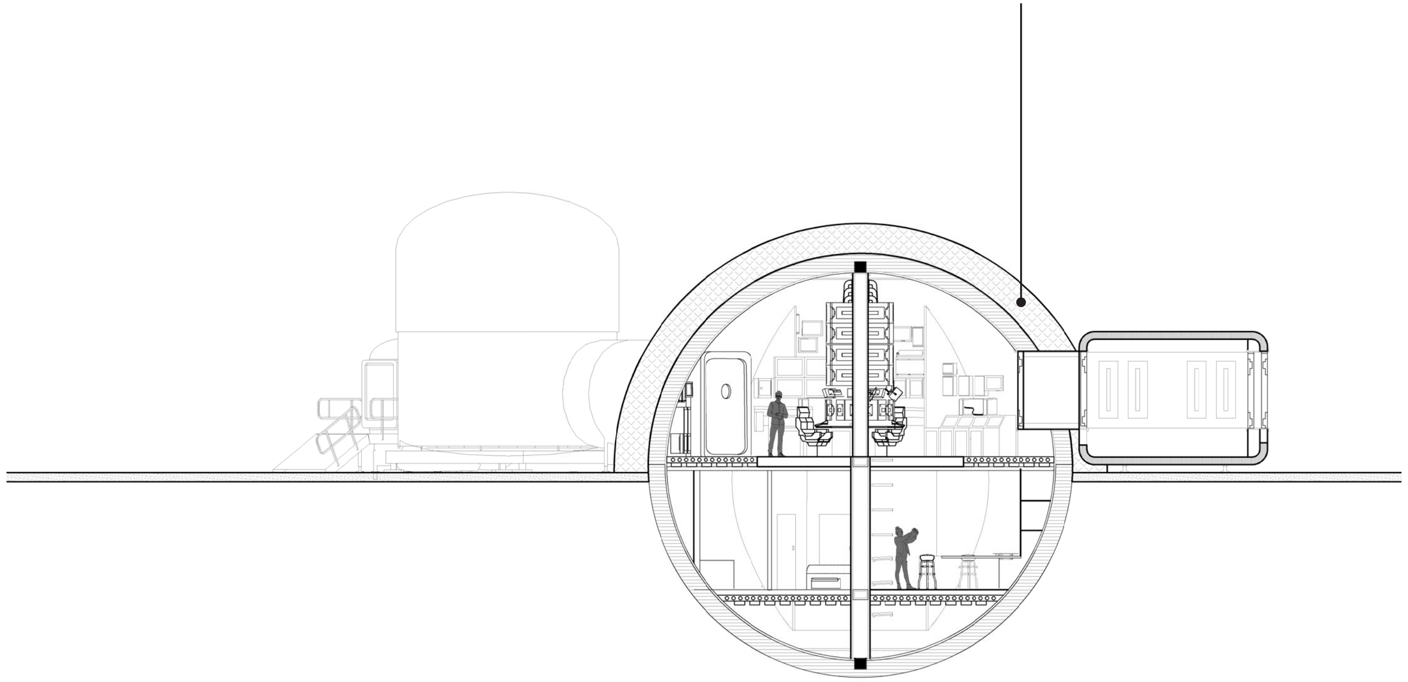
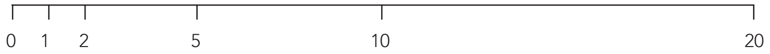
Section B-B′

Usage of loose regolith in the internal layer will minimize the quantity of printed wall while keeping the same level of protection.





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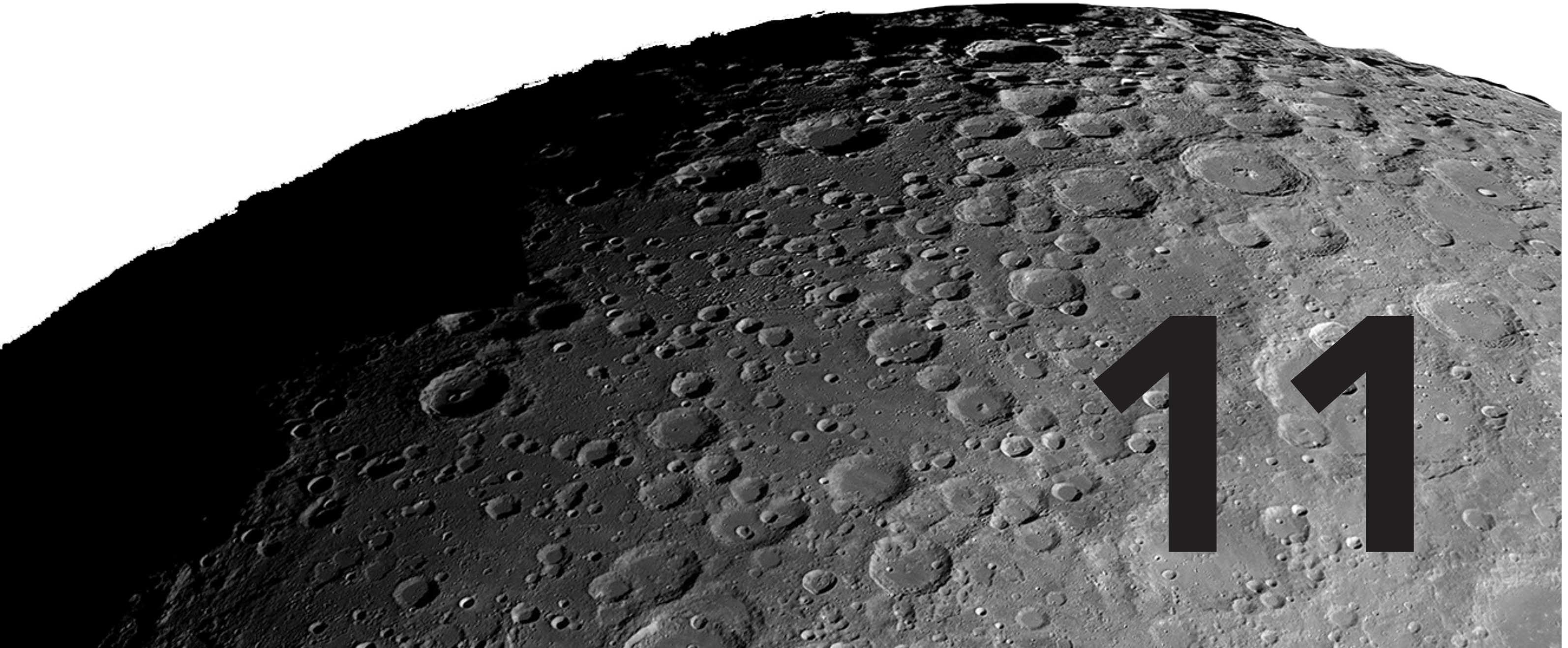
Master Plan



Before determining the master plan decisions, We analyzed several stages that we needed to go through. Creating an efficient organization of the different areas within the settlement requires careful consideration of various factors. This process needs a methodical approach that takes into account the needs of people, the demands of the environment on the Moon, sustainability, and long-term development.

1. Defining Objectives: We began by clearly defining the objectives and goals of the lunar habitat project. This includes considering the purpose of the settlement (e.g., research, colonization, tourism) and the desired outcomes (e.g., scientific discoveries, self-sufficiency). During the whole process, we reconsidered them according to the current data we had. For the definition of the objectives, we created several phase diagrams that show the whole process of lunar colonization. In addition, we highlighted the phase step in which we want to develop the architectural project.

2. Conducting Site Studies: We made an analysis of potential landing sites and examined factors such as topography, geology, resource availability, sunlight exposure, PSR (Permanently Shadow Area), and closeness to important features such as water ice deposits, and lava tubes. This analysis was to help identify the most suitable locations for lunar settlements. This study can be seen in chapter 7 which is named Site Decision.

3. Establishing Zoning: For this step, we divided the lunar settlement into functional zones and we determined the allocation of different zones

Overview towards master plan

1. Definition of Objectives
↓
2. Conducting Site Studies
↓
3. Establishing Zoning
↓
4. Designing Habitat Modules
↓
5. Determination of Resource Utilization
↓
6. Ensuring Safety and Emergency Preparedness:
↓
7. Adapting Expansion Scenarios

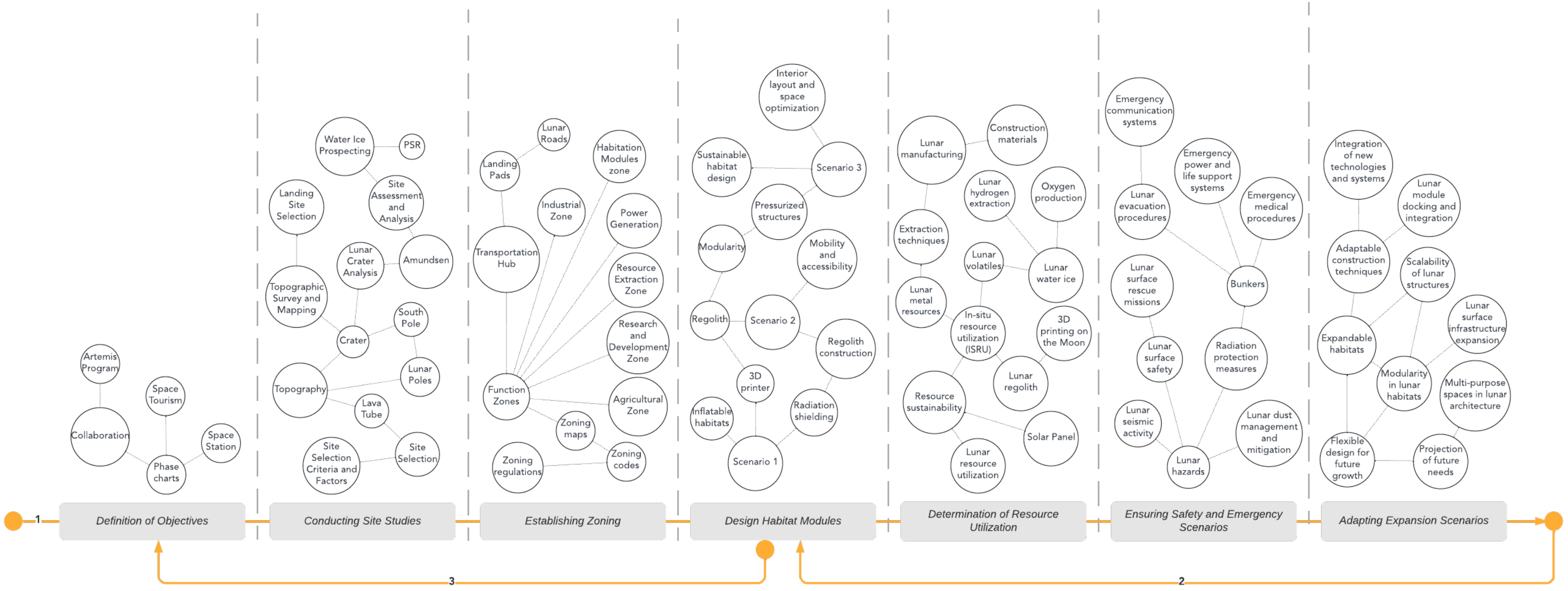
based on their specific requirements. Finally, we worked on planning of infrastructure such as roads, power systems, and networks to support the settlement's needs.

4. Design Habitat Modules: We developed plans and sections for habitat modules that meet the needs of lunar inhabitants by considering factors such as structural integrity, radiation protection, thermal management, life support systems, and human factors which we discussed in previous chapters. (e.g., living space, privacy, psychological well-being).

5. Determination of Resource Utilization: We researched and found the potential resources available on the Moon, such as water ice, regolith, and solar energy. We plan to use systems for resource extraction, processing, and utilization to support the habitat's energy, water, and material needs.

6. Ensuring Safety and Emergency Scenarios: We developed infrastructure to address potential risks and emergencies. This includes establishing emergency bunkers, radiation protection, meteorite impact mitigation, fire safety, medical emergencies, and evacuation procedures. Because safety considerations are essential to protect the inhabitants.

7. Continual Assessment and Adaptation: We created expansion scenarios on advancements in technology, scientific discoveries, and changing needs.



Master Plan Process Mapping Diagram
Created by E. N. Yavuz, E. Kirmiziyesil, 2023

We tried to sustain a flexible approach that allows for adaptation and improvement as new information and capabilities emerge.

It is important to note that developing a master plan for lunar habitats is a complex endeavor that requires collaboration among multidisciplinary people, including experts in space science, architecture, engineering, sustainability, and social sciences. References to specific research and technical details will vary depending on the specific context and the latest developments in lunar exploration and settlement.

While creating the master plan, we tried to follow the steps we set above. The first two steps, the Definition of Objectives and Conducting Site Studies have been explained in detail in previous chapters (chapters 5 and 7). So we move on to the Zoning plan step.

Zoning Plan

In order to create a zoning plan, we first reviewed the areas we determined in line with our previous research and made additions. The functions and places that should be in each determined zone are written under those headings. It was crucial to define these zones well. Because we understood that in order to create an effective master plan, good zoning must be done first. The zones that we defined for the Lunar Habitation Project are the habitation modules zone, research and development zone, industrial zone, transportation hub, agricultural zone, power generation zone, and finally resource extraction zone.

Habitation Modules Zone: This zone is dedicated to providing suitable living spaces for lunar residents. It includes residential units and support amenities such as medical centers and recreational zones. The planning of these residential sections prioritizes the provision of comfort, safety, and a communal atmosphere for the inhabitants. Apart from residential spaces, the habitat modules also encompass agricultural production zones and research&development areas. The greenhouses concentrate on food production and sustainability and involve controlled environment agricultural setups, hydroponic systems, and innovative farming techniques to ensure a self-sufficient food source for lunar settlers. This zone plays a pivotal role in promoting the overall health and nutrition of the lunar inhabitants. The research and development area is indispensable for advancing scientific knowledge and technological innovation on the Moon. It accommodates laboratories, research centers, and workshops where scientists and engineers can carry out experiments, analyze lunar samples, and devise new technologies to enhance our comprehension of the Moon and support future space exploration.

Industrial Zone: This zone centers on production and manufacturing activities essential for the self-sufficiency of the lunar community. It includes facilities for resource processing, manufacturing equipment and components, and production of essential goods. This zone ensures the efficient utilization of lunar resources and reduces dependency on Earth for supplies.

Transportation Hub: The transportation hub serves as a central point for transportation activities within the lunar settlement. It includes landing pads and docking stations for spacecraft and rovers. Efficient transportation infrastructure is essential for connecting different areas of the settlement and facilitating travel to and from Earth.

Power Generation and Resource Extraction Zone: The power generation and resource extraction zone is responsible for meeting the energy needs of the lunar settlement and extracting valuable resources from the lunar surface. It includes solar power farms, nuclear power facilities, and mining operations. This zone ensures a stable and sustainable energy supply and facilitates resource utilization for various purposes. In the Moon Village Project, solar panels can be seen an aerial view of the plan.
Before we moved to allocate zones that we listed above, we tried to find extra information about Amundsen Crater. We found its topography map and sections. We could manage to create a 3D model of the crater using isohips. (Figure.1&2)

For a well-organized master plan, site studies play an important role because site studies on the Moon are essential for gathering data and knowledge about the lunar environment, enabling the creation of a well-informed master plan that considers scientific objectives, resource utilization, safety considerations, infrastructure placement, and long-term sustainability. These studies can be seen in the previous chapters. In this chapter, we did deep research about the PSR of the Moon.

Reference Project 4
Moon Village by ESA & MIT & SOM
Image Source: ESA & MIT & SOM

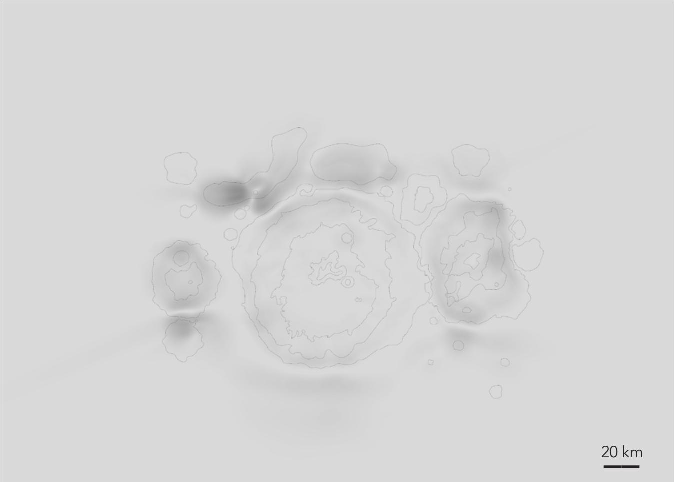
Importance of PSR:
Permanently shadowed regions (PSRs) on the surface of the moon are of great importance for creating a master plan for several reasons;

1. Water Source: PSRs are believed to contain water ice deposits. Water is a critical resource for future lunar missions and human exploration. It can be used for life support, drinking water, agriculture, and most importantly, as a source of oxygen and hydrogen for rocket propellant (Nozette et al., 1996). Identifying and characterizing PSRs helps in targeting areas with potential water ice deposits, which can significantly enhance the sustainability of lunar activities.

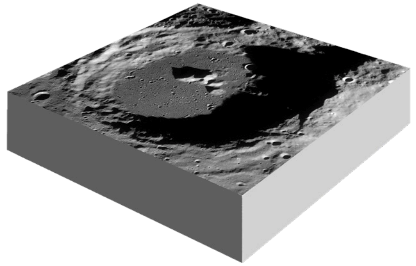
2. Scientific Exploration: PSRs provide unique opportunities for scientific research. These regions have extremely low temperatures and limited sunlight, preserving volatile compounds and materials that can reveal valuable information about the Moon's history, such as the impact history, volatile migration, and potential organic compounds (Lupisella & Koch, 2019). Studying PSRs can contribute to a deeper understanding of the Moon's evolution and its relationship with the solar system.

3. Thermal Stability: PSRs can be utilized for thermal management. The extreme cold temperatures in these shadowed regions can act as a natural cold trap for sensitive instruments or equipment that require low temperatures for optimal performance (Paige & Siegler, 2010). Utilizing PSRs strategically can help in efficiently managing thermal conditions on the lunar surface.

Screenshot from topography making process
Created by E. N. Yavuz & E. Kirmiziyesil, 2023



Screenshot from topography making process
Created by E. N. Yavuz & E. Kirmiziyesil, 2023



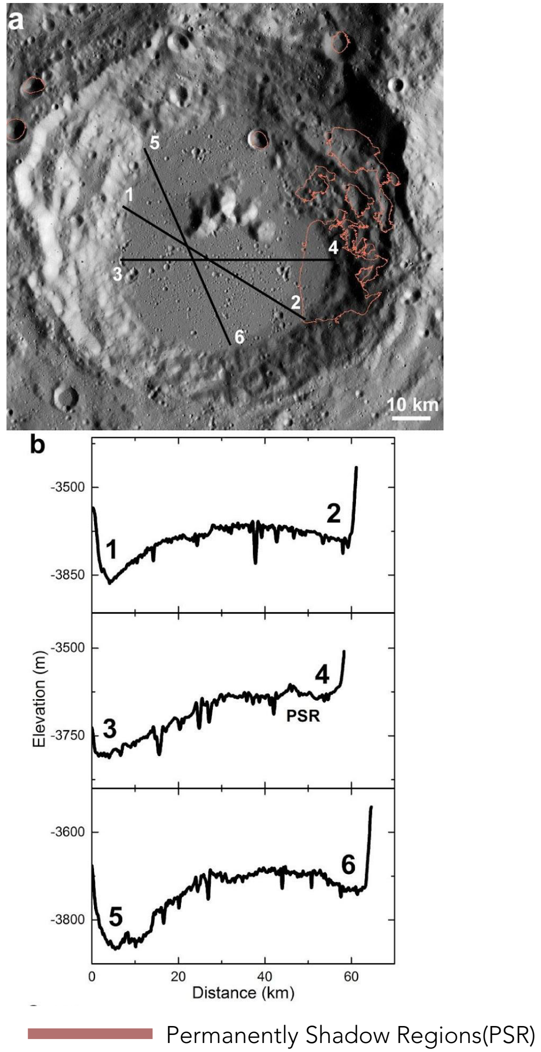
Screenshot from topography making process
Created by E. N. Yavuz & E. Kirmiziyesil, 2023

4. Power Generation: PSRs can be utilized for generating power through solar concentrators. By placing solar arrays on the rim of a PSR, sunlight can be reflected or refracted into the permanently shadowed area, providing a continuous source of power (Kargel et al., 2018). This enables sustained operations even in regions with limited sunlight.

5. Radiation Shielding: The topography of PSRs, which includes steep crater walls and rims, provides natural shielding from harmful cosmic and solar radiation. This shielding is critical for protecting both humans and sensitive equipment in lunar habitats (Cucinotta et al., 2005).

6. Resource Utilization: In addition to water ice, PSRs may also contain other valuable resources. For example, they could harbor deposits of rare minerals, metals, or helium-3, which could have various scientific, industrial, and economic applications (Lawrence et al., 2015). Identifying and studying PSRs can contribute to the assessment and utilization of these resources.

In summary, understanding and exploring permanently shadowed regions on the moon are crucial for creating a master plan. The potential presence of water ice, opportunities for scientific research, thermal stability, power generation, radiation shielding, and resource utilization collectively make these regions promising candidates for future lunar bases or habitats. These regions offer unique advantages and can significantly contribute to the sustainability and success of lunar missions and human exploration.

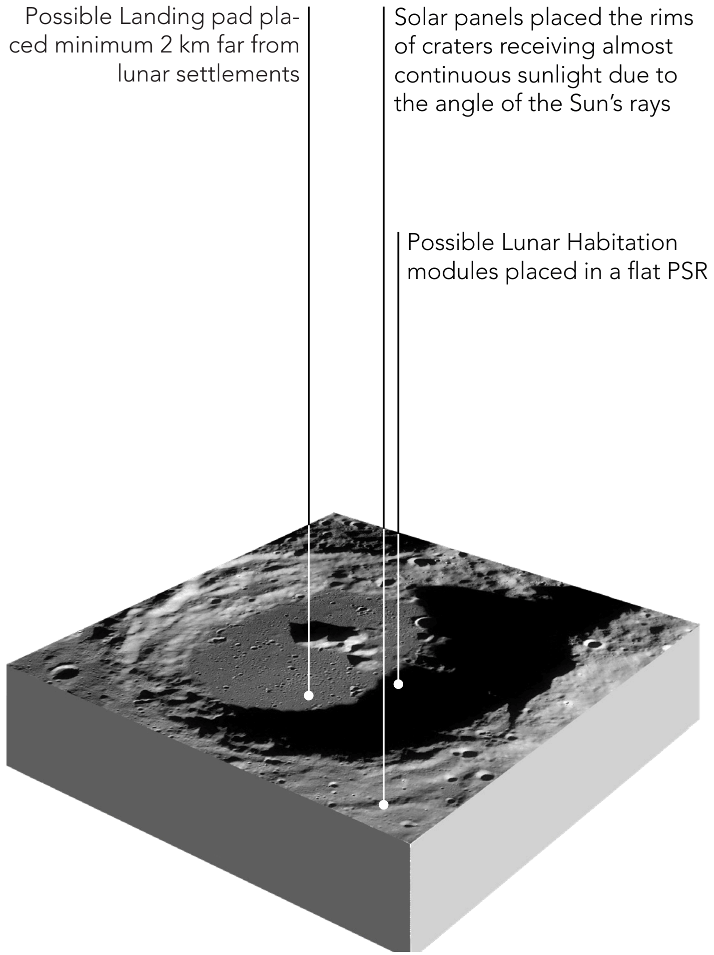


a) LRO-WAC and LOLA blended image of Amundsen crater with PSR regions overlaid. b) The topographic profiles taken along three sides suggest possible uplift within the crater. The PSR present on the eastern side of the crater floor is partially located within this uplifted region.
Image Source: 53rd Lunar and Planetary Science Conference (2022)

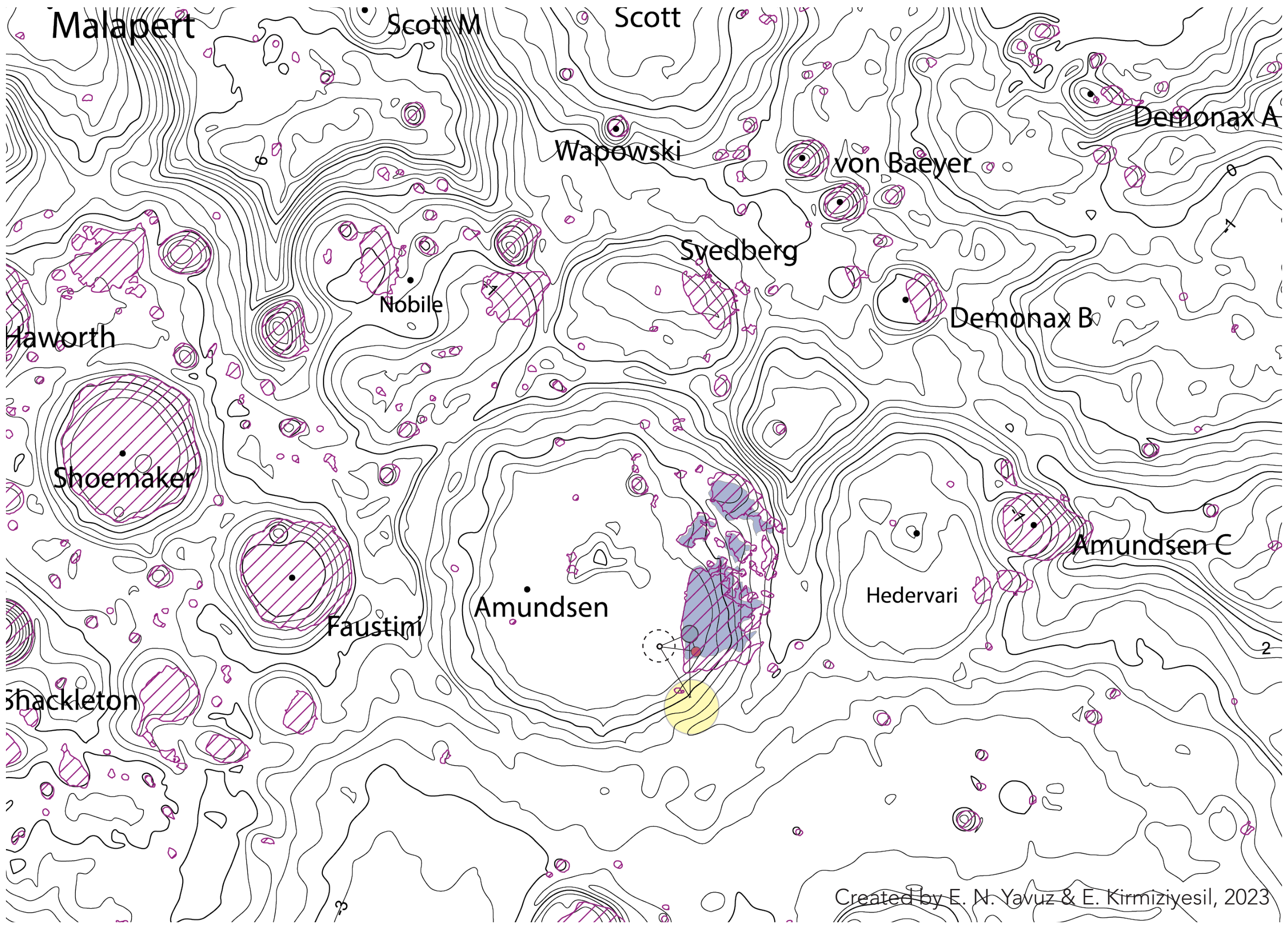
After defining all necessary zones and PSR for creating an efficient master plan, we started to allocate all these zones into our drawings.

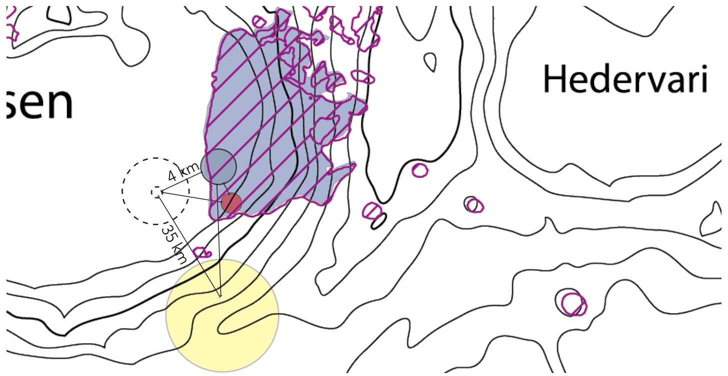
The rims of craters near the lunar poles receive almost continuous sunlight due to the angle of the Sun’s rays and could provide a more stable source of energy. Additionally, some of these rims may be permanently shadowed, providing access to water ice that could be used to produce rocket fuel and sustain a lunar colony.

The location of the settlement has been chosen because of it being a flat PSR which makes it a perfect place to build and protect our settlement from radiation.



3D model of Amundsen Crater
Created by E. N. Yavuz & E. Kirmiziyesil, 2023

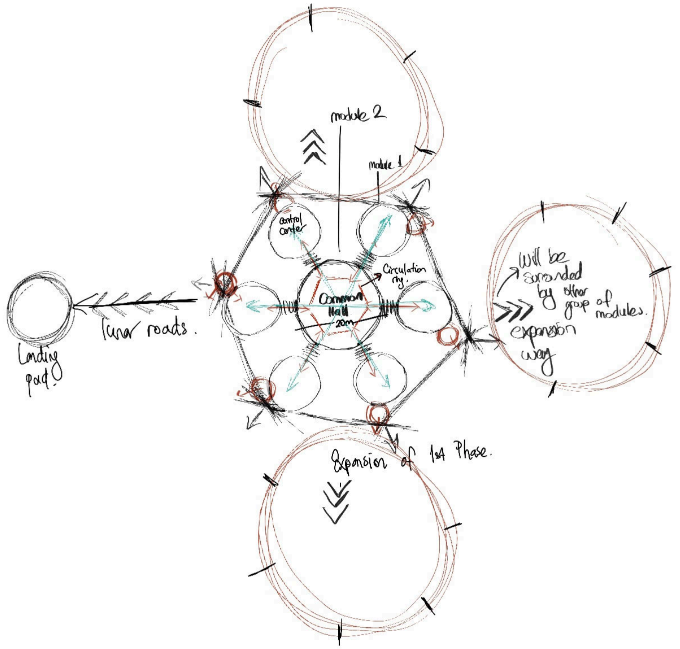




km
0 10 20 50 80 90 100

Permanently Shadow Regions(PSR)
Habitation Modules Zone&Green houses
Landing Pad
Power Generation Zone
Resource Extraction and Processing Zone

Space Station Overview: Expansion Scenario
Version 1



Sketch by E. Kırmızıyeşil, E. N. Yavuz, August 2023

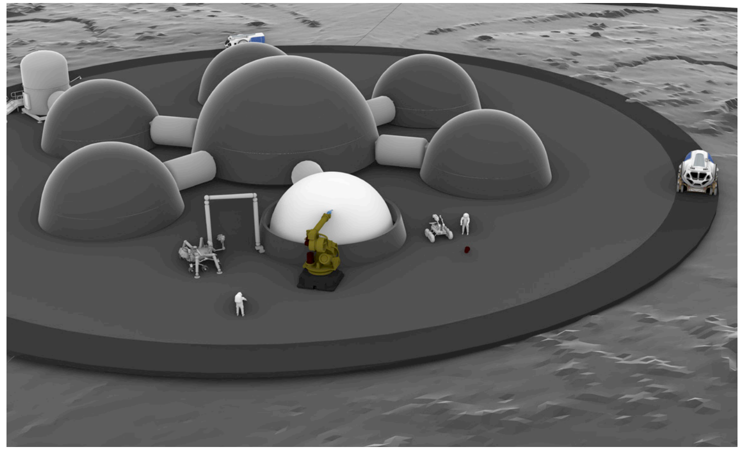


Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023

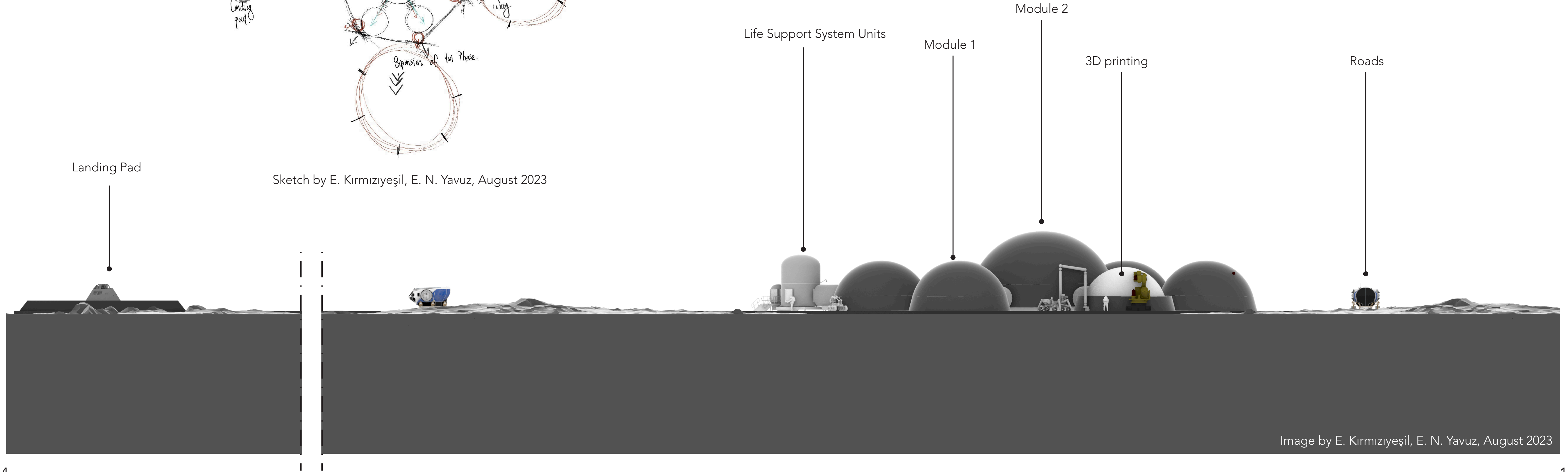


Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023

Space Station Overview: Expansion Scenario

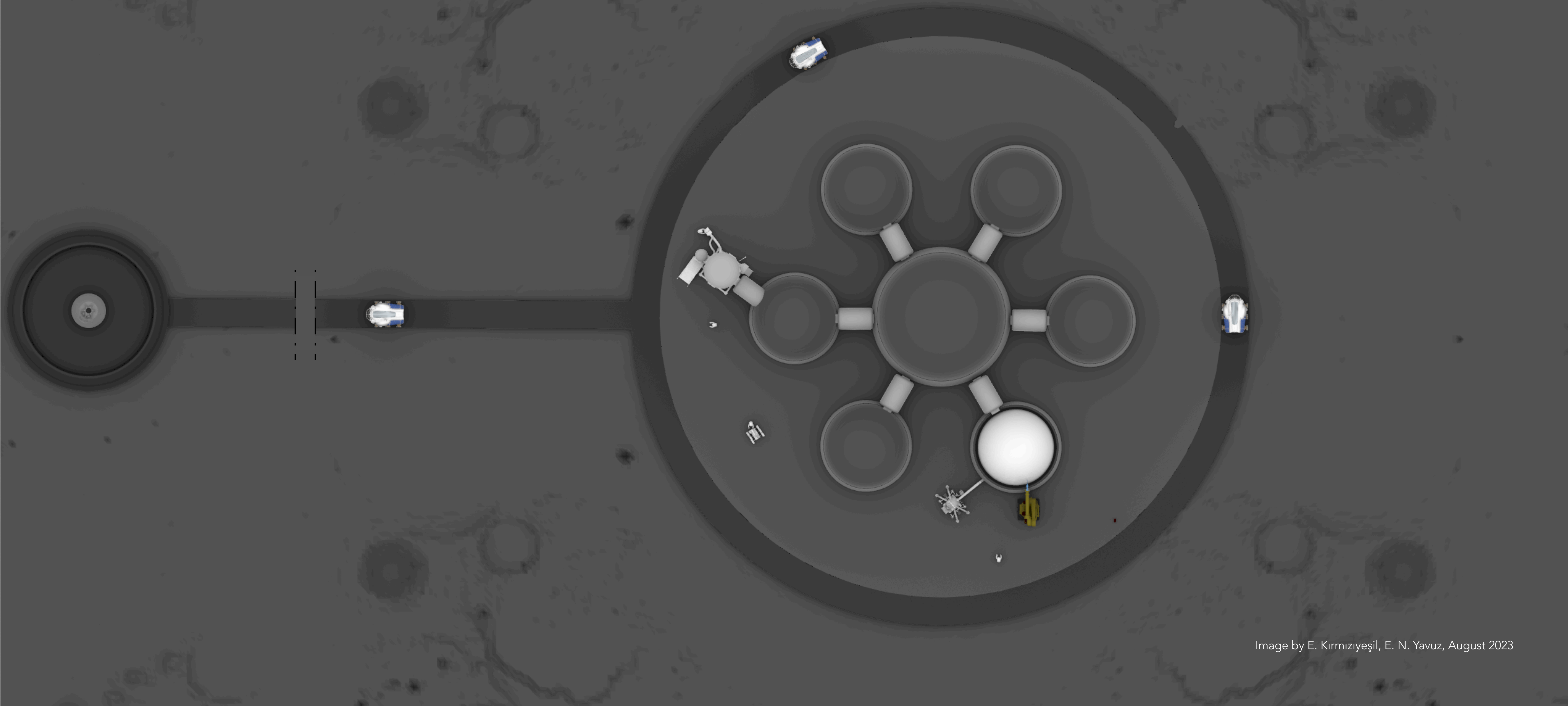


Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023

Space Station Overview: Expansion Scenario

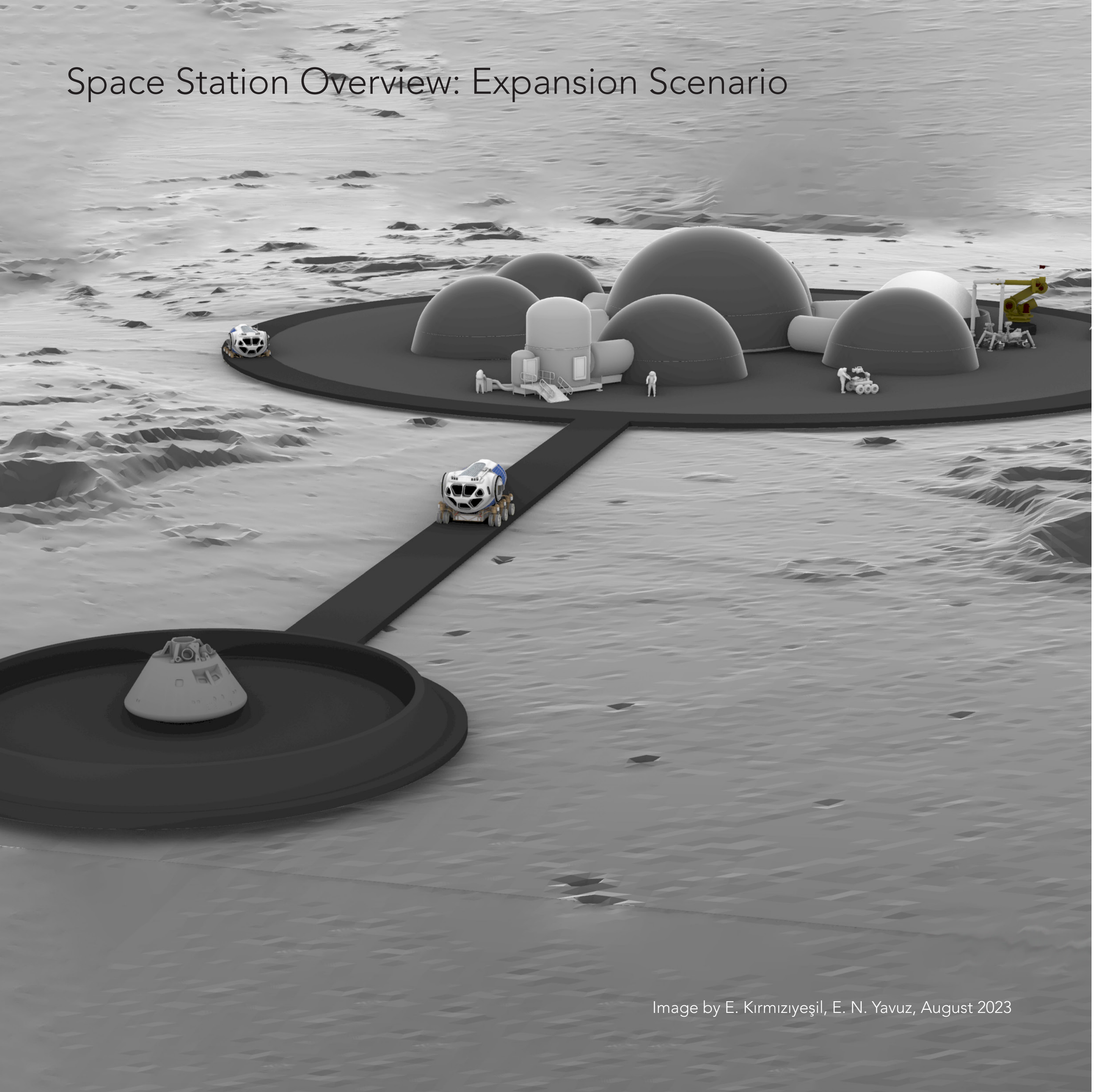


Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023

Expansion Scenario Version 1

In our master plan, we introduce Module 2, designed to comfortably house a large group of 12 individuals. We designed this module considering key factors such as space requirements, functionality, and creating a comfortable living environment.

We started our design with a detailed planning process, which included sketching and drafting plans and sections. We carefully outlined various rooms, including crew quarters, common areas, a greenhouse, and other necessary facilities. Our plans also specify dimensions and proportions, ensuring compliance with safety regulations and creating a suitable living environment.

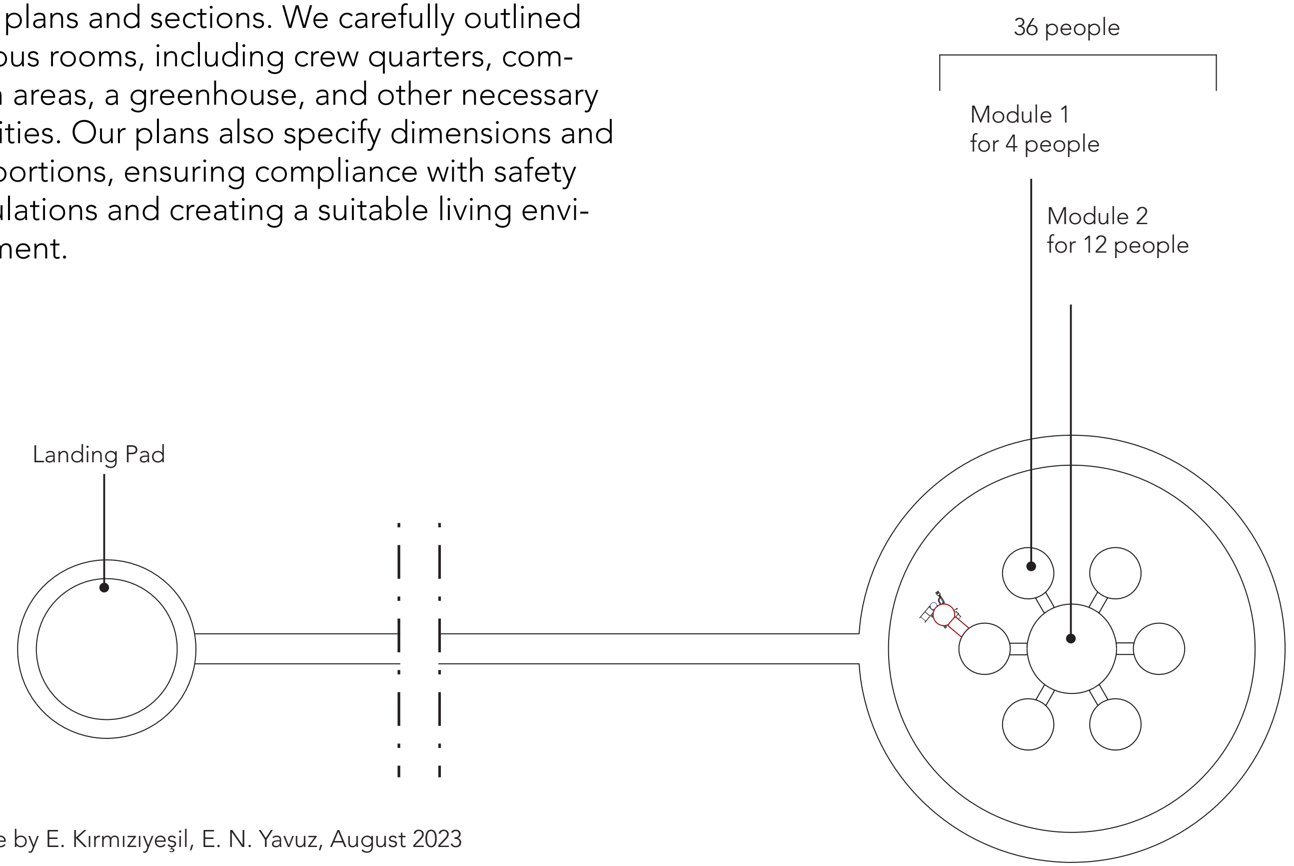
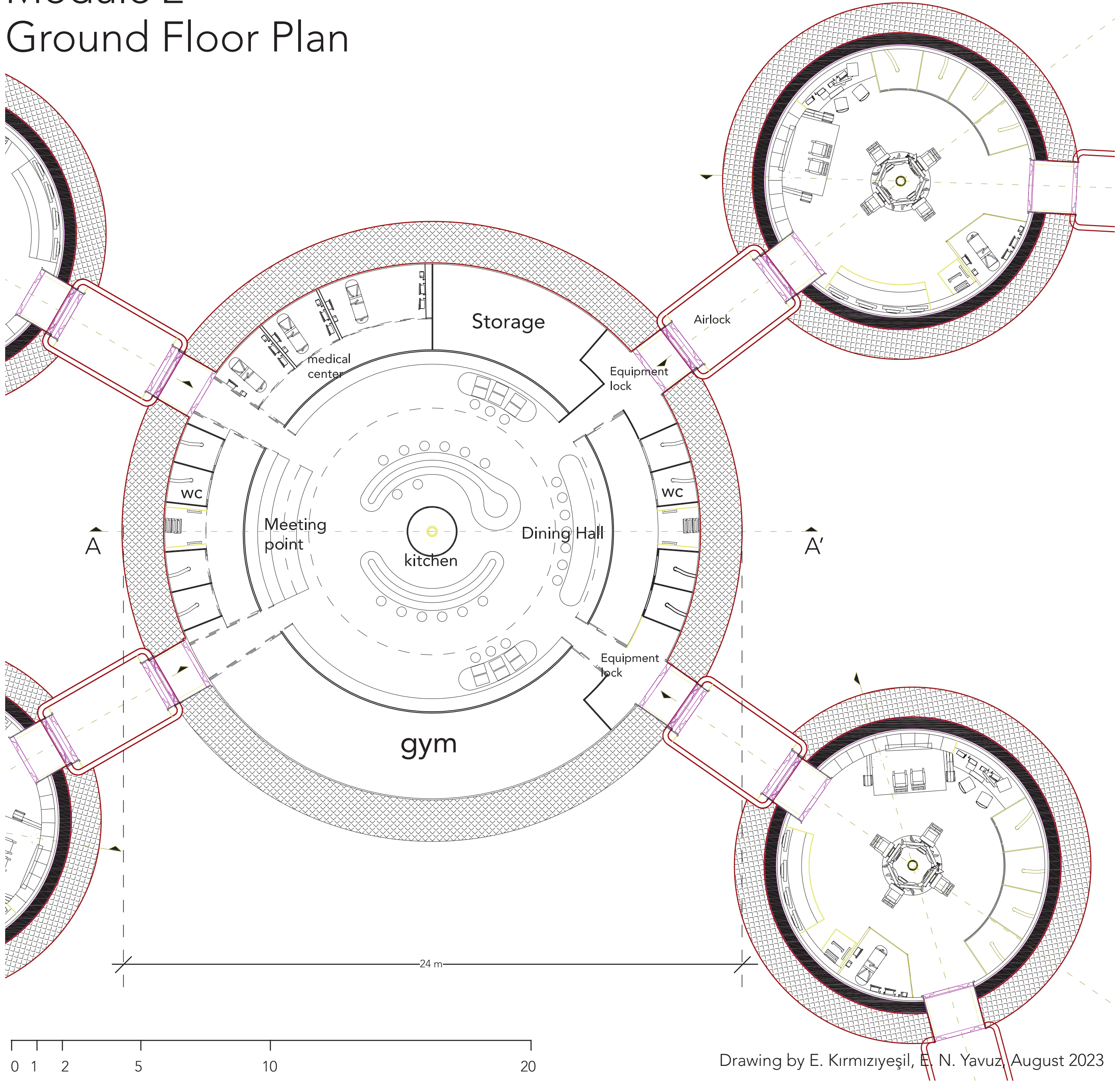


Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023

Module 2
Ground Floor Plan

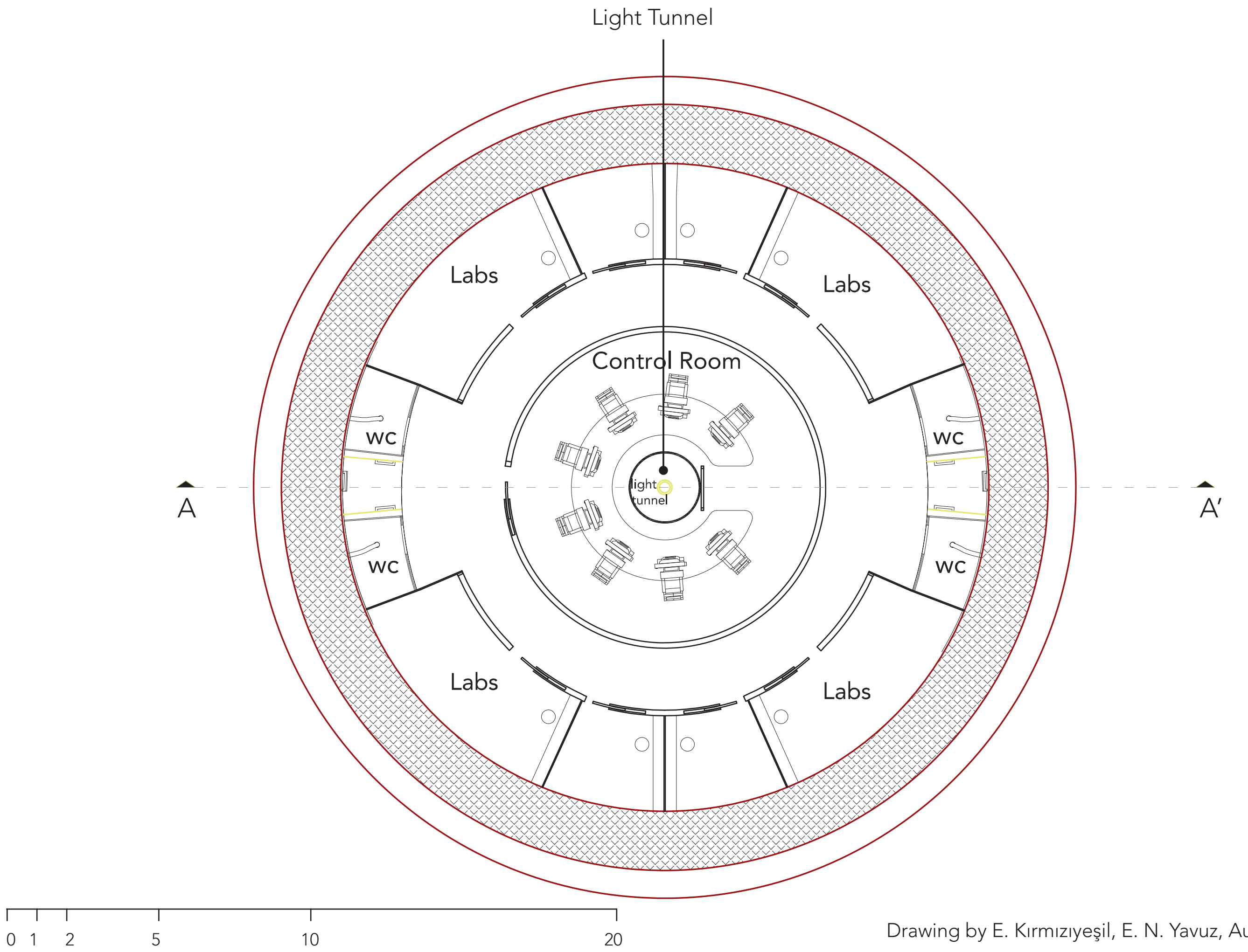


Drawing by E. Kırmızıyeşil, E. N. Yavuz, August 2023

First Floor Plan

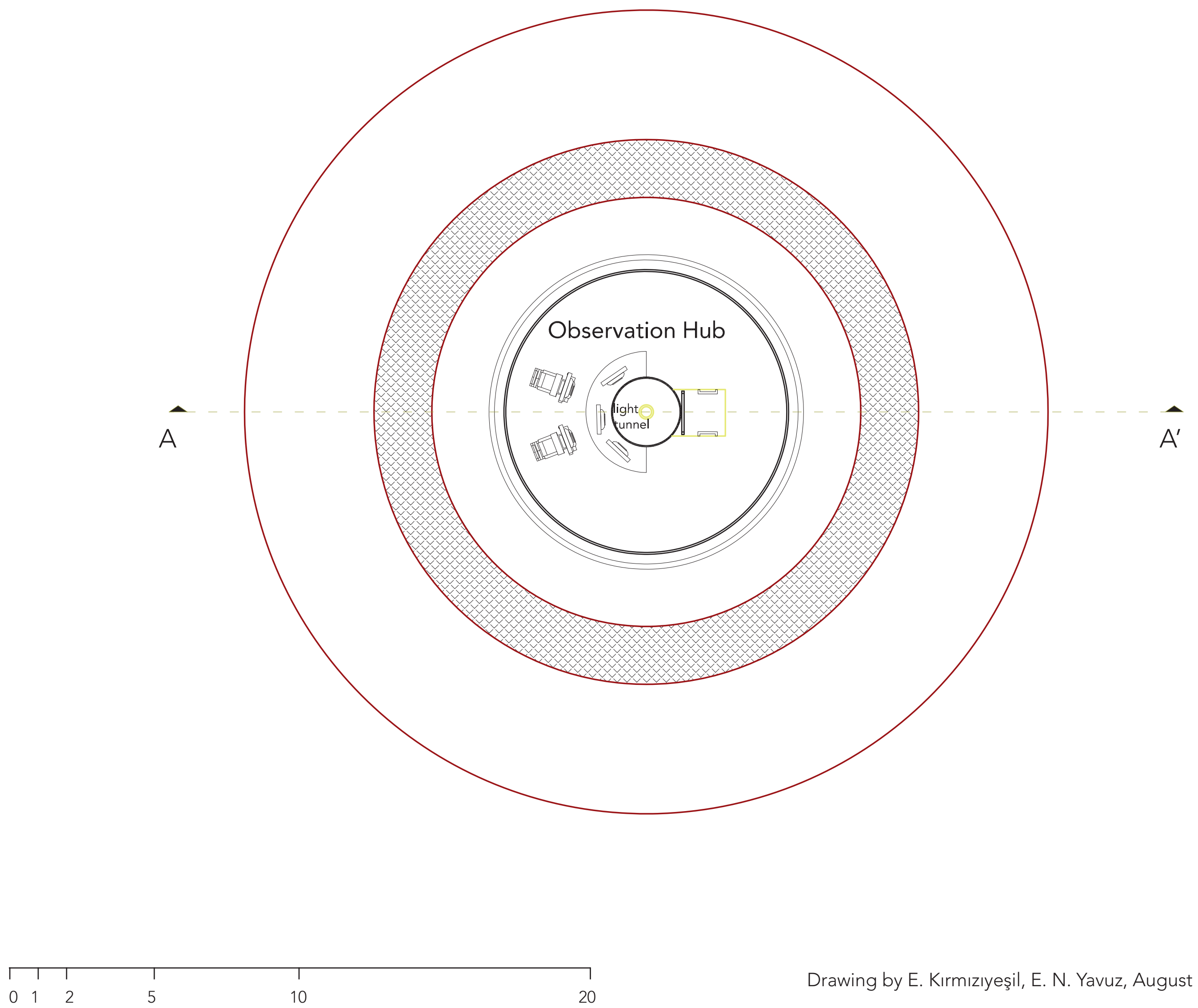
To enhance the lighting within the space station, we propose the use of natural sunlight, which offers a more pleasant and visually accurate experience compared to artificial lighting. Our concept involves a light tube that captures sunlight and directs it into the station. This can have positive effects on the well-being, mood, and circadian rhythm of the residents.

Furthermore, harnessing sunlight as a primary light source can lead to substantial energy savings by reducing the need for artificial lighting. The captured sunlight can be efficiently distributed throughout the space station, decreasing the dependence on electric lights and minimizing power consumption.



Drawing by E. Kırmızıyeşil, E. N. Yavuz, August 2023

Second Floor Plan

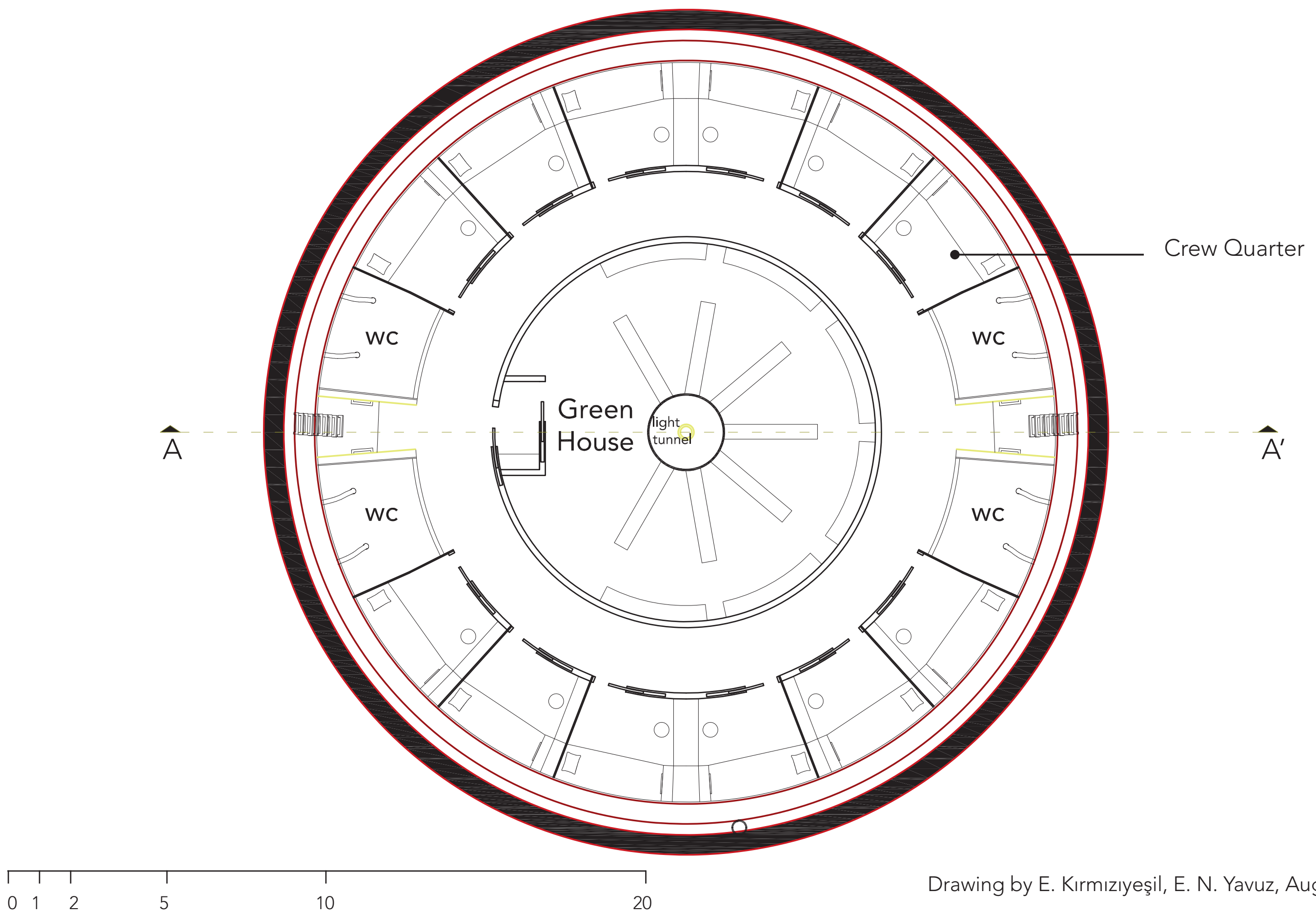


Drawing by E. Kırmızıyeşil, E. N. Yavuz, August 2023

-1 Floor Plan

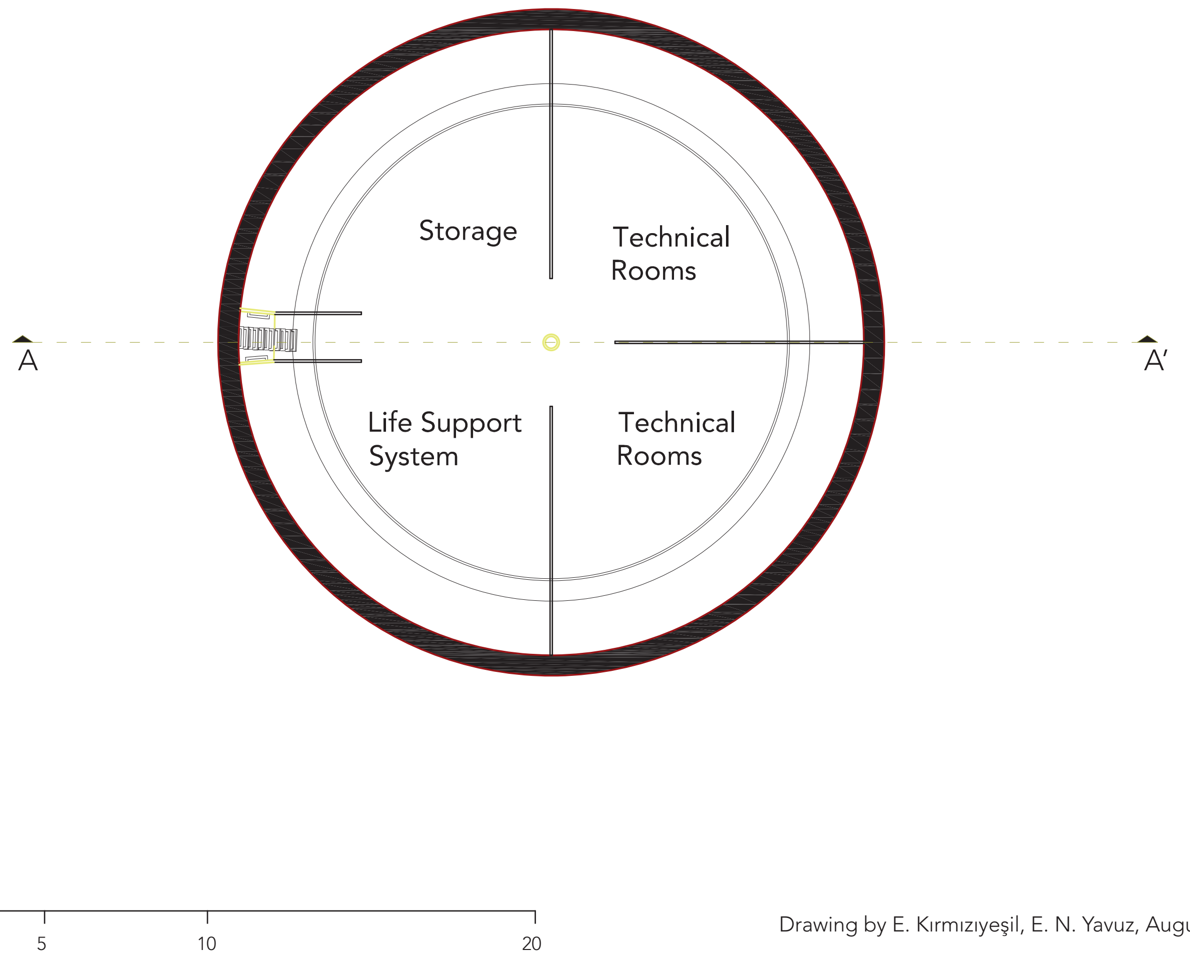
On the -1 floor, there are 12 separate rooms for the crew members. As can be seen in the drawing, there is a dedicated space in the middle for production units. This area is kept separate so that it works properly and safely. However, it is not completely cut off, it is put in a way that crew members can still see it easily. This design choice makes sure the production area is not just functional but also connected to the crew's space.

The isolated production area is designed with a dual purpose: practical functionality and the psychological well-being of the crew. This way, the design ensures things work efficiently while also letting the crew interact with what is happening in the production area.



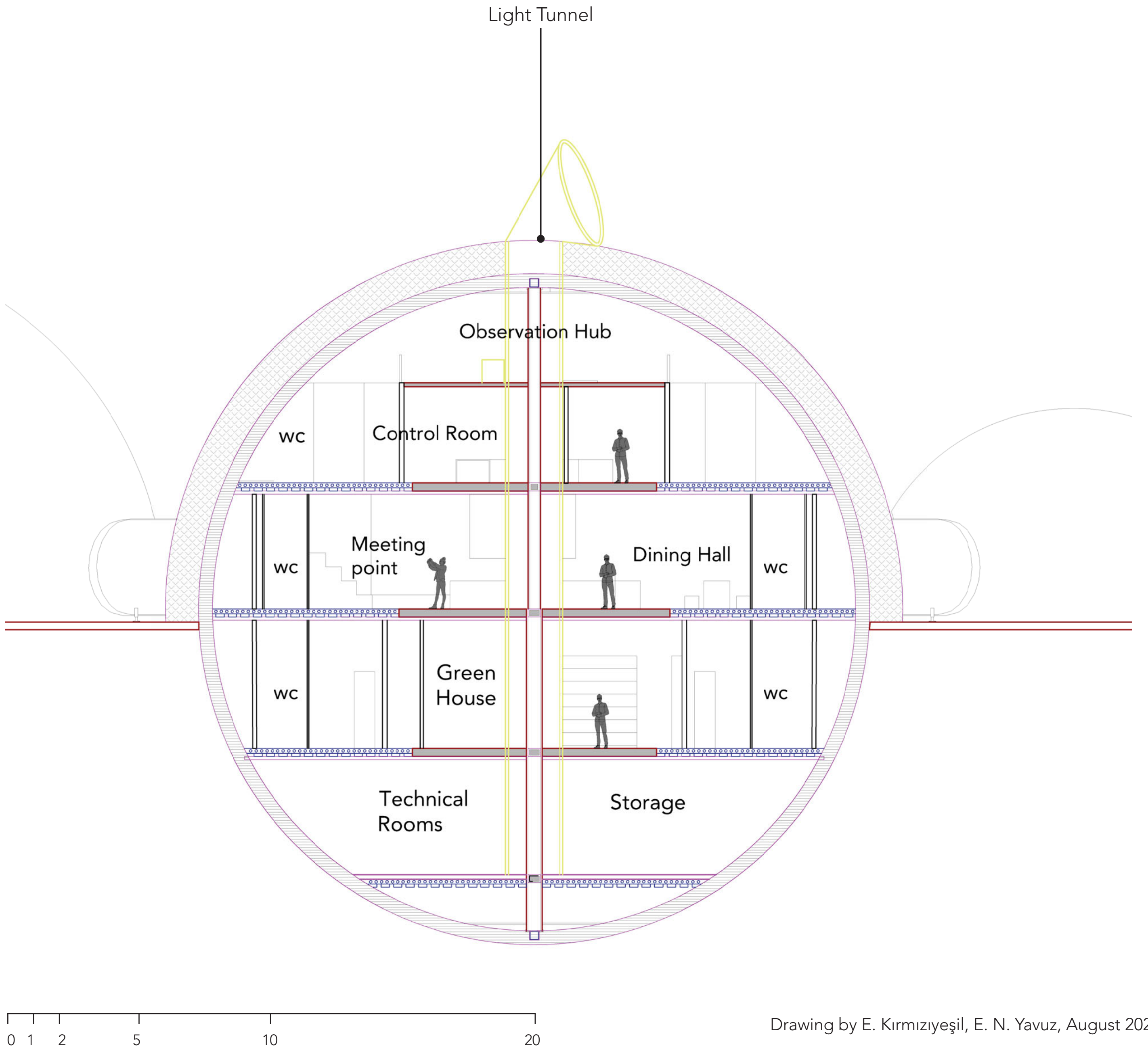
Drawing by E. Kırmızıyeşil, E. N. Yavuz, August 2023

-2 Floor Plan



Drawing by E. Kırmızıyeşil, E. N. Yavuz, August 2023

Section A-A'



Drawing by E. Kırmızıyeşil, E. N. Yavuz, August 2023


Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023

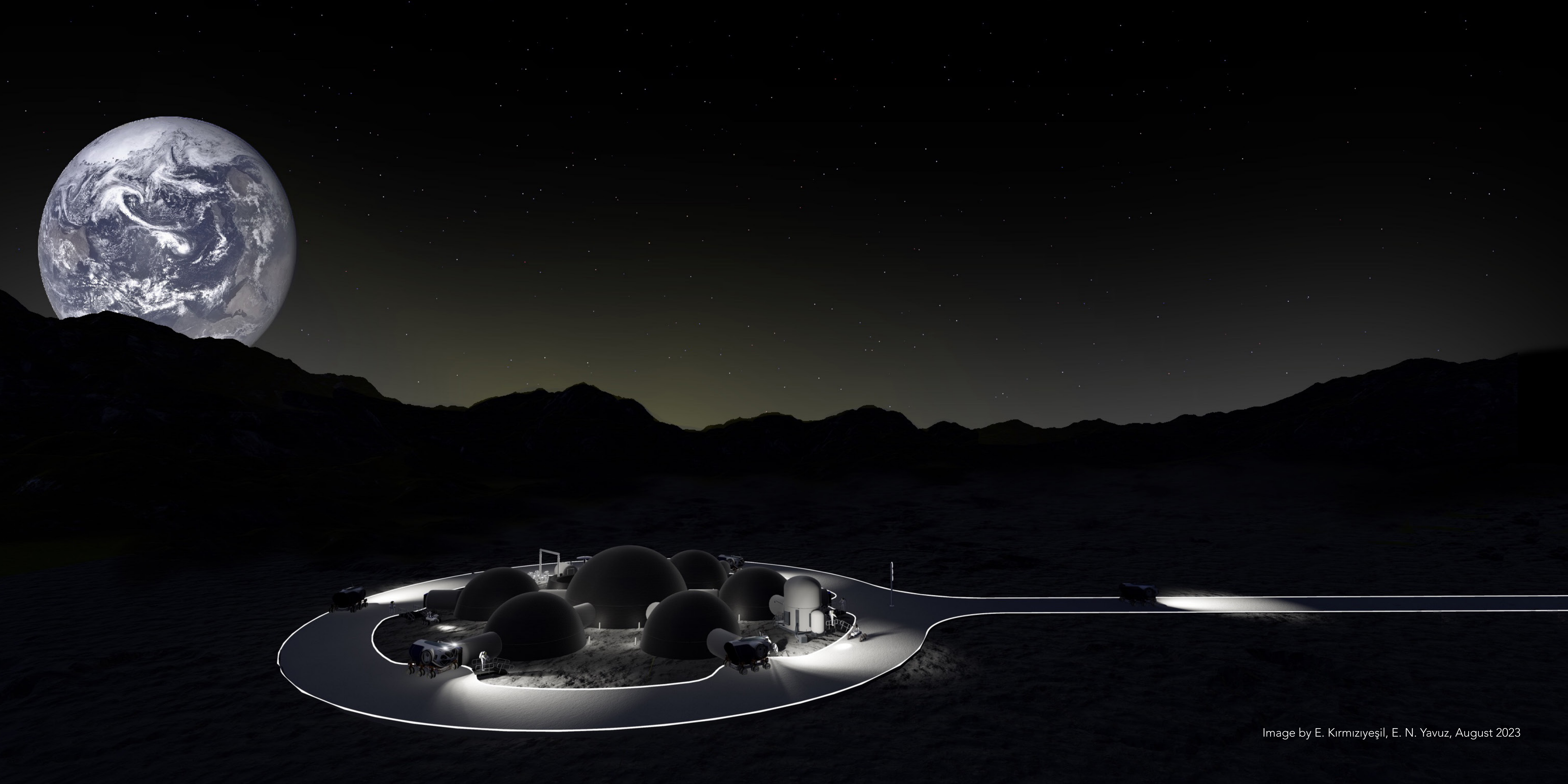


Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023


Image by E. Kırmızıyeşil, E. N. Yavuz, August 20

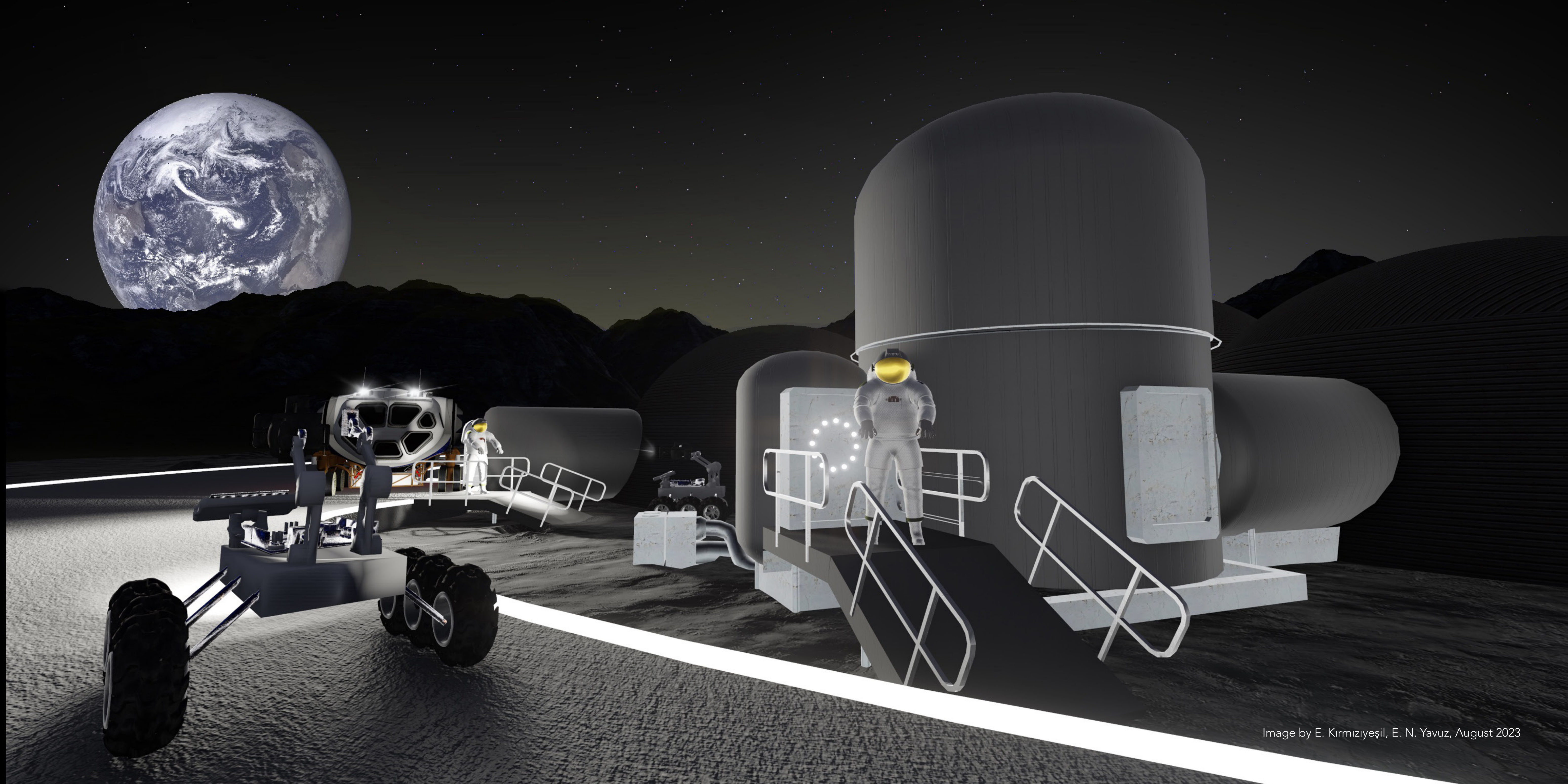


Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023

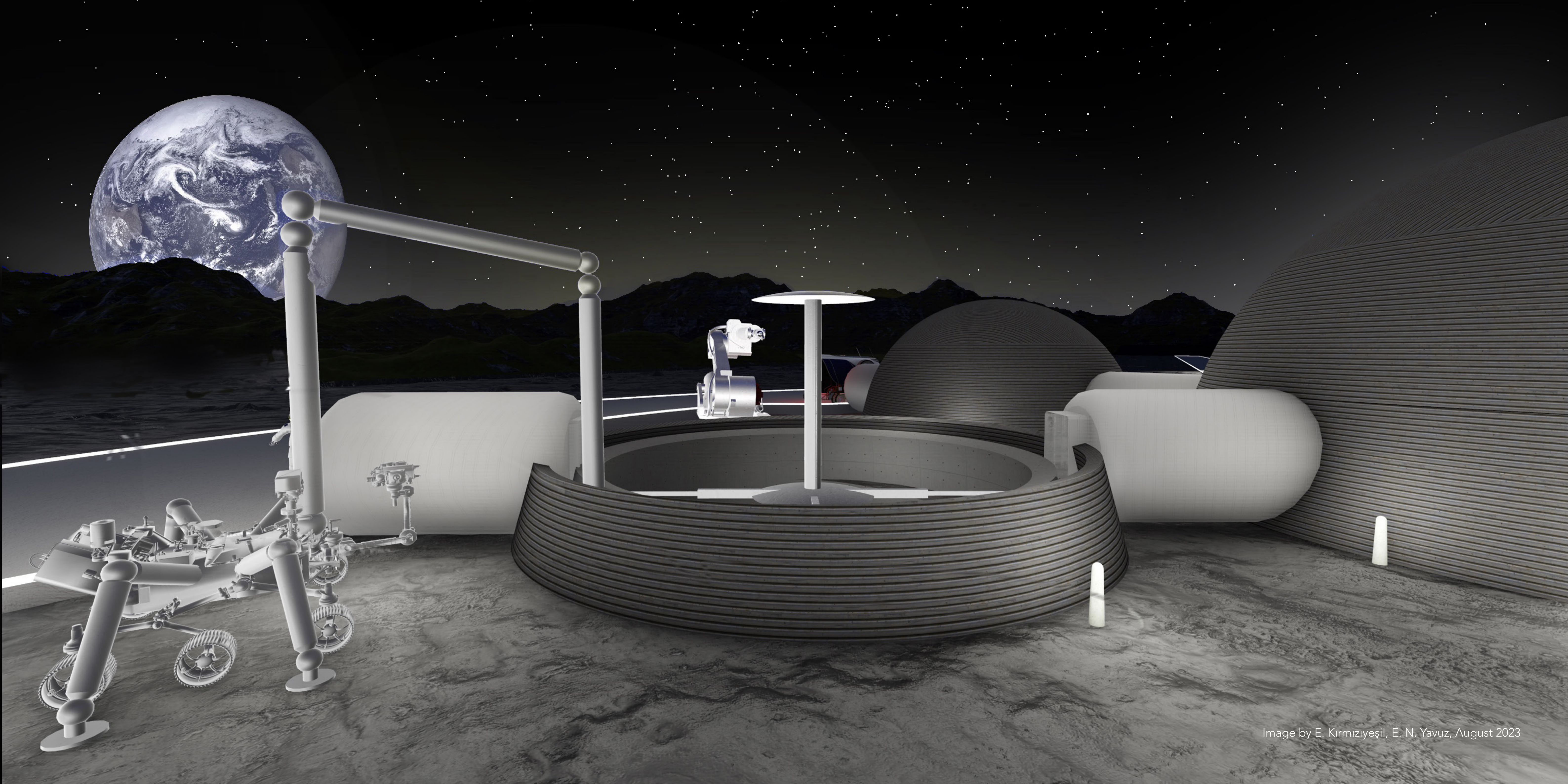


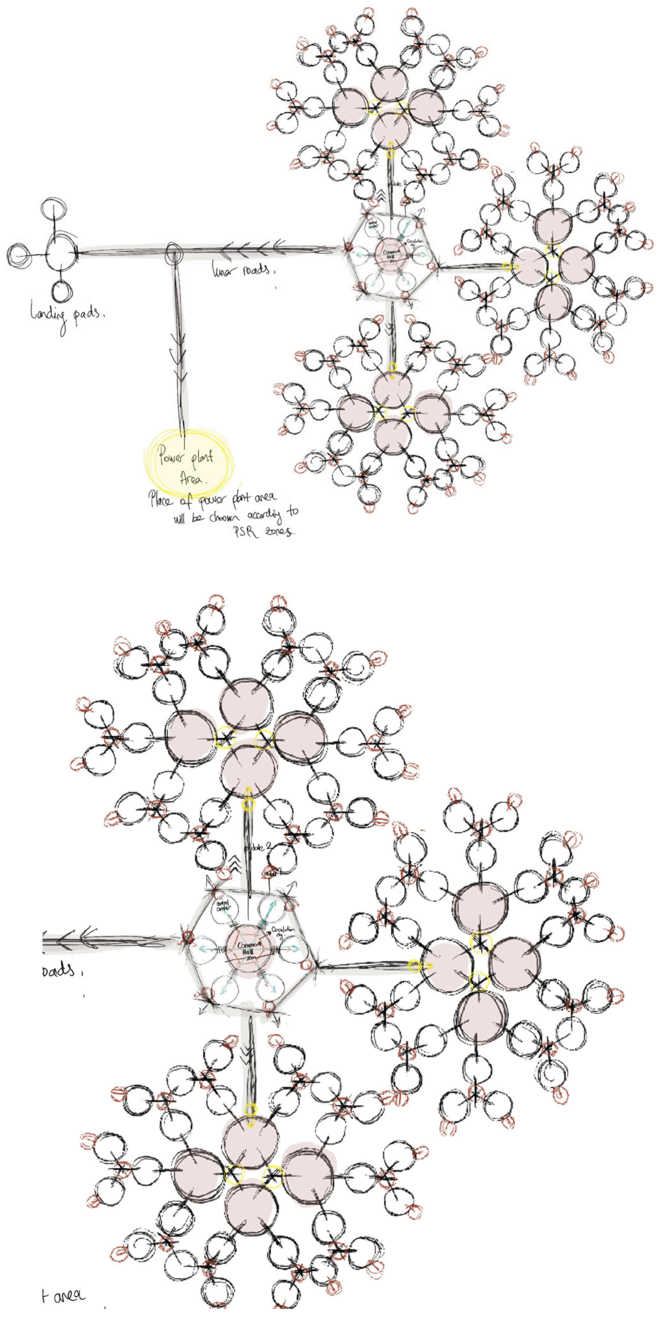
Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023

Expansion Scenario Version 2

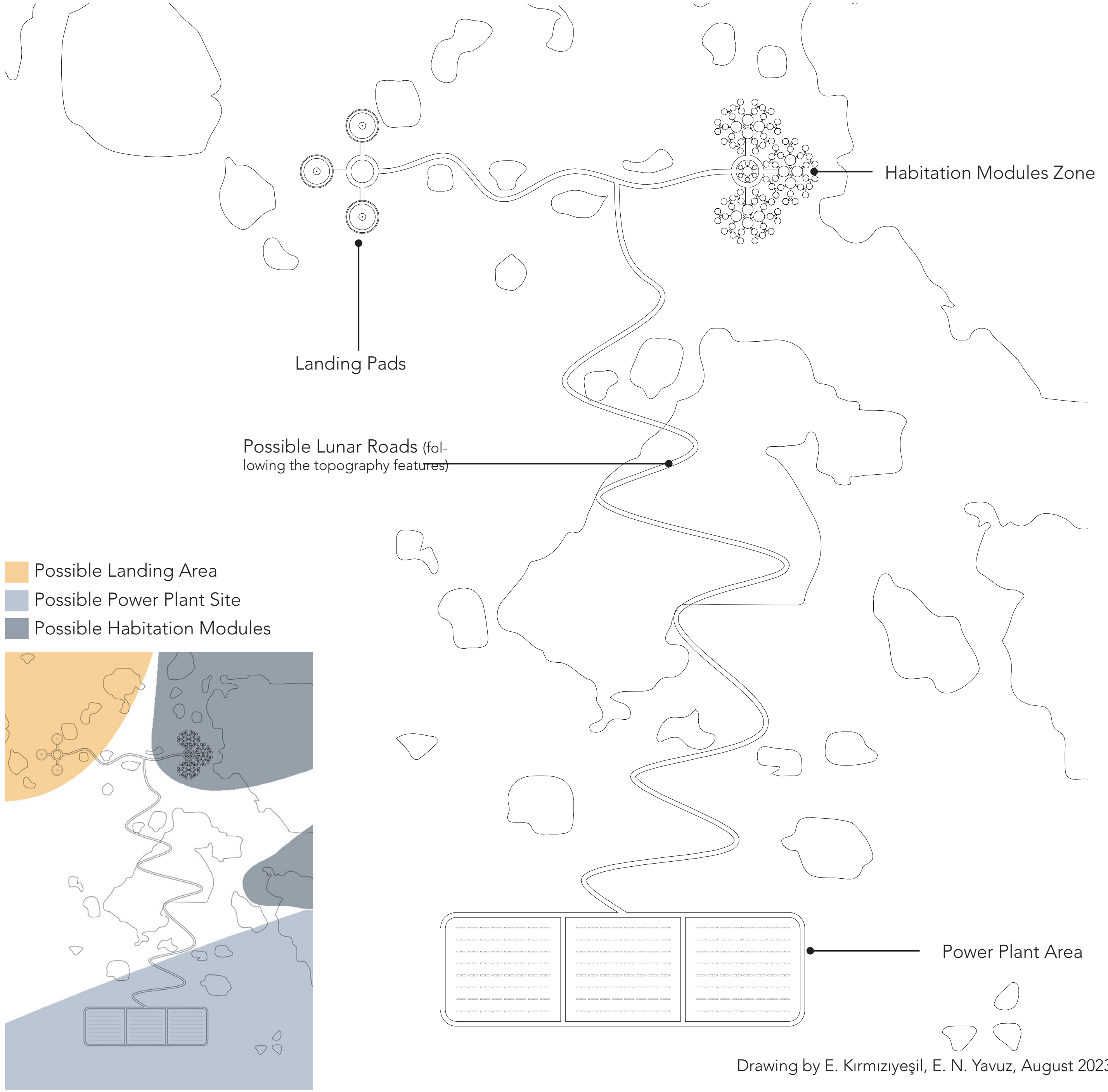
In the new master plan, we have undertaken the task of designing a comprehensive layout to accommodate a significantly larger number of people, specifically 456 individuals. This updated plan reflects our foresight into future scenarios and the need to provide suitable living and working spaces for a larger population.

To effectively design for such a substantial number of people, various factors were taken into consideration, including space allocation, functionality, circulation, and community engagement. The aim was to create an environment that promotes productivity, social interaction, and overall well-being.

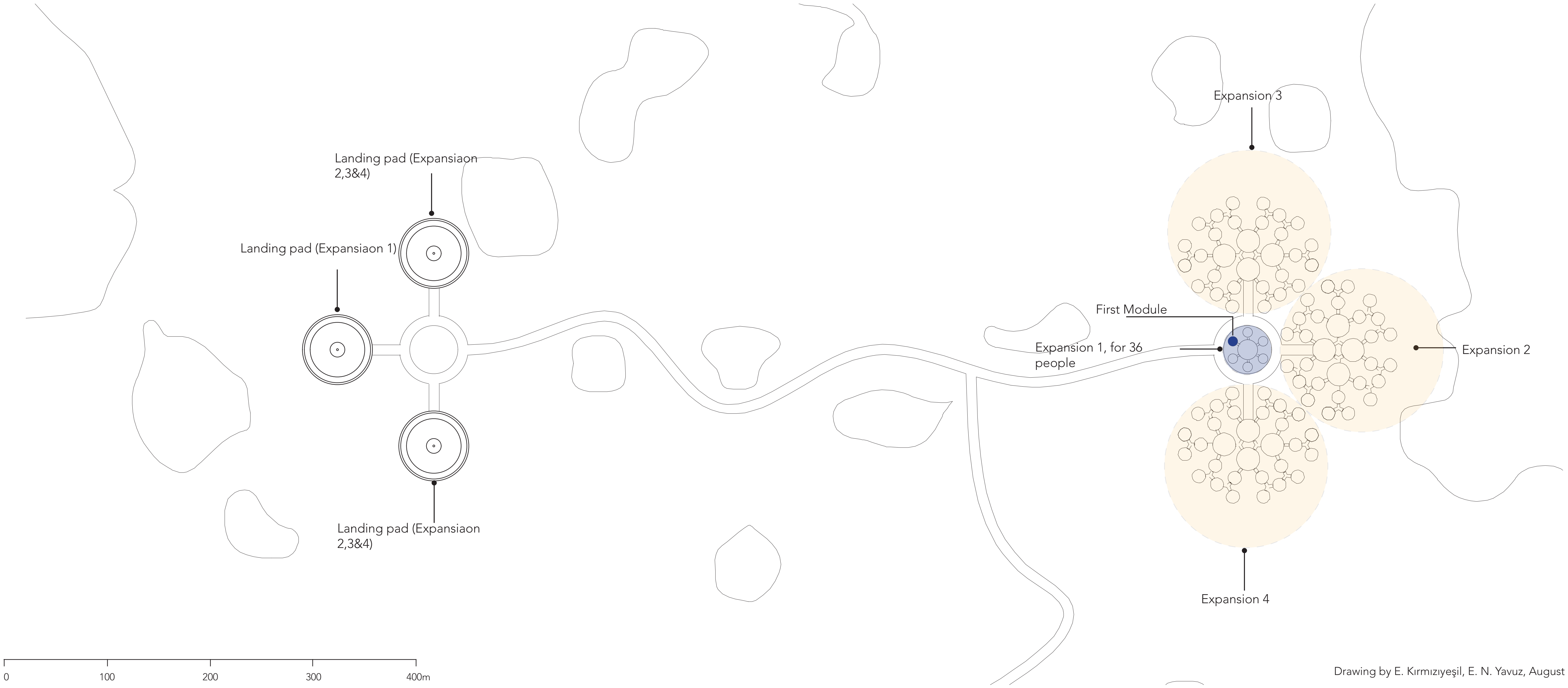
The updated master plan includes an extensive analysis of the site, taking into account its size, topography, and surrounding infrastructure. This information helps determine the most suitable arrangement for buildings, amenities, and open spaces to efficiently accommodate 456 individuals while considering the site's constraints.



Sketch by E. Kırmızıyeşil, E. N. Yavuz, August 2023

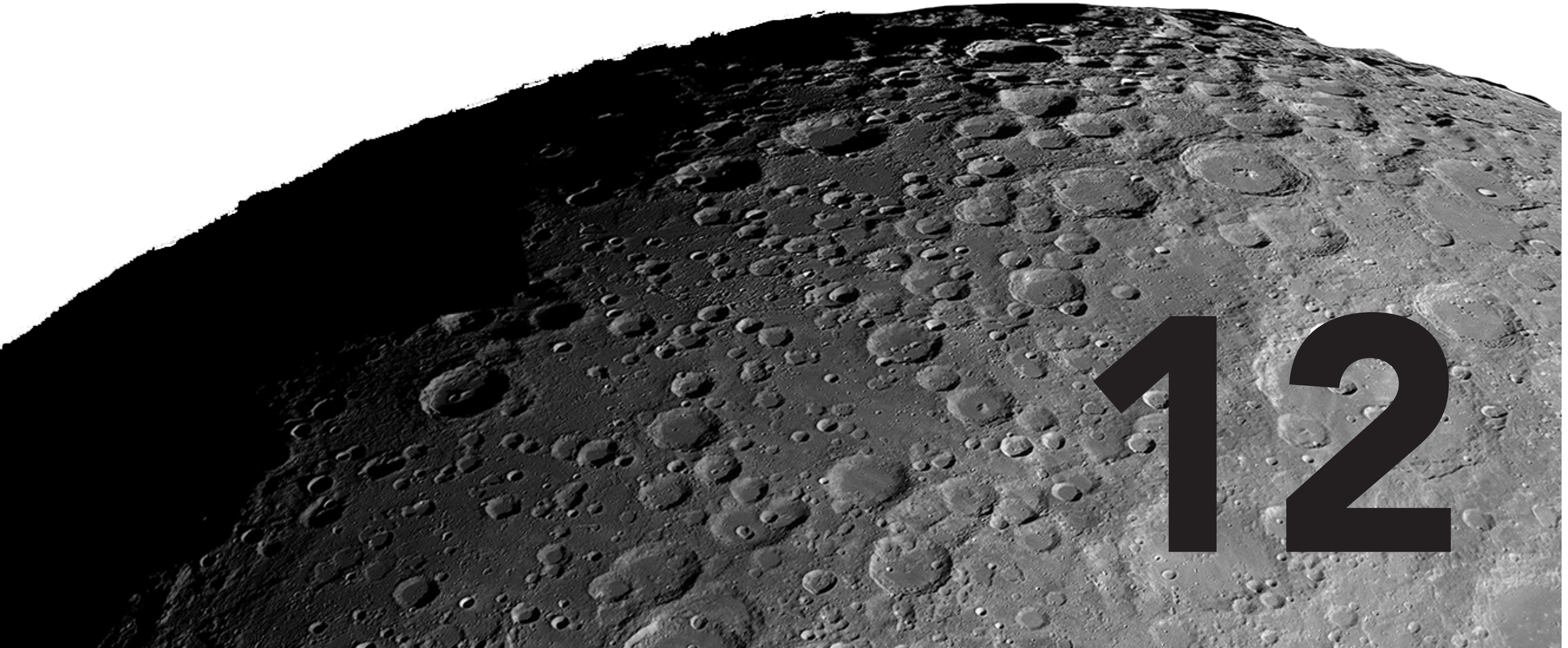


Drawing by E. Kırmızıyeşil, E. N. Yavuz, August 2023



Drawing by E. Kırmızıyeşil, E. N. Yavuz, August 2023

Interior Design



As humanity advances in space exploration, habitation on the Moon becomes an important stepping stone. When considering the well-being of lunar inhabitants, the design of lunar station interiors plays a crucial role.

The initial modules of this station are planned to house scientists and explorers, then in the future with the addition of new modules, it is planned to house a broader community of lunar researchers and even tourists. And for this plan to work, we had to ensure the comfort of its residents so we took great care and thought on the interior design of our modules, where we tried to harmonize the aesthetics and innovation seamlessly.

Designing these lunar habitats presented unique challenges. Traditional windows, common on Earth, proved unsuitable due to lunar radiation. However, we found an innovative solution to this that prioritizes safety while still being able to have the sunlight into our design, a light tunnel system.

This network of mirrored conduits crisscrossed through the station, reflecting and channeling light. Yet, reproducing Earth's natural light patterns within the extended lunar days and nights presented difficulties. Our solution was inspired by the circadian light system which we learned from a guest lecturer Sebastian Arıstotelis in a class by Prof. Valentina Sumini. This adaptable lighting system imitates terrestrial transitions, reinforced by circadian rhythms to synchronize our internal clocks with the lunar environment.

The Moon’s light gravity introduced unique health considerations. To address this, we established fitness zones within the station, acknowledging the importance of maintaining the physical well-being of our residents.

Looking ahead, we ensured our designs could accommodate the evolving requirements of lunar exploration. Modularity and multi-functionality emerged as an important principles, enabling the seamless expansion of the station as humanity’s lunar aspirations expanded.

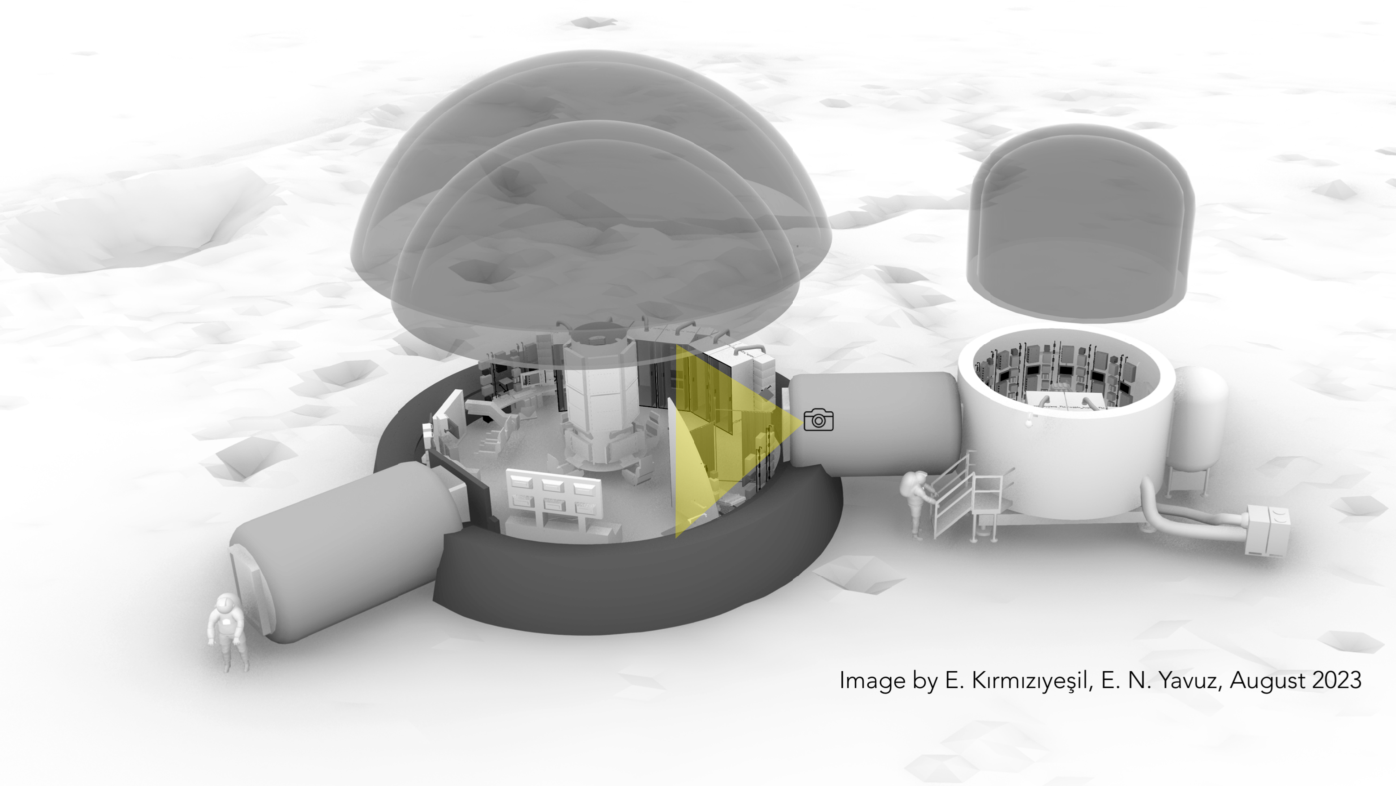
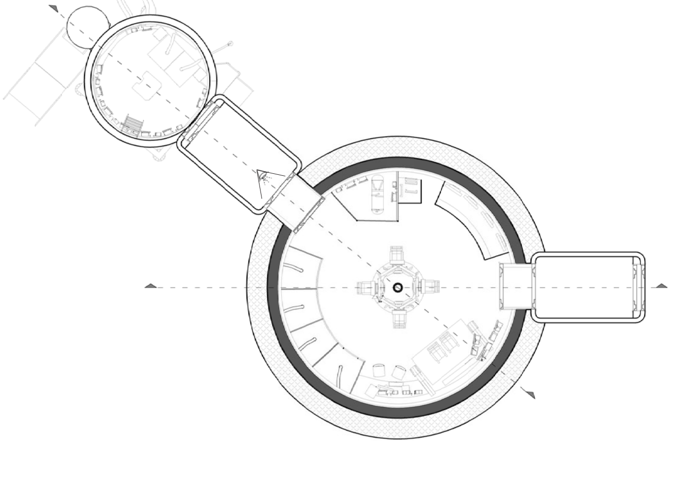


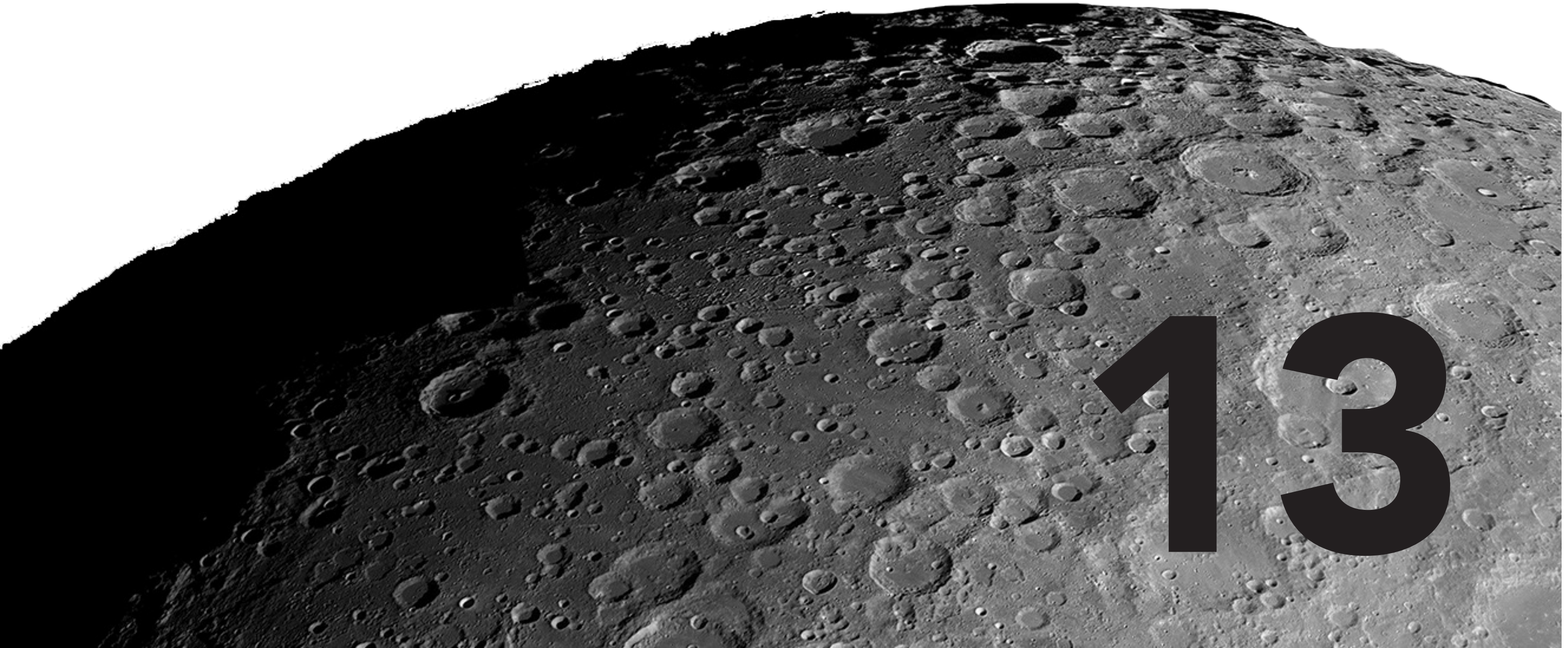
Image by E. Kırmızıyeşil, E. N. Yavuz, August 2023

Module 1’s render view from the airlock. We see the control room in the middle. On the left, medbay can be seen.
Created by E. N. Yavuz & E. Kirmiziyesil, 2023



Module 1 Ground Floor
(Indicating the point of render view)

Conclusion



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In conclusion, the architecture of a lunar station represents a remarkable fusion of technological innovation, scientific exploration, and human ability. This thesis delved into the multifaceted aspects that contribute to designing a functi-onal and self-sufficient habitat on the Moon's surface, considering the challenges related to the lunar environment and the diverse needs of its inhabitants.

By thoroughly studying past lunar missions, space station plans, and innovative materials, this research emphasized the crucial signifi-cance of adaptability, making the best use of resources, and efficiency in designing lunar structures. The use of semi-autonomous ro-bots, 3D printing technologies, and modular building techniques is essential for creating a lunar station that can endure the Moon's tough conditions and support extended human stays.

Throughout the course of our research, the evolution of our lunar station's architectural design was enriched by the feedback gathered during our collaborative meetings. This process allowed us to make significant refinements to the module designs, ensuring that they not only met the functional and technical require-ments but also aligned with the practical needs and preferences of future inhabitants.

Furthermore, the psychological and physio-logical well-being of astronauts emerged as a central concern in lunar architecture. This thesis explored the significance of incorporating ele-ments that foster mental health and mitigate the effects of isolation, while also emphasizing the importance of efficient space utilization to counteract potential feelings of confinement.

In light of the increasing interest and investment in lunar exploration by international space agencies and private entities, the findings of this research offer valuable insights for future architects and engineers tasked with realizing a self-sufficient lunar station. Collaboration, knowledge-sharing, and interdisciplinary approaches will play essential roles in overcoming the challenges that lie ahead.

Ultimately, the architecture of a lunar station extends beyond the boundaries of mere infrastructure, it symbolizes humanity's spirit of exploration and our ability to push the boundaries of our understanding and capabilities. As we look towards a future where the Moon serves as a stepping stone for further space exploration, the lessons learned from this architectural practice will not only shape the way we inhabit other celestial bodies but also inspire us to reach for new horizons in our unique planet Earth.

With the rapid advancement of space exploration in recent years, we found ourselves presented with a remarkable occasion to undertake research and conceptualize a prospective lunar station for the forthcoming era.

In conclusion, our project fulfilled the desire to connect human capability with the backdrop of outer space while also allowing us to explore the possibilities of architectural design beyond of our terrestrial limits. Because of this, the idea of developing existence in space is no longer limited to science fiction movies. It is developing into an interesting and feasible concept. For architects, working in this field is incredibly stimulating, difficult, and forward-thinking because it involves unique design philosophies and principles unlike anything else on Earth.

Finally, this thesis has given us new viewpoints in the field of architecture, offering valuable insights that affect our professional outlook. The knowledge we gained has been transformative, making us reconsider long-held assumptions and usual practices in architecture. We now find ourselves questioning and reimagining established norms, which has enriched our work as architects. We owe a debt of gratitude to our professors and mentors who provided us with the opportunity to proceed on this intellectual journey.

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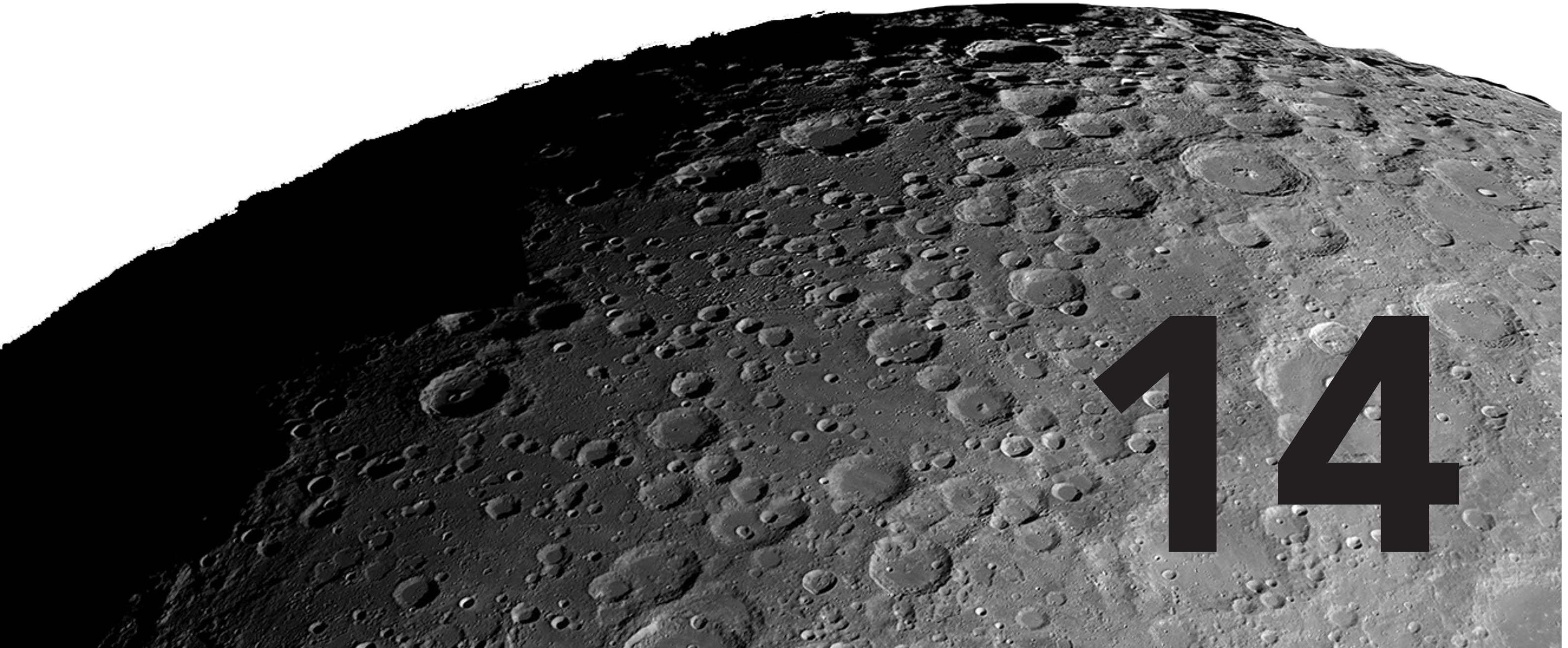

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