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LLRU – Designing for Future Flexibility on the Lunar Landscape

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ABSTRACT

Humanity has its eyes set on returning to the Moon for the first time in over 50 years; however, it is no longer for political gain as it was during the Cold War. We are returning in order to take advantage of the untapped resources and potential of an extraterrestrial refueling base. The plans set forth by NASA and the Artemis program neglect how little we still know about the Lunar surface and the exploring and experience we will need before we can exploit and settle on a new world. The intent of this study is to develop a new Lunar architecture typology by proposing a Lunar module system designed for mining and research that factors in the ethical and responsible use of intergalactic materials.

The Lunar Lab and Research Unit, LLRU, is an adaptable system that grows with the changing needs of astronauts as we begin to develop a more permanent residence on the moon. It is a modular system of sealed, pressurized, and fully equipped life support systems combined with accessories to assist astronauts in a broad range of missions and experiments near the Lunar South Pole. Prior to the completion of a permanent Lunar base, the astronauts stationed on the Moon will need an advanced semi-mobile, semi-permanent, unit which ultimately acts as a base for astronauts as NASA learns how to live on a new celestial body. Brand N. Griffin in *Space Architecture Education for Engineers and Architects* explain that the Moon offers a "simpler, safer, quicker, and less expensive way to learn how to *Settle*".[1] The ability to move and test different locations prior to the full commitment of a permanent base will prove to be an

[1] Sherwood. "Space Architecture Education—Site, Program, and Meaning." *Space Architecture Education for Engineers and Architects*. 47

invaluable asset in our pursuit to become an interplanetary species. Once we begin to design, and subsequently build, a permanent solution to live on the Moon, the LLRU can transition into a mobile hub for long-term missions away from the base.

The most influential factor for returning to the Moon is the vast quantity of untapped natural resources. More specifically, the abundance of frozen water which can be converted into fuel for missions that stretch deeper into outer space, rare earth metals to provide economic autonomy for countries participating in the Artemis Accords, and the helium-3 isotopes which could provide humanity with the key to renewable energy.

We plan to become an interplanetary species; therefore, it is more paramount than ever to establish a new vernacular of architecture that facilitates a good quality of life for astronauts through thoughtful consideration of the effect of a new environment on the human body and seamlessly integrate this with the inevitability of a Lunar economy derived from mining. Ultimately, the LLRU is fundamentally ingrained in our process to gain a foothold on the Lunar surface by acting as a typological tool for habitation and experimentation prior to the completion of a Lunar City.

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ACKNOWLEDGEMENTS

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Chapter 1

Environmental Considerations on the Lunar Surface

The drastically diverse and radically harsh environments that occur on extraterrestrial bodies paves the way for a new vernacular architecture to be developed by space architects. Traditionally, designers have implemented architectural decisions to maximize the quality of living for inhabitants ranging from material choices, shading devices, heat sources, and overall form. The well documented site conditions of the Lunar surface create a unique set of challenges for the LLRU which guide the architectural design choices.

Sub-Chapter 1 Atmospheric Concerns

The lack of atmosphere on the Moon poses a threat to astronauts because of a heightened risk for micrometeoroids and their potential to damage equipment. These micrometeoroids are small enough to burn up inside of Earth's atmosphere, but at an average mass of 10^{-10} kg to 10^{-8} kg while reaching speeds of approximately 72 km/s, it is important to design LLRU with a strong outer shell. The Earth's atmosphere also protects humans on a more regular basis from harmful radiation given off by the Sun. The Earth is bombarded by 0.001 to 0.002 Sv/year while astronauts on the Moon faces 0.3 Sv/year.[2]

[2] Benaroya. *Building Habitats on the Moon*. 46.

Sub-Chapter 2 Temperature Variations

The 29.53 (Earth-days) day-night cycle on the Moon creates a violent and drastic change in temperature. The shift from the blisteringly hot 127 degree Celsius to the frigidly cold -173 degree Celsius occurs at a staggering 5 degrees Celsius/hour.[3] Thermal comfort is an integral aspect to consider when rating the quality of living in any building. Beyond the temperature fluctuation, the prolonged periods of light and dark pose a threat to the natural circadian rhythm that humans have adapted to follow over a 24-hour Earth day. The Lunar south pole is a prime area for a settlement because the “Sun never completely sets there, and that the Earth is visible 100 percent of the time”.[4] This is vital for the psychological state of astronauts. Architecture, in general, holds the responsibility to protect from physical and psychological damage to inhabitants. While this is consistent on the Moon, the stakes are higher and threats to well-being are more intense.

Sub-Chapter 3 Weaker Gravitational Field

The Lunar surface has approximately 1/6th of the 9.8m/ s^2 gravity on Earth. The weaker gravitational force on the Moon requires a consistent and rigorous exercise regimen to maintain the overall health of the astronauts. Exercise to reduce muscle loss and maintain bone strength in astronauts is essential on the International Space Station, equating to 2 hours of different types of

[3] Benaroya. *Building Habitats on the Moon*. 43, Table 3.1.
[4] Benaroya. *Building Habitats on the Moon*. 210

exercise per day.[5] Beyond the physical benefits, the implementation of leisure activity, such as exercise into daily routine is proven to act as a valuable entity to preserve mental health.

Sub-Chapter 4 Lunar Regolith

Lunar regolith is the fine, gray, dusty soil coating the surface of the Moon. It is comprised of rock chips, mineral fragments, volcanic glass, and “agglutinates” (mineral fragments held together by glass that is formed from micrometeorite impacts). Regolith is impacted by “space weathering” from a combination of meteoroid strikes, radiation, and solar wind particles.[6] The material properties and lack of wind or water erosion create a soil that is extremely sharp and rough which is prone to damaging equipment and spacesuits.

[5] Canadian Space Agency. “Physical Activity in Space”
[6] Noble, Sarah. “The Lunar Regolith”

Chapter 2

Lunar Mining

NASA has its sights set on the Lunar South Pole (Shackleton Crater located near the center of figure 1 and detailed in figure 2) for the Artemis Missions. The conceptual idea of returning to the Moon for the first time in over 50 years and a human's philosophical destiny to explore the unknown is not enough to convince lawmakers to continue dedicating money to rocketry and innovative technology.

The solution is to create a self-sustaining space-economy in order to offset the cost for space exploration while generating revenue for participating countries. Beginning with In-Situ Resource Utilization (ISRU), mining on the Lunar surface can incite a "Moon Rush."[7] A continued presence on the Moon will require us to learn how to live off the land and inform humanity how to better live on Earth. The discovery of valuable resources has driven groups of people to assume the risks and costs of venturing into the unknown throughout human history. The westward expansion of the United States through Manifest Destiny was ignited and amplified by the discovery of gold in California.[8]

[7] Thangavelautham, Jekan, Aman Chandra, Erik Jensen. "Autonomous Robot Teams for Lunar Mining Base Construction and Operation

[8] American YAWP. "Manifest Destiny and the Gold Rush"

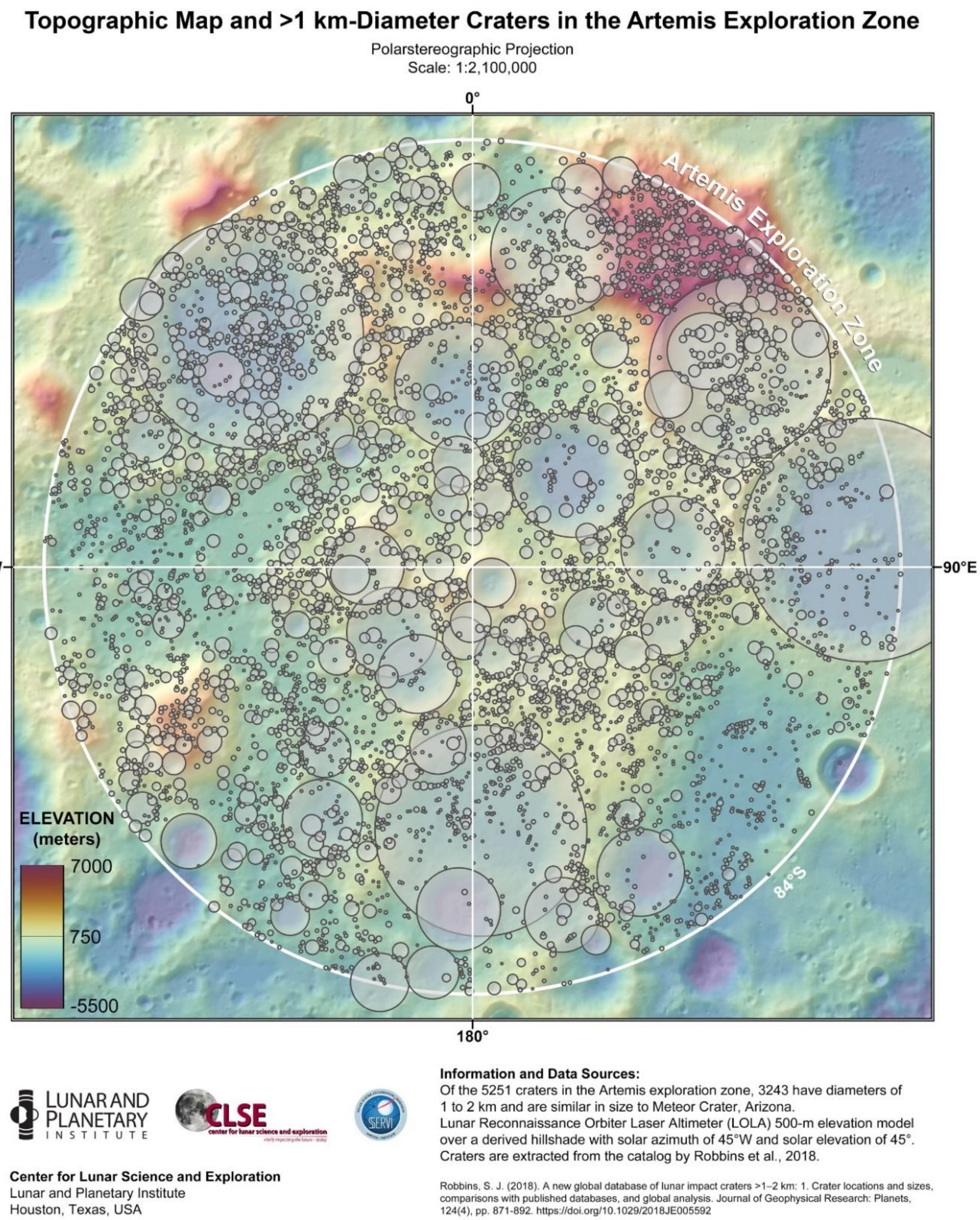

Figure 1 Artemis Exploration Zone and Relevant Craters near the Lunar South Pole [9]

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[9] Stopar; Meyer. "Topographic Map of the Moon's South Pole (80ºS to Pole)"

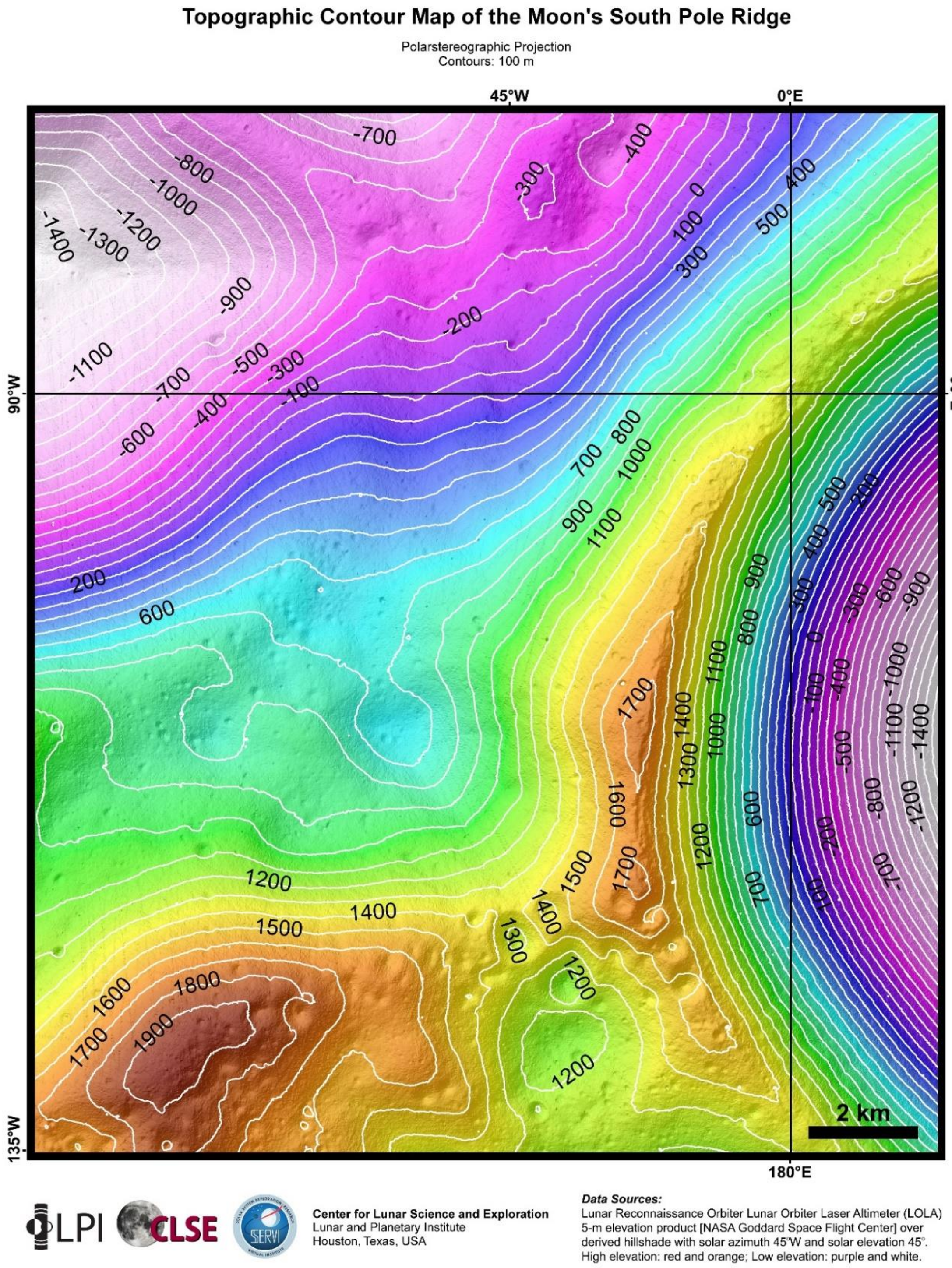

Figure 2 Topographic Contour Map of Shackelton Crater near the Lunar South Pole [10]

[10] McCanaan; Kathryn; Animireddi; Barrett; Boazman; Gawronska; Gilmour; Halim; Harish; Shah; Kring "Topographic Contour Map of the Moon's South Pole Ridge"

The resources on the Moon will not allow for an average citizen to “get rich quick” but the abundance of frozen water will allow for exploration deeper into our solar system and the prevalence of rare earth metals or a helium-3 isotope will improve the quality of life for mankind by creating a means to more renewable energy.

Ethically speaking, we hold a unique opportunity when discussing the altering of the Lunar landscape to provide benefits to Earth. There are groups of people who are concerned about the damage that could be done to the Lunar surface during a race to control the most mineral rich areas. Astronomer Richard Green explains that some sites on the Moon are incredibly unique and are important for scientific research; but “they could be lost forever.”[11] Humanity is entrusting a limited number of nations and corporations to conduct sustainable and humane mining operations that maintain the knowledge on the Moon and the overall appearance. Given the destruction we have caused to our home world, Earth, it would be a travesty to ignore what we have learned about preservation.

The architectural vernacular on the Moon must reflect the economic implications placed on natural resource acquisition. Mining on the Moon will be conducted by autonomous robotics, thus the LLRU functions as a hub for astronauts to comfortably manage concurrent extraction operations. For example, the mobility of the LLRU is the tool that allows astronauts to monitor mining operations at different craters for longer periods of time than a simple rover would allow. The LLRU also grants astronauts the flexibility to explore new regions of the Moon and conduct experiments off-site from the water-rich craters. Because this unit’s capabilities are so broad, an

[11] Clery, Daniel. “Moon’s Scientifically important sites could be ‘lost forever’ in mining rush”

architect offers a special set of skills to design the spaces to ensure the quality of life for astronauts is maintained. The mobility of these units will benefit the maintenance of equipment without the need for constant human intervention and presence at quarries.

Sub-Chapter 1 Water

Water is the most important natural resource in the world so it is no surprise that the discovery of massive quantities frozen in deep south pole craters has driven NASA to decide that this region will be our target for the future Artemis Missions. The main location of interest is Shackleton Crater, located near the center of figure 3. Obviously, this water can be refined and filtered to create potable water for astronauts, but NASA has bigger plans.

Water, composed of two hydrogen atoms and one oxygen atom (H2O), holds the key for the ability for humanity to travel to Mars and beyond. Splitting the water molecule allows for rocket fuel to be created In-Situ, dramatically reducing the cost and complexity of launching a rocket to Mars.[12] The Moon will function as a refueling station for breaking new frontiers in outer space. Space-sourced water can also act as coolant for mining equipment or life-support systems.[13]

[12] Wang; Hao; Li; Sun; Sun; Huang; Li; Tang; Wang; Xiao. In-situ utilization of regolith resource and future exploration of additive manufacturing for lunar/martian habitats: A review

[13] Clery, Daniel. “Moon’s Scientifically important sites could be ‘lost forever’ in mining rush”

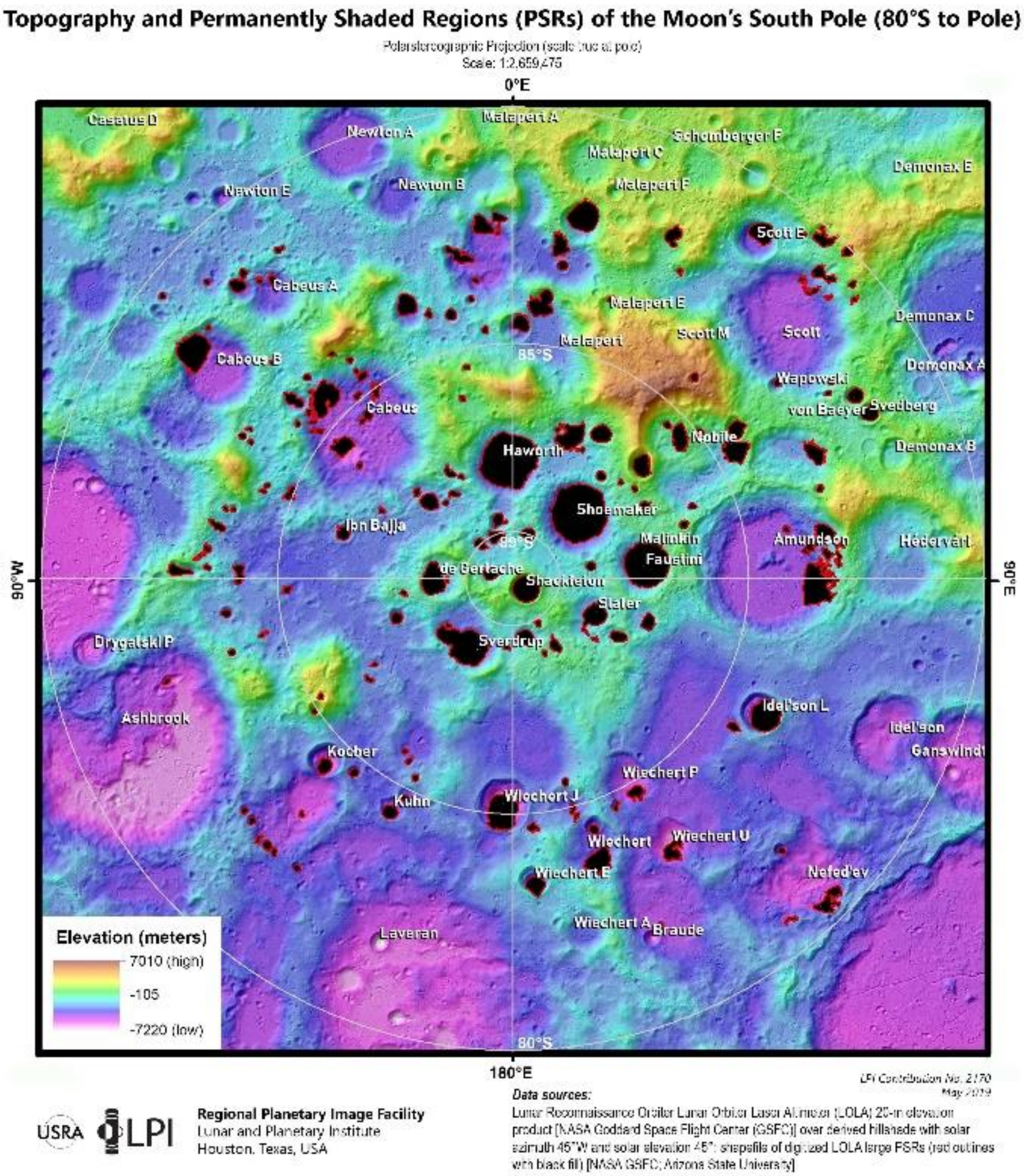

Figure 3 PSRs and Frozen Water near the Lunar South Pole [14]

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[14] Stopar; Meyer. "Topography and Permanently Shaded Regions (PSRs) of the Moon's South Pole (80°S to Pole)"

Sub-Chapter 2 Rare Earth Metals

Arriving to the Moon before China is an extra motivating factor for the participating states in the Artemis Accords because those nations can implement treaties and policies that act in the interest of humanity. There is also a growing concern that the rapid increase in demand for rare earth metals for technology related devices will lead us to extract all that the Earth has. Therefore, it will eventually become a necessity to look elsewhere in our solar system for these resources.

Rare Earth Metals:

lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), scandium (Sc), and yttrium (Y)[15]

Moreover, the United States is aiming to establish economic sovereignty from China and their subsequent reliance on unethical mining practices. China not only mines the greatest quantity of rare earth metals, but they also have 37.9% of the world's rare earth metal reserve. Utilizing the full potential of the rare earth metals on the Moon and returning them to Earth is integral to the United States plan.[16]

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[15] Visual Capitalist. "Rare earth elements: Where in the world are they?"
[16] McCanaan; Kathryn; Animireddi; Barrett; Boazman; Gawronska; Gilmour; Halim; Harish; Shah; Kring. *Settlement Missions Based on the Earth's Mining Experiences: Lunar Regional Navigation Transceiver System"*

Sub-Chapter 3 Helium-3

Scientists, such as Aaron D.S. Olson, argue that "nuclear fusion could play an important role in meeting the demands of Earth's energy future".[17] Helium-3 is a relatively light isotope because it consists of two protons and one neutron, so the thought is that it will be required for successful and safe fusion reactions. The isotope is radiated from the Sun through solar wind but cannot easily penetrate the atmosphere and magnetic field of Earth. In order to harvest enough helium-3 for adequate testing and subsequent energy production, researchers have been forced to look around our solar system. Samples of Lunar regolith obtained from the Apollo missions revealed a large quantity of the rare isotope, enough to rationalize a permanent human presence on the Moon by itself. Moreover, systems can be created to harness helium-3 directly from the solar wind and radiation on the Moon which limits the amount of scarring done to the environment.[18]

[17] Olson, Aaron. *Lunar Helium-3: Mining Concepts, Extraction Research, and Potential ISRU Synergies*
[18] Olson, Aaron. *Lunar Helium-3: Mining Concepts, Extraction Research, and Potential ISRU Synergies*

Chapter 3

Assessment of Treaties

Comparing the function and efficacy of land-grant related treaties and outer space treaties establish a framework to assess the impact of prolonged inhabitance on the Lunar surface. Precedents such as the Svalbard Treaty of 1920 and the Outer Space Treaty of 1967 demonstrate the prolonged success of peaceful operation in a domain that is mutually beneficial for mankind. Treaties acts as a necessary design constraint before we move beyond surviving on a new world, but begin to establish the new vernacular for convenience, comfort, and aesthetics.[19] A background analysis of these instances will lead us to understand why the Artemis Accords, and any future related treaty pertaining to the Moon or other celestial bodies, will be equally as successful in promoting ethical extraction of material and peaceful operations.

Sub-Chapter 1 Svalbard Treaty of 1920

Svalbard is a Norwegian Archipelago seated north of the Artic circle, rich in minerals and wildlife: coal, iron ore, zinc, copper, phosphorus, and fish. Beginning in 1920, this treaty was established to allow more countries to utilize the vast resources available while benefitting Norway through taxation. However, the taxes collected from signing states cannot be used to increase the revenue for Norway and must be used for the administration of the archipelago. No

[19] Bannova, Olga. *The Future of Lunar Architecture.* 37-38

foreign or domestic military activity is permitted except for the Norwegian Coast Guard for the enforcement of fishing regulations.[20]

Signing Countries as of Spring 2024 (46):

Afghanistan, Albania, Argentina, Australia, Austria, Belgium, Bulgaria, Canada, Chile, Czech Republic, Denmark, Dominican Republic, Egypt, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, India, Italy, Japan, Latvia, Lithuania, Monaco, New Zealand, North Korea, Norway, People's Republic of China, Poland, Portugal, Romania, Russia, Saudi Arabia, South Africa, South Korea, Spain, Sweden, Switzerland, The Netherlands, United Kingdom, United States, and Venezuela [21]

The peaceful occupation of Svalbard by countries with different geopolitical systems and ideologies is a defining link to prove that the Moon can be used for peaceful purposes to benefit humanity. The clearest example is the occupation of Svalbard by both the United States and USSR during the midst of the Cold War. Why did the treaty stand the test of tensions between the world's largest and most powerful superpowers despite the strategic position of the archipelago? The benefits of scientific collaboration and resource acquisition were strong enough to deter either side from daring to break.[22] This is directly associated to the outlook towards the Moon because the draw to return and establish a permanent presence is predicated on the utilization of resources and scientific exploration. The unanimous awareness of the inherent risks

[20] Offerdal, Kristine. *The 1920 Svalbard Treaty*
[21] The Svalbard Treaty (1920)
[22] Østhagen; Andreas; Svendsen; Bergmann. "Arctic Geopolitics: The Svalbard Archipelago"

associated with space travel and the necessary coexistence is incumbent on the cooperation between nations of all ideologies.

An important risk associated with planting our roots on a new world is the potential abandonment of a base or city. This occurred at Svalbard in the 1990s at the Russian city of Pyramiden as a result of poor economic situations, lack of political support, shrinking coal reserves, and an airplane crash at a nearby airport.[23] Due to the heightened cost and risk of space exploration and settlement, it is easy to imagine nearly identical situations occurring on the Moon.

Although these can be nearly unavoidable, the architectural foundations of the LLRU can alleviate future arguments to abandon a settlement on the Moon. For example, a sustainable system that can be adapted to growing or shrinking support from the home country will prove to be vital in maintaining a presence despite political and/or economic turmoil. The modularity of the LLRU aims to address this concern by creating a system that is easily adaptable to the needs of astronauts without the engagement of home countries. Furthermore, the dwindling resources or lack thereof in the planned site for a base can be addressed by the mobility of the system. The LLRU's presence on the Lunar surface prior to the construction of a permanent settlement will allow for astronauts to traverse the landscape in search for the most beneficial and fruitful location that can sustain the inhabitance for the longest available period of time. Abandonment of manmade objects on the Moon is inevitable; however, the architecture of a system such as the LLRU lowers the odds and risks associated.

[23] Spitzbergen | Svalbard. *Pyramiden (Billefjord, Spitsbergen)*

Sub-Chapter 2 Outer Space Treaty of 1967

During the midst of the space race between the United States and the USSR, the Outer Space Treaty of 1967 established legally binding rules and regulations to promote peaceful activity by establishing a ban on military activities in outer space or on extraterrestrial bodies. More specifically, it outlawed the stationing of weapons of mass destruction in outer space. The formation of this treaty ensured that space and the Moon would be free for exploration and scientific studies accessible to all countries in order to benefit all mankind while keeping states liable for damage or contamination by government or non-government entities. This did not attempt to place restrictions on the amount of space debris.[24] Lastly, the OST'67 claims that outer space or celestial bodies may "not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means".[25] This treaty is legally binding which can result in economic sanctions on violating states.

Signing Countries as of Spring 2024 (91):

Afghanistan, Antigua and Barbuda, Argentina, Australia, Austria, Bahamas, Bangladesh, Barbados, Belgium, Benin, Bolivia, Botswana, Brazil, Brunei, Bulgaria, Burkina Faso, Burma, Burundi, Byelorussian S.S.R., Cameroon, Canada, Central African Republic, Chile, China, Taiwan, Colombia, Cuba, Cyprus, Czech Republic, Denmark, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Ethiopia, Fiji, Finland, France,

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[24] United Nations Office for Outer Space Affairs. *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*

[25] Outer Space Treaty of 1967. *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*

Gambia, Germany, Ghana, Greece, Grenada, Guinea-Bissau, Guyana, Haiti, Holy See, Honduras, Hungary, Iceland, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Republic of Korea, Kuwait, Laos, Lebanon, Lesotho, Libya, Luxembourg, Madagascar, Malaysia, Mali, Mauritius, Mexico, Mongolia, Morocco, Nepal, Netherlands, New Zealand, Nicaragua, Niger, Nigeria, Norway, Pakistan, Panama, Papua New Guinea, Peru, Philippines, Poland, Romania, Rwanda, Saint Christopher-Nevis, Saint Lucia, San Marino, Saudi Arabia, Seychelles, Sierra Leone, Singapore, Solomon Islands, Somalia, South Africa, Spain, Sri Lanka, Swaziland, Sweden, Switzerland, Syria, Thailand, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkey, Uganda, Ukrainian S.S.R., Union of Soviet Socialist Republics, United Kingdon, United States, Uruguay, Venezuela, Vietnam, Yemen, Yugoslavia, Zaire, Zambia [26]

The success of this treaty is apparent in the prolonged success of the International Space Station. The coalition of countries regularly inhabiting the orbiting technological marvel over the past 23 years is direct proof that the treaty can prove to create similar success in the Lunar environment. The coalition of nations involved in the crusade back to the Moon can utilize the modularity of the LLRU in order to develop an outpost that links the Earth to a new celestial body.

[26] Outer Space Treaty of 1967. *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*

Sub-Chapter 3 Artemis Accords

The Artemis Accords are seated in the legality and schema of the Outer Space Treaty of 1967 with the goal to ensure a common vision and sustainable future in outer space. It also aims to increase the transparency of work so every country on Earth can benefit from the work done in space. The Accords also elaborate on plans to increase interoperability, like the success of the ISS, between signees in order to make space travel more robust. Vital to this agreement of interoperability is a mutual agreement to assist countries and astronauts who are in an emergency.

Signing Countries as of Spring 2024 (36):

Angola, Argentina, Australia, Bahrain, Belgium, Brazil, Bulgaria, Canada, Colombia, Czech Republic, Ecuador, France, Germany, Greece, Iceland, India, Israel, Italy, Japan, Luxembourg, Mexico, Netherlands, New Zealand, Nigeria, Poland, the Republic of Korea, Romania, Rwanda, Saudi Arabia, Singapore, Spain, Ukraine, the United Arab Emirates, the United Kingdom, the United States, and Uruguay [27]

The practical implementation of the Artemis Accords is intrinsically bound in the Outer Space Treaty of 1967. The extraction of water, rare earth metals, and other Lunar material is the most important motivational factor to return to the Moon because of the economic benefits to signing countries. Mining and laying claim to land could be seen as a violation of the OST '67 principle about outer space or celestial bodies "not subject to national appropriation by claim of

[27] NASA.gov. *"The Artemis Accords: Principles for a Safe, Peaceful, and Prosperous Future"*

sovereignty, by means of use or occupation, or by any other means".[28] The caveat is the inclusion in the OST '67 of the phrase that operations and exploration must "benefit and in the interests of all countries and shall be the province of all mankind" which was reinterpreted for the Artemis Accords.[19] This new understanding aims to exemplify that a permanent outpost on the Moon and extracting materials will result in benefiting humankind and allow for the most efficient sustainable operations in outer space.

Critics, specifically China, argue that the accords favor the United States too heavily. However, without the Artemis Accords, we would be relying on the discretion of a country's interpretation of the OST '67. It is important to reestablish the rules for those wishing to set up a Lunar outpost on the new frontier of exploration.

Of the defining principles listed by NASA, transparency, interoperability, and protecting heritage define the architecture gestures displayed in the LLRU. Creating a system rooted in future flexibility based on the resource allocation from Earth is an architectural problem as much as it is geopolitical.

[28] U.S. Department of State. *Artemis Accords*

Chapter 4

Precedents

The architectural foundation and human interaction with the LLRUs have been inspired by a coalition of terrestrial and non-terrestrial precedents. Although the Lunar building typology is unprecedented and unique, past, and current architectural and engineering wonders that encounter similar obstacles are vital to research. Utilizing the thoughtful breakdown of spaces into sleep, hygiene, food, work, and leisure by Sandra Häuplik-Meusburger in *Architecture for* Astronauts, architectural spaces of Apollo's Command Service Module and Lunar Excursion Module, the International Space Station, Halley IV, and Quonset Huts will be highlighted and discussed. The increasing efforts from private companies to enter the modern-day space race gives financial freedom to space architects, allowing them to reinterpret what we know about extraterrestrial design.[29] Examining the spatial organization and the architecture's impact on users of the following precedents will inform the design process and allow for the most effective adaptation of architecture to the human presence on the Moon.

Sub-Chapter 1 Apollo

During the late 1960s, the goal of the Apollo missions was not only to "land a man safely on the Moon and returning him safely to Earth" (Kennedy, May 25th, 1961), but to beat the Soviet Union. This competition drive fueled by the Cold War created an intense development that features numerous technological breakthroughs. The main architectural elements of the

[29] Meuser, Paul. *Architecture Guide: Moon*. 20

Apollo missions were the Lunar Command Module (CSM) and Lunar Excursion Module (LEM). They would travel from Earth's orbit to the Moon's, where the LEM would descend to the surface and eventually reunite with the CSM to return to Earth. The missions were highly scientifically driven which resulted in a utilitarian design philosophy and all activities would take place in the LEM, CSM, or Lunar Surface.[30] The LEM is the only habitat humans have inhabited on the Moon which makes it a good starting point for the new Lunar typology.

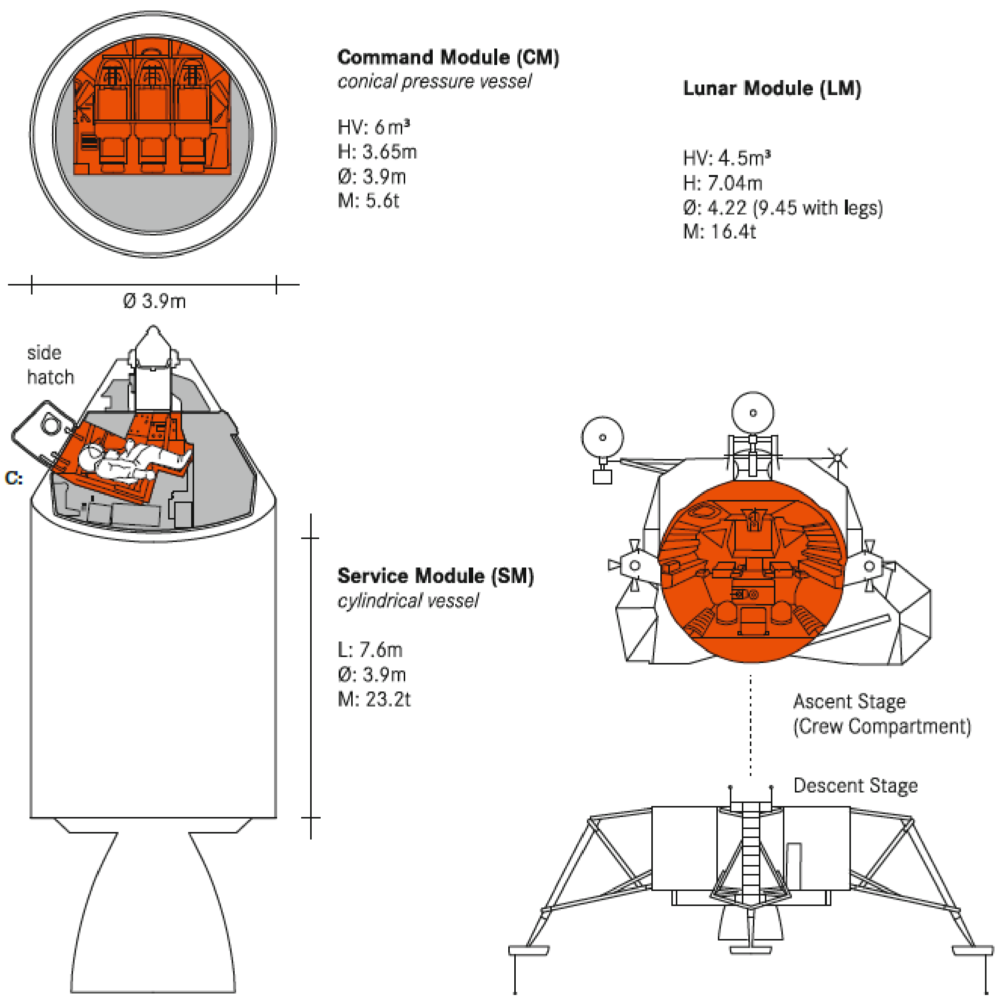

Figure 4 Apollo CSM & LEM Spatial Organization [31]

[30] Häuplik-Meusburger; Bannova. *Architecture for Astronauts*. 36-43

[31] Häuplik-Meusburger; Bannova. *Architecture for Astronauts*. 39

Table 1 Apollo | CSM & LEM [32]

Habitable Volume	LEM - 159 ft^3 CSM - 212 ft^3
Mission Duration	LEM - 3 days, 3 hours CSM - 12 days, 17 hours
Crew	LEM - 2 CSM – 3
Life Cycle	Each used once and no growth is planned or possible
Sleep	LEM or CSM (depending on location)
Hygiene	LEM or CSM (depending on location)
Food	LEM or CSM (depending on location)
Work	CSM or Lunar Surface
Leisure	CSM or Lunar Surface

Sub-Chapter 2 International Space Station

The International Space (ISS) is arguably the greatest feat of human engineering as it is the largest and longest running space station in human history. It has functioned as a center for scientific discovery in Earth's orbit for 23 years and counting. The ISS has been a habitat for astronauts from various countries, such as the United States, Russia, Japan, Canada, and

[32] Häuplik-Meusburger; Bannova. *Architecture for Astronauts*. 36-43

European nations. It was assembled through a collection of rigid shell capsules with 360-degree racks and life support systems. Moreover, the scale of the ISS allowed for private crew quarters that have proved to be invaluable for the psychological health of astronauts and provided us with invaluable research on the effects of environmental factors in space on the human body.[33] The separations of activities, private crew quarters, and successful coalition of involved nations places the ISS at the forefront of proof that a Lunar settlement, such as the LLRU, can be successful.

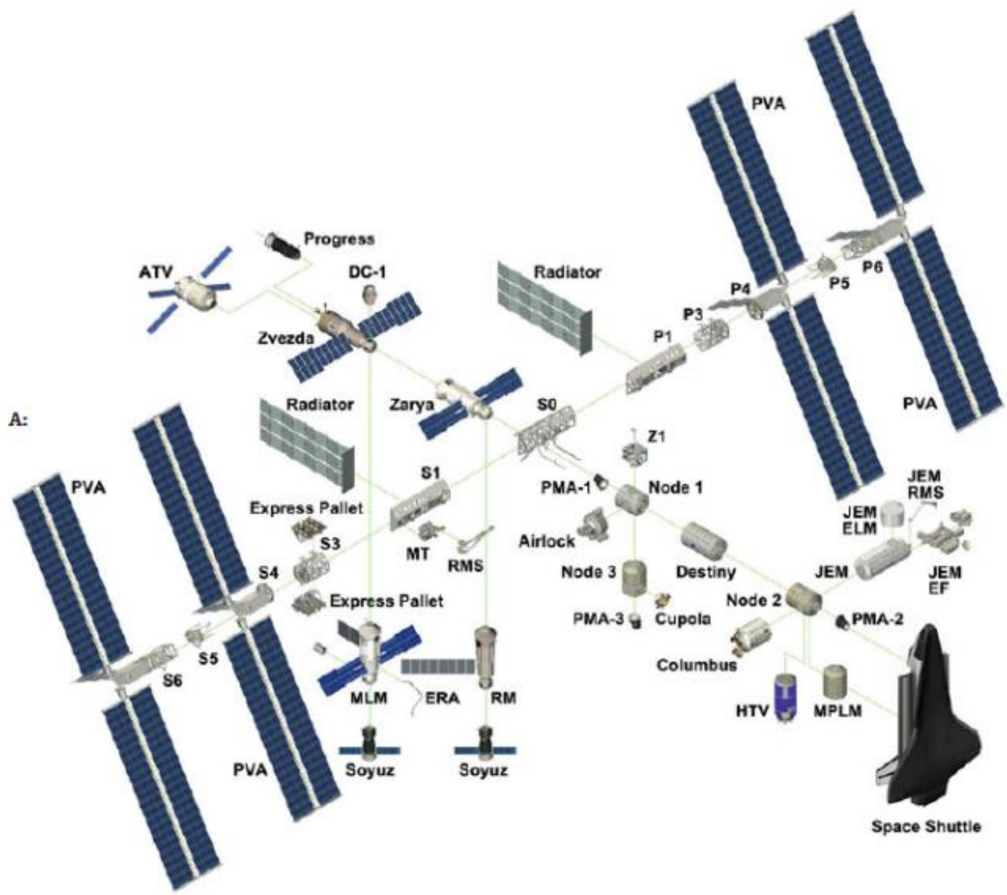

Figure 5 ISS Module Exploded Axonometric [34]

[33] Häuplik-Meusburger; Bannova. *Architecture for Astronauts*. 76-85
[34] Häuplik-Meusburger; Bannova. *Architecture for Astronauts*. 79

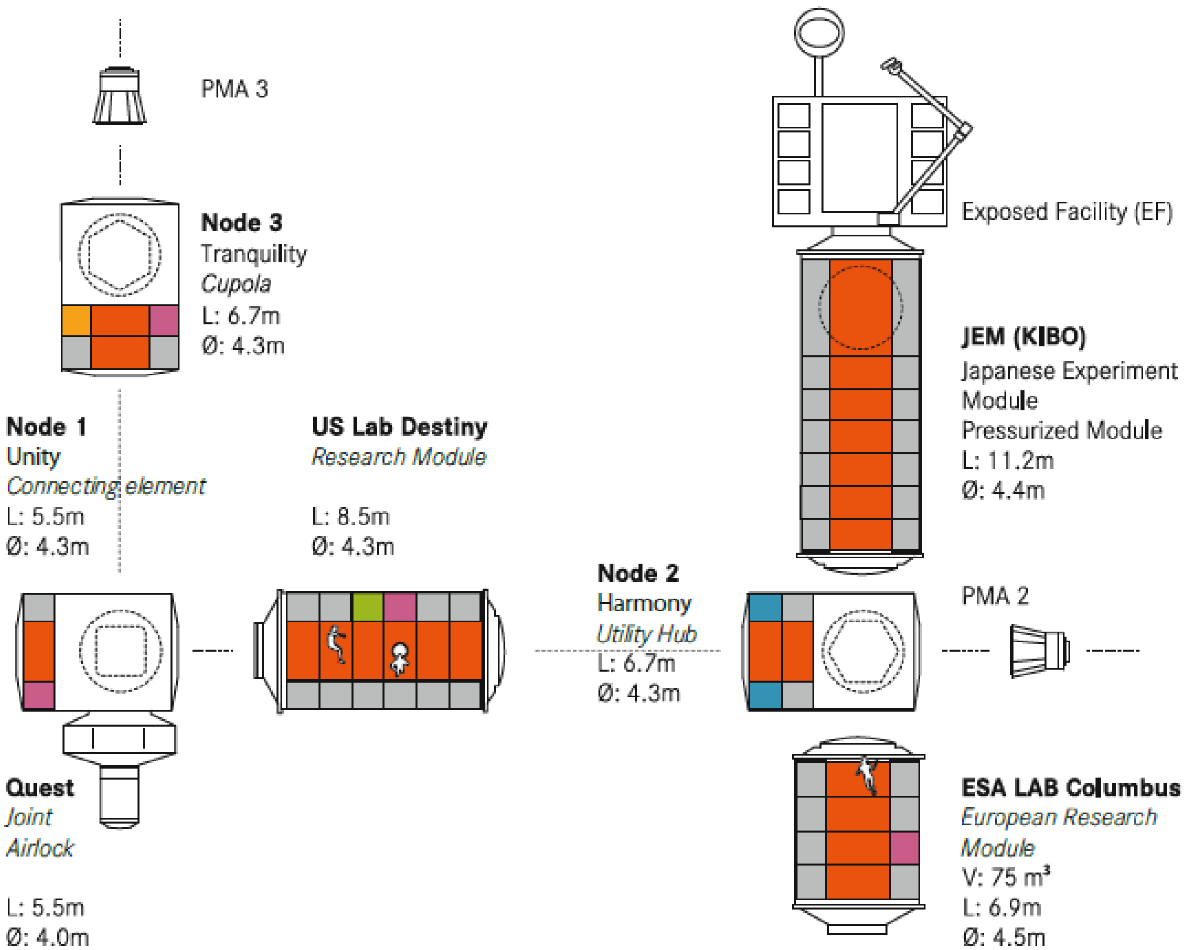

Figure 6 ISS Spatial Organization [35]

[35] Häuplik-Meusburger; Bannova. *Architecture for Astronauts*. 83

Table 2 International Space Station [36]

Habitable Volume	33,019 ft^3
Mission Duration	6 months per astronaut 23 years continued occupation
Crew	6+
Life Cycle	Expandable and inhabited since 2000
Sleep	Individual crew quarters
Hygiene	Cleaning wipes and two toilet compartments
Food	Food cabinets and shared table
Work	Modules and racks, EVAs
Leisure	Exercise in work areas and recreational activities in crew quarters

Sub-Chapter 3 Halley VI

Halley VI, designed by Hugh Broughton Architects, is the current iteration of the longstanding British Antarctica Survey (BAS) research station. The BAS required an easily assembled facility with adequate spaces for scientific and leisurely activities that can be moved in extreme environmental conditions. The solution was an elevated linear system of modules placed on skis so a bulldozer could pull it across the barren ice and snow. It was also designed to

[36] Häuplik-Meusburger; Bannova. *Architecture for Astronauts*. 76-85

house redundant life support systems to prepare for emergency situations.[37] The decision considerations pertaining to both the quality of life for inhabitants and adaptability to the environment are key ideologies in the vernacular of Antarctic architecture. Due to the inherent isolation and harsh conditions, Halley VI has many lessons to infer design decisions on the LLRU and teach aspiring space architects the lessons to be learned from terrestrial architecture.

Figure 7 Halley IV Sectional Axonometric [38]

[37] Hugh Broughton Architects. "Halley VI British Antarctic Research Station: A pioneering relocatable polar science research station"

[38] Hugh Broughton Architects. "Halley VI British Antarctic Research Station: A pioneering relocatable polar science research station"

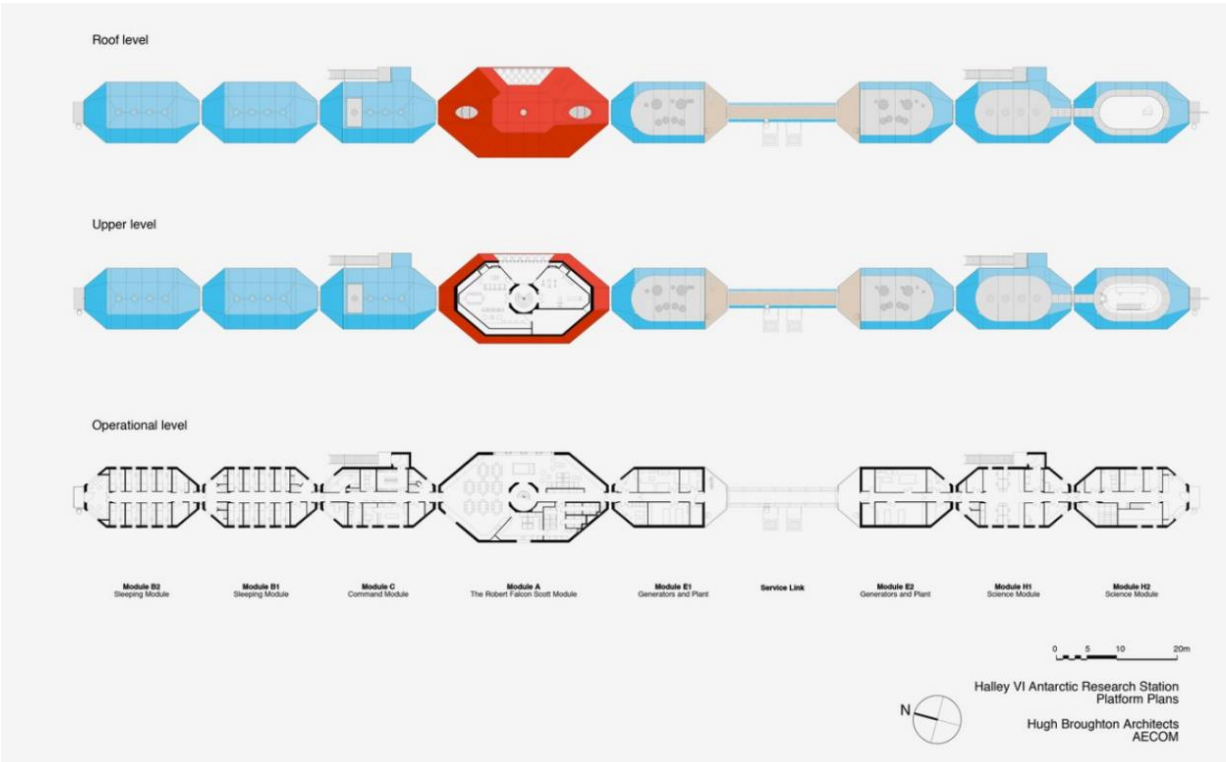

Figure 8 Halley VI Spatial Organization[39]

[39] Hugh Broughton Architects. "Halley VI British Antarctic Research Station: A pioneering relocatable polar science research station"

Table 3 Halley VI [40] [41]

Habitable Area	22,000 ft^2
Mission Duration	October-February
Crew	Summer - 70 Winter - 16 (no longer occurring)
Life Cycle	Used each year since 2013, Only summers since 2017 (”The Halloween Crack”)
Sleep	B1 and B2 (Sleeping Modules), shared rooms
Hygiene	B1 and B2 modules
Food	A (Living Module) and plants are grown in E1 and E2 modules
Work	C (Command Module), H1 and H2 (Science Modules)
Leisure	A (Living Module), B1 and B2 (Sleeping Module)

Sub-Chapter 4 Quonset Huts

Quonset huts were developed by the United States military during World War II in order to provide housing to troops through a simple to manufacture and assemble system. The kit of

[40]Hugh Broughton Architects. “Halley VI British Antarctic Research Station: A pioneering relocatable polar science research station”
[41] Hunt, David. “Halley VI Research Station, Halley VI, Brunt Ice Shelf, Caird Coast”

parts came with structural steel ribs and a corrugated metal lining then could be adapted to serve up to 86 uses.[42] The huts went through various stages of modification and redesign to improve the efficiency of material usage and comfort for inhabitants. After the war, the huts were repurposed to be used as affordable/student housing, industrial applications, or in areas of extreme climate.[43] The LLRU can learn from the structural framework and mass production of the Quonset huts when considering design and interior applications.

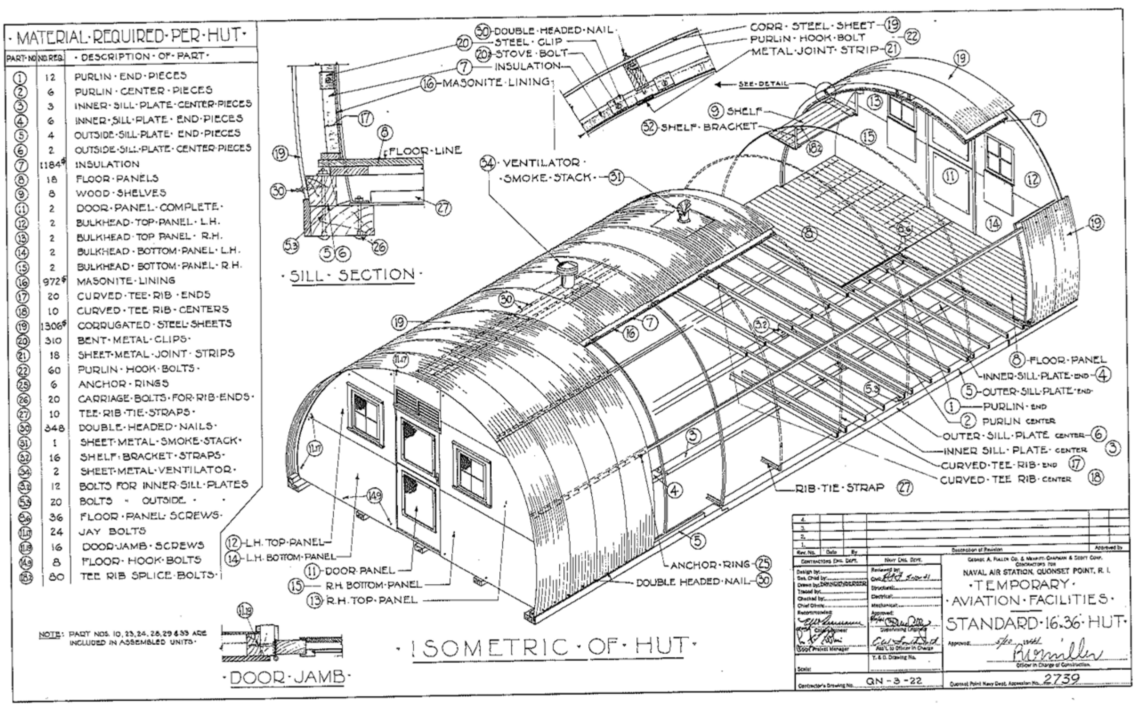

Figure 9 Isometric of Quonset Hut Construction [44]

[42] DAHP. "Quonset Hut"
[43] Lobner, Peter. "Quonset Huts". 4-14
[44] Fuller, George. "Quonset Hut – General Plans and Layouts". 33

Table 4 Quonset Huts [45] [46]

Habitable Area	960 ft^2
Mission Duration	Indefinite
Crew	Assembled by 10 1-30 beds
Life Cycle	Assembled on site in less than a day without skilled labor and shipped in 12 crates
Sleep	Adaptable for barracks or private residence
Hygiene	Either within same hut or neighboring
Food	Either within same hut or neighboring
Work	Either within same hut, neighboring, or outside
Leisure	Either within same hut, neighboring, or outside

[45] DAHP. "Quonset Hut"
[46] Lobner, Peter. "Quonset Huts". 1-4

Chapter 5

Transportation with Rockets

Architecture in outer space and on celestial bodies holds a unique constraint, fitting inside a cylindrical container mounted on top of a rocket as it is pointed to the heavens. Weight, size, and shape are the biggest determining factors for the overall form in the ultimate battle between form and function. It is our job as space architects to merge the disciplines required for space flight to create a system that is adequately human-centered. Much of the form for the LLRU was determined by these circular constraints and financial limitations. Moreover, the Silo structure which houses the LLRU inside the rocket cargo bay has been designed to be converted into a raw material storage device for the Lunar outpost.

The current plan utilizes two rocket systems for these operations, the NASA Space Launch System Block variants, or SLS, and the SpaceX Starship as seen in figure 10 and table 5. The defining differentiating factors is that SLS is non-reusable and government funded while Starship is reusable and privately funded. However, the success of a system such as the LLRU will require the interdisciplinary actions of private and government sectors from every country participating in the Artemis Accords. Not every rocket sent to the Moon will need to be rated for human travel because some would act as cargo ships to a foreign world to facilitate development or resupply astronauts. Currently, SLS is a more capable cargo rocket and Starship is a more capable crew rocket.

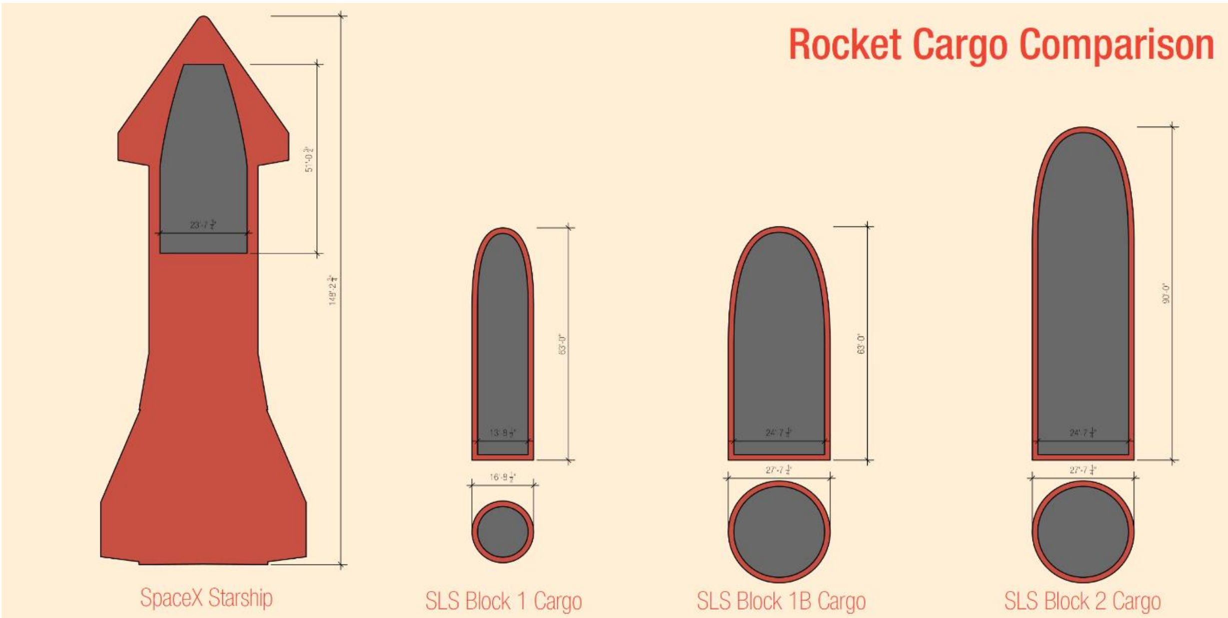

Figure 10 Rocket Cargo Comparison [47] [48]

Table 5 SLS Block 1 vs. Starship [49]

	NASA's SLS Block 1	SpaceX's Starship
Capability to Low Earth Orbit (LEO)	95t	100-150t
Capability to Translunar Injection (TLI)	27t	N/A
Height	321.5 ft	394 ft
Maximum Diameter	27.5 ft	29.5 ft
Reusability	Expendable	Fully Reusable

[47] NASA. "Space Launch System Capabilities"
[48] SpaceX. "Starship: Service to Earth Orbit, Moon, Mars, and Beyond"
[49] Guerrieri. "SLS vs. Starship: Size, Launch, Cost"

Chapter 6

Architecture's Impact on Astronauts

Architecture holds a unique place in the lives of humans as it is a frontal component in nearly every aspect of life. Primitively, it acts as a vessel to protect us from the environment while defining spatial qualities. As we have evolved, the architecture around us has subsequently evolved to hold purpose or act as a symbol that can affect a person's psychological state. [50] This typology shift is rooted in how a space capsule must act in similar ways to a building designed for Earth but be extremely refined and maximize comfort/mobility. It is this philosophy that architecture is the largest defining action to affect quality of life which is why the field of space architecture is so important. The fundamental principles of terrestrial architecture remain constant on the Moon with the added risks of the harsh environmental conditions.[51] As a result, it is important to note that the advancements in Lunar architecture will have direct correlations to issues we face on Earth, such as sustainable development of our rapidly expanding population. "Space architecture is not only for architects" says Haym Benaroya in *Building Habitats on the Moon* because the deep understanding and integration of human proportions and needs is vital for every component in a Lunar capsule, such as the LLRU.[52] Engineers are required to look beyond the small details and ask themselves questions that are usually reserved for architects. Furthermore, Brand N. Griffin explains that "engineers think architects make things prettier,

[50] Hollein, Hans. "Everything is Architecture!", *Architectural Guide: Moon.* 11-13
[51] SpaceArchitect.org. "HOW TO BECOME A SPACE ARCHITECT"
[52] Benaroya, Haym. *Building Habitats on the Moon*. 93

difficult to build, and more expensive. Some can, but space architects are different. They analyze like an engineer and synthesize like an architect."[53]

On our terrestrial world, the architect remains a key figure in much of the process to design and build a building. This is equally important for a space architect. There are key architectural motifs that must be present in a Lunar habitat in order to sustain a good quality of life for the astronauts because they have a direct impact on their physical and psychological states.

Lighting design in space has the obvious benefit of provide adequate working areas, but it is even more important role in visual comfort benefits to maintain the diurnal cycle and circadian rhythms for astronauts.[54] Depending on the location on the Lunar surface, astronauts could experience long periods of extended dark/low-light and high-intensity light. The prolonged darkness can cause seasonal depression-like symptoms and the intense light periods can affect sleep patterns. The LLRU combats this issue through a combination of autonomous variable window tinting and autonomous ambient lighting. The goal is to artificially mimic the lighting conditions of a typical day near the equator of Earth to create a better quality of mental state for astronauts despite the prolonged periods of light and dark on the Moon.

Olga Bannova and Sandra Häuplik-Meusburger explain in Space Architecture Education for Engineers and Architects explains that "the ability to see Earth is vital for maintaining

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[53] Griffin. "The Role of the Space Architect". *Space Architecture Education for Engineers and Architects*. 31
[54] Häuplik-Meusburger; Bannova. *Space Architecture Education for Engineers and Architects*. 118, 121

psychological health and morale." Moreover, windows also allow for astronauts to monitor their surroundings, find damage on the capsule, and operate robotic devices from a safe location.[55] Solutions to this phenomenon became vital in much of the decision making for the LLRU. First, a prefabricated system that is assembled on Earth, similar to the ISS, makes the most sense for the LLRU because it allows for the easiest engineering integration of windows. The construction philosophy of laying, folding, or creasing soft materials to follow the contours of an aluminum shell creates a high-quality seal that doesn't leak.[56] Next, the windows and floor are arranged in such a way inside the LLRU that while walking through the central corridor or stepping up to a seated workstation, the band of horizontal windows remains at eye level. This creates an involuntary architectural experience that connects astronauts with Earth throughout every operation of their daily routine or a chosen leisure activity (see figure 11).

The effects of isolation are heightened in space or on the Moon because of the inherent distance from home and small crew sizes. Consistent team-based projects, cultural differences, and general mental fatigue can generate tensions between crew members. This is a crucial issue for a space architect to design for because it can result in negative health implications and decreased performance for the astronauts.[57] While the human body is already experiencing drastic changes to their physical environment, mental health must be taken seriously because it can directly impact how one's body responds to the outside factors. These can be resolved with architecture in the LLRU by designing areas that promote social interaction and collaboration such as workspace, eating/food preparation area, or leisure activities. Consequently, spaces must

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[55] Häuplik-Meusburger; *Bannova. Space Architecture Education for Engineers and Architects*. 184-186
[56] Häuplik-Meusburger; Bannova. *Space Architecture Education for Engineers and Architects*. 178-183
[57] Benaroya, Haym. *Building Habitats on the Moon*. 160

be designed for astronauts to keep private. Their living pods in the LLRU create artificial and physical personal space boundaries which can be adjusted based on the cultural or social needs of astronauts.[58] The attention to detail in terms of human interaction on the LLRU is an architectural concern because of the profound impact that it can have on our behavior and perception of the environment.

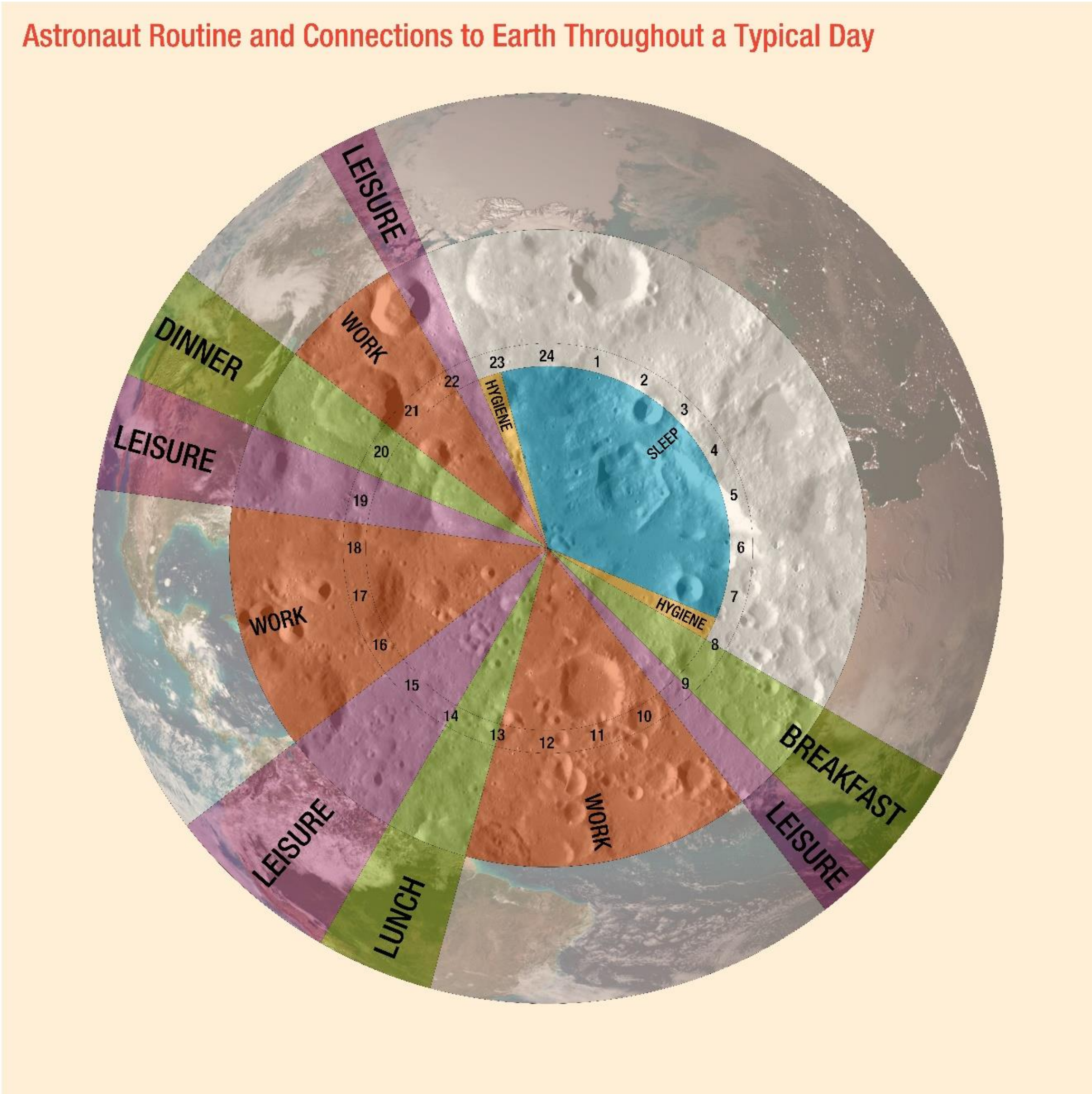

Figure 11 Astronaut Routine and Connection to Earth

[58] Häuplik-Meusburger; Bannova. *Space Architecture Education for Engineers and Architects*. 109-110

Designed mobility is a key architectural and engineering feature for the LLRU because it allows for safe exploration of the Moon as we search for the ideal location for the beginnings of a Lunar City. Mobile habitats have the unique ability to expand the ability of astronauts as they conduct scientific or economic missions while subsequently limiting the number of risky EVA (Extravehicular Activity) missions.[59] Moreover, mobility allows us to reorganize the LLRU depending on mission specifics, personal reasons, or geopolitical issues on Earth or between crew members. This flexibility could result in saving our ability to have constant habitation on the Moon. Capsule mobility can help to improve the lives of astronauts by acting as an invaluable tool for exploration; however, it is even more important for maintaining the sustainability of our footprint on the Moon. The LLRU will be used immediately upon arrival and well beyond the completion of a Lunar City because of the adaptability integrated in the architectural thought process through a mobile based system.

Sub-Chapter 1 Life Support Systems

In order to take advantage of the critical architectural features for the quality of astronaut lives, each LLRU will feature proper life support equipment so they can function independently of one another. When examining the life cycle of extraterrestrial precedents, it is found that redundancy is necessary for the safety of astronauts, robustness of design, and overall functionality.[60] Moreover, following the completion of the permanent base the LLRU will be

[59] Häuplik-Meusburger; Bannova. *Space Architecture Education for Engineers and Architects*. 197-202
[60] Bannova, Olga. *The Future of Lunar Architecture*. 27

assigned to complete a wide range of missions that demand new utilizations of the capsule modules. The following seven systems are required for life to flourish on extraterrestrial bodies:

1. Potable Water Supply (water reclamation)
2. Food Supply
3. Breathable Air Supply (Oxygen generation System)
4. Air Pressure Control (Maintained at 101kPa)
5. Air Temperature Regulation (Heat Exchanger)
6. Human Waste Management (Waste Disposal)
7. Fire Detection and Suppression

[61]

Sub-Chapter 2 Spatial and Organizational Layout

The breakdown of spaces in the LLRU is based on the extraterrestrial and terrestrial precedents discussed in Chapter 4 and Sandra Häuplik-Meusburger breakdown of human activities (Sleep, Hygiene, Food, Work, Leisure) in *Architecture for Astronauts*. These activities allow for comparative analysis between the new Lunar typology and precedents. Furthermore, the presence of a gravitational field, albeit a weak one, leads the LLRU to have a set floor and ceiling. This is more closely related to the spatial relationship of Halley VI than the ISS; instead of being arranged linearly, the units are arranged in arrays around a connector node.

[61] NASA. “Environmental Control and Life Support System (ECLSS)”

The early stage of the LLRU has the highest reliance on other units for the survival of astronauts because every system will not always be operational in order to limit the wear and tear on each unit. Moreover, the geometry of the LLRU in transverse section provides necessary dead space for these large units to be housed (see figure 14). All the systems listed above are accessible from the exterior behind protective hatches to allow for easy repair and maximize spatial functionality on the interior of LLRU.

Figure 12 LLRU Spatial Organization Array and Life Support

Chapter 7

Design

Based on the research and interpretation on architecture's impact on astronauts, the LLRU is a mobile, prefabricated capsule module designed for mining and research that factors in the ethical and responsible use of intergalactic materials as we grow our presence on the Lunar surface. Because of their ease of deployment and immediate usability, rigid structures will be our first semi-permanent structures for our return to the Moon.[62] They lay the groundwork for a Lunar outpost while giving astronauts the leeway to learn how to live on the Moon.

The LLRU is foremost designed as a system that can grow and adapt with the needs of Artemis Accord Countries over its life span. Beginning its life as the primary vessel to support life on the barren Lunar surface, transitioning to a tool to aid in the construction of the permanent Moon base and Lunar City, and finally becoming a mobile outpost caravan system to allow for long term missions to explore other areas of the Moon. There are a variety of array configurations, as seen in figure 13, which can be beneficial depending on the mission. These ideology at the forefront of design ensures that the LLRU maintains a degree of usability, livability, and flexibility throughout the life span of an LLRU.[63]

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[62] Benaroya, Haym. *Building Habitats on the Moon*. 105-114

[63] Häuplik-Meusburger; Bannova. *Architecture for Astronauts*. 288-289

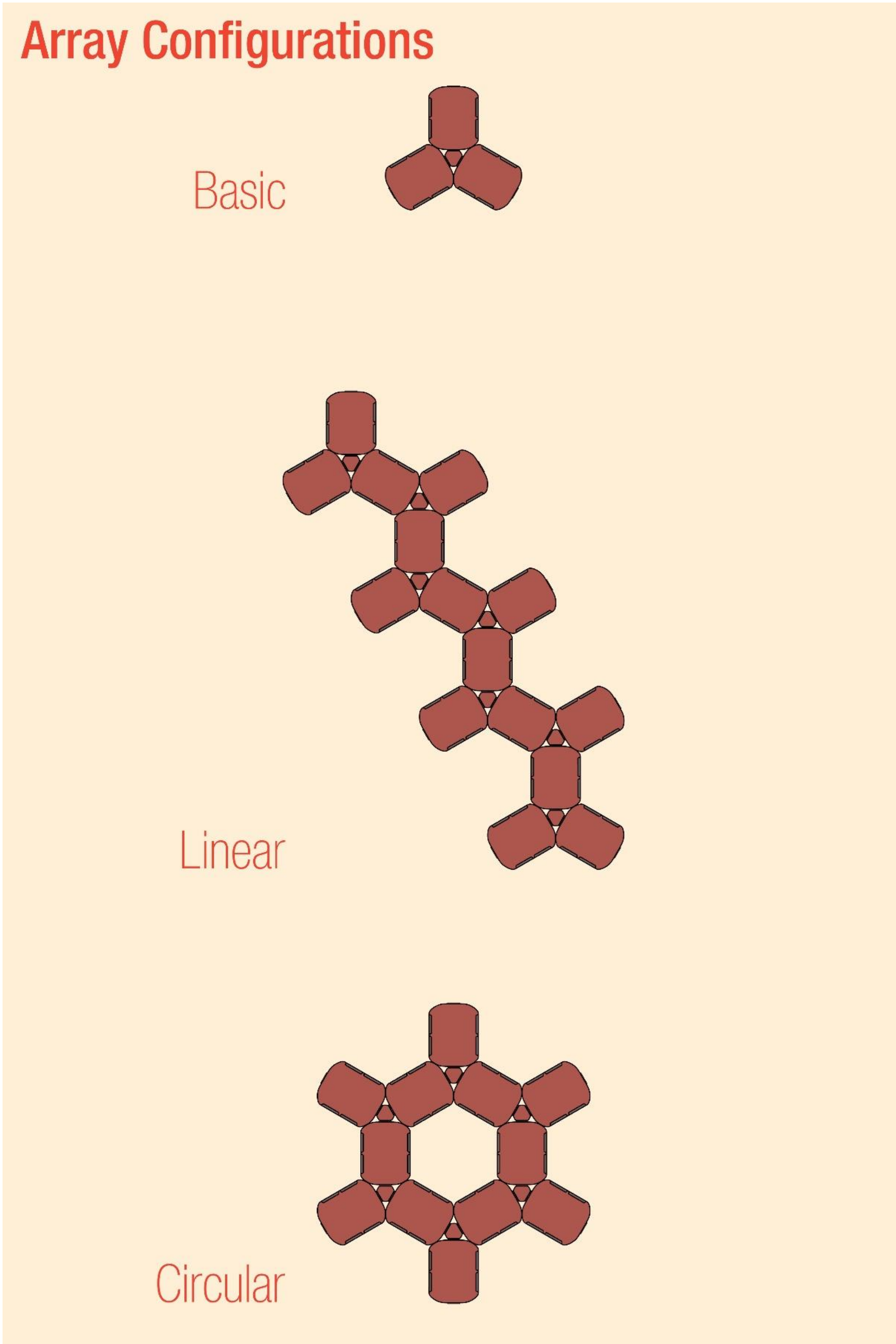

Figure 13 Array Configurations

Sub-Chapter 1 LLRU

The main structure and rigid outer skin of the LLRU will be constructed out of a magnesium alloy for its advantageous qualities over aluminum. It makes up 13% of Lunar regolith which allows for eventual in-SITU resource utilization and for repairs or fabrication of new tooling. Moreover, magnesium is excellent at electromagnetic shielding, vibration dampening, and impact resistance which makes it an ideal candidate to combat the unforgiving environment on the Moon. The risks associated with magnesium are not issues on the Moon. For example, a weaker overall strength when compared to aluminum but the Moon's gravity is $1/6^{th}$ of Earth's so this won't be a factor and the ability to ignite under the presence of oxygen is alleviated by the near vacuum on the Lunar Surface.[64] The exterior will be cloaked in Kevlar, similar to the ISS for protection and extra sealant. The interior spaces will follow a similar structural framework and accents with "less cold" and more comfortable surface finishes in order to create a better living and working environment.

[64] Benaroya, Haym. *Building Habitats on the Moon*. 181-183

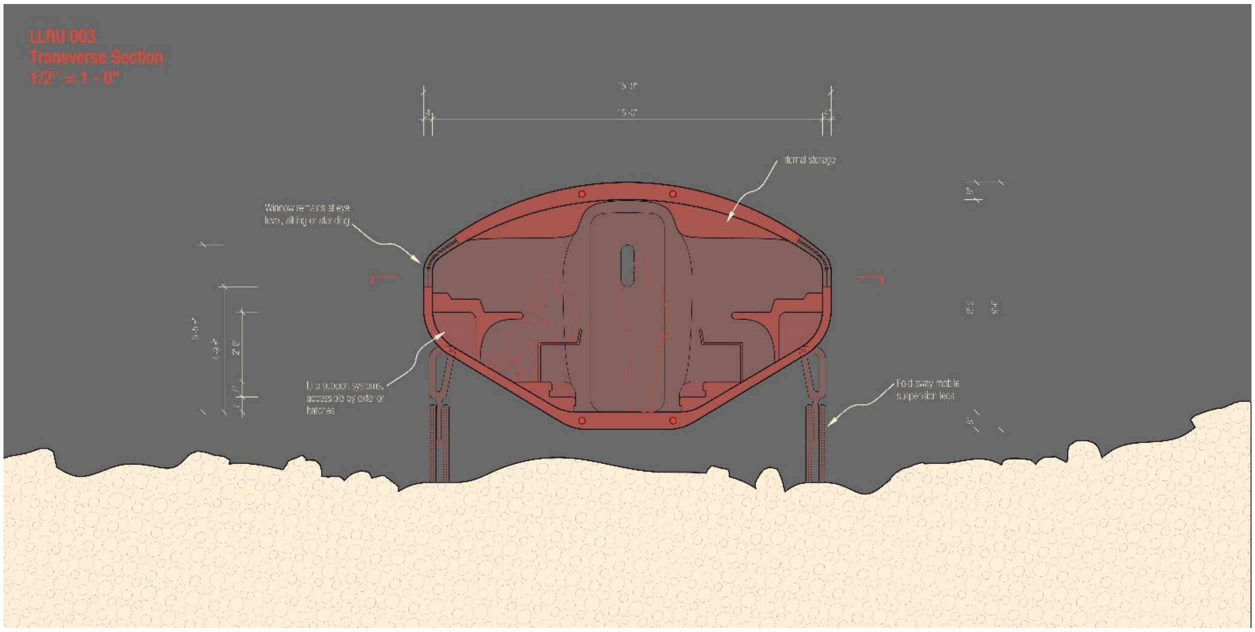

Figure 14 LLRU 003 Transverse Section

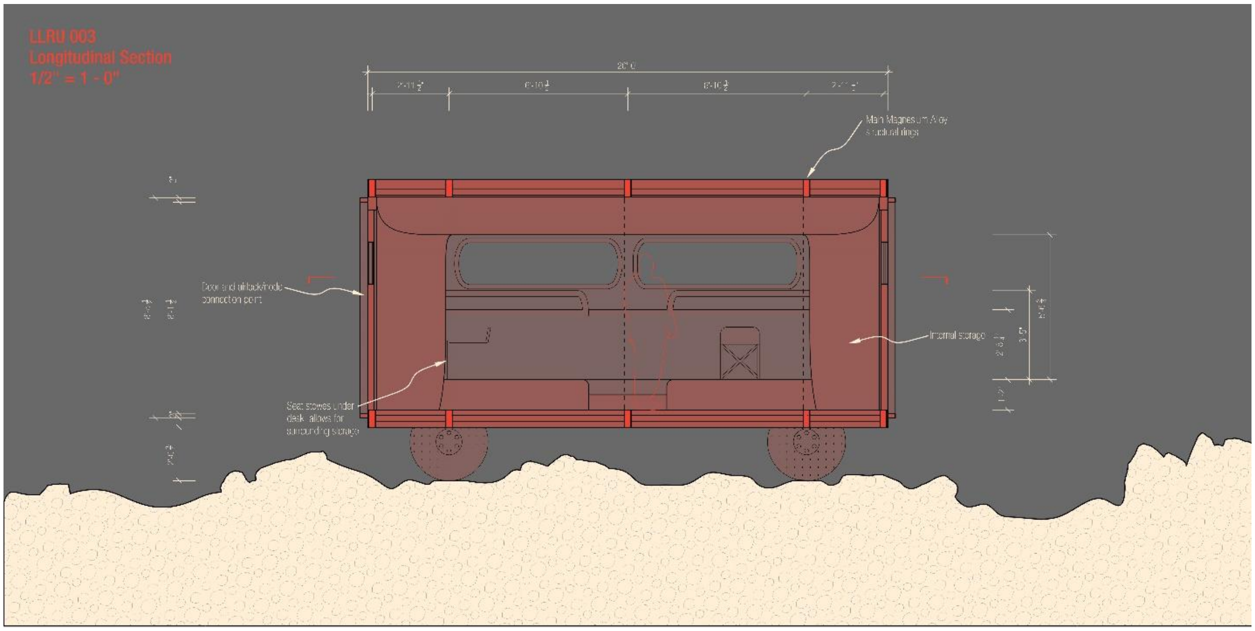

Figure 15 LLRU 003 Longitudinal Section

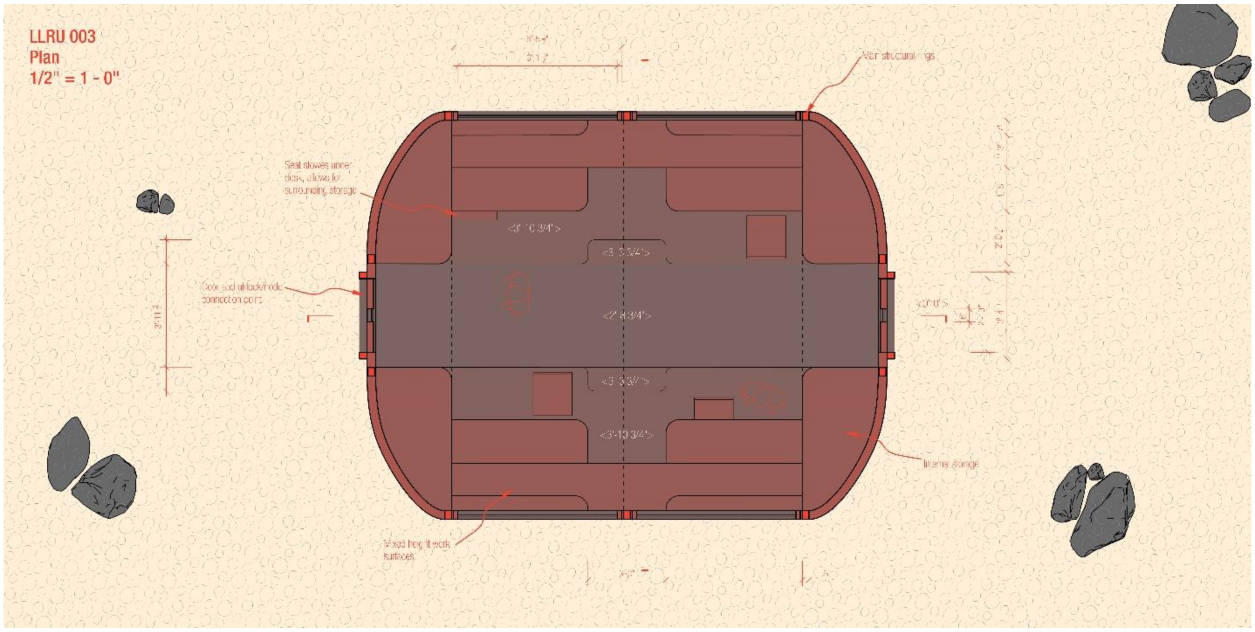

Figure 16 LLRU 003 Plan

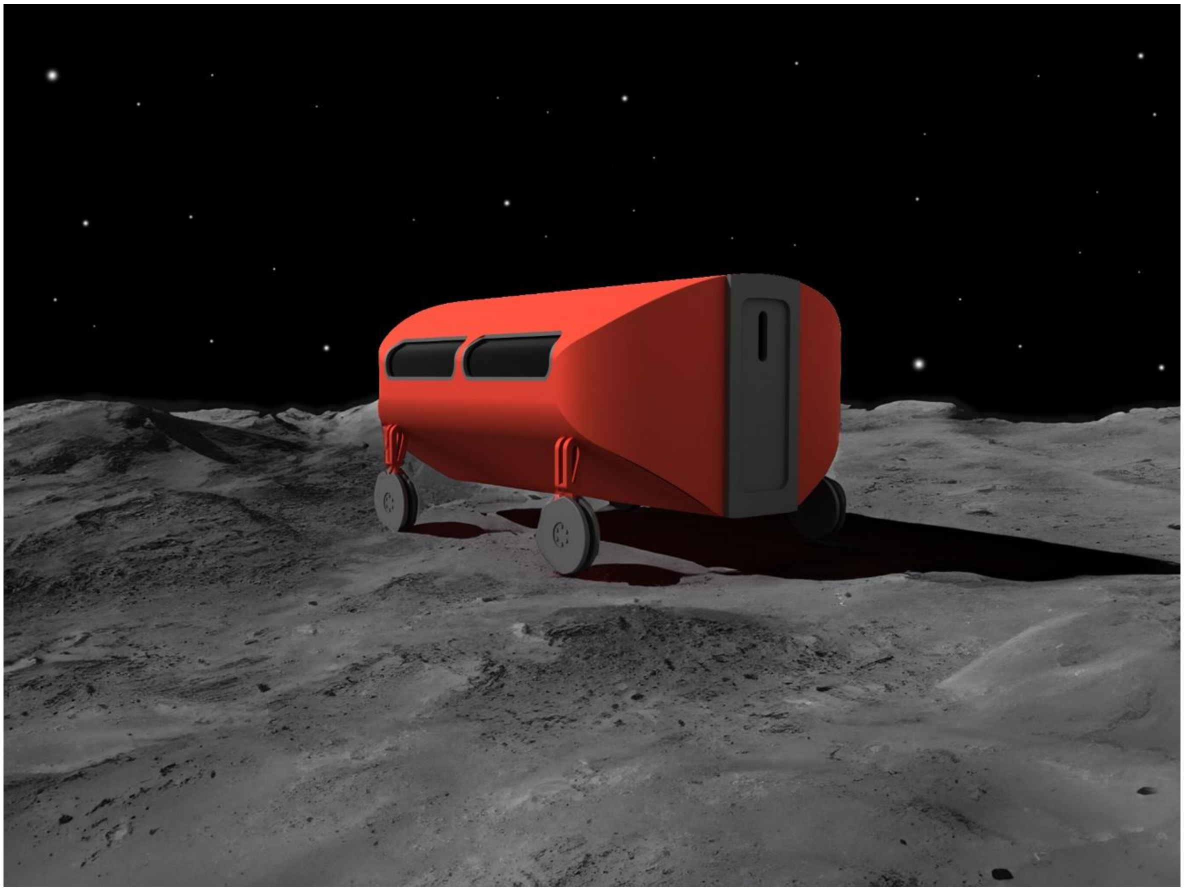

Figure 17 LLRU Render on Moon

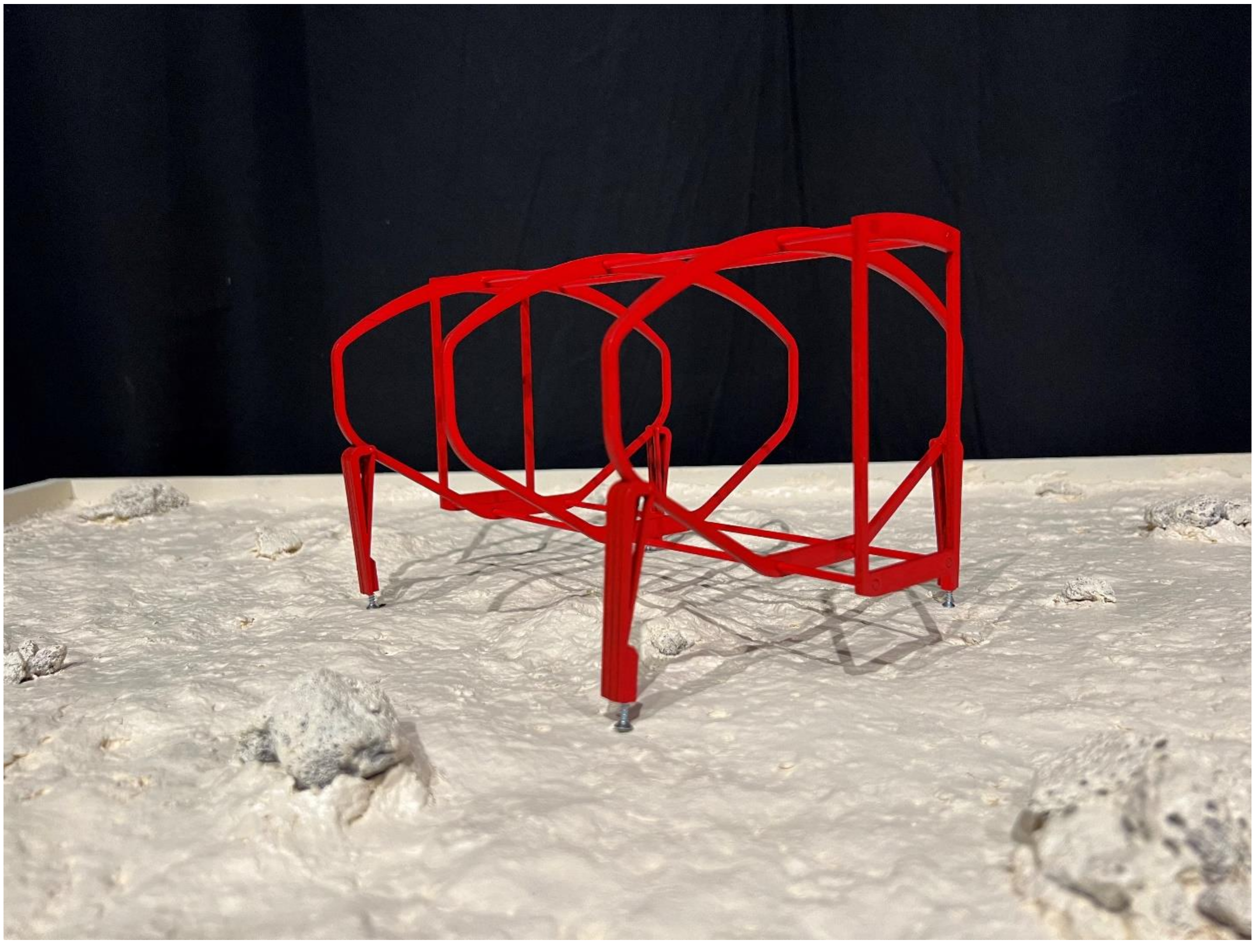

Figure 18 Lunar Landscape and Structural Model

Sub-Chapter 2 Connector Node

The connector node does not contain any life support systems, but it is capable of being pressurized. It allows for multiple LLRU to be connected for the optimal living experience for the astronauts. Moreover, the connector node allows for the various array configurations shown in figure 13.

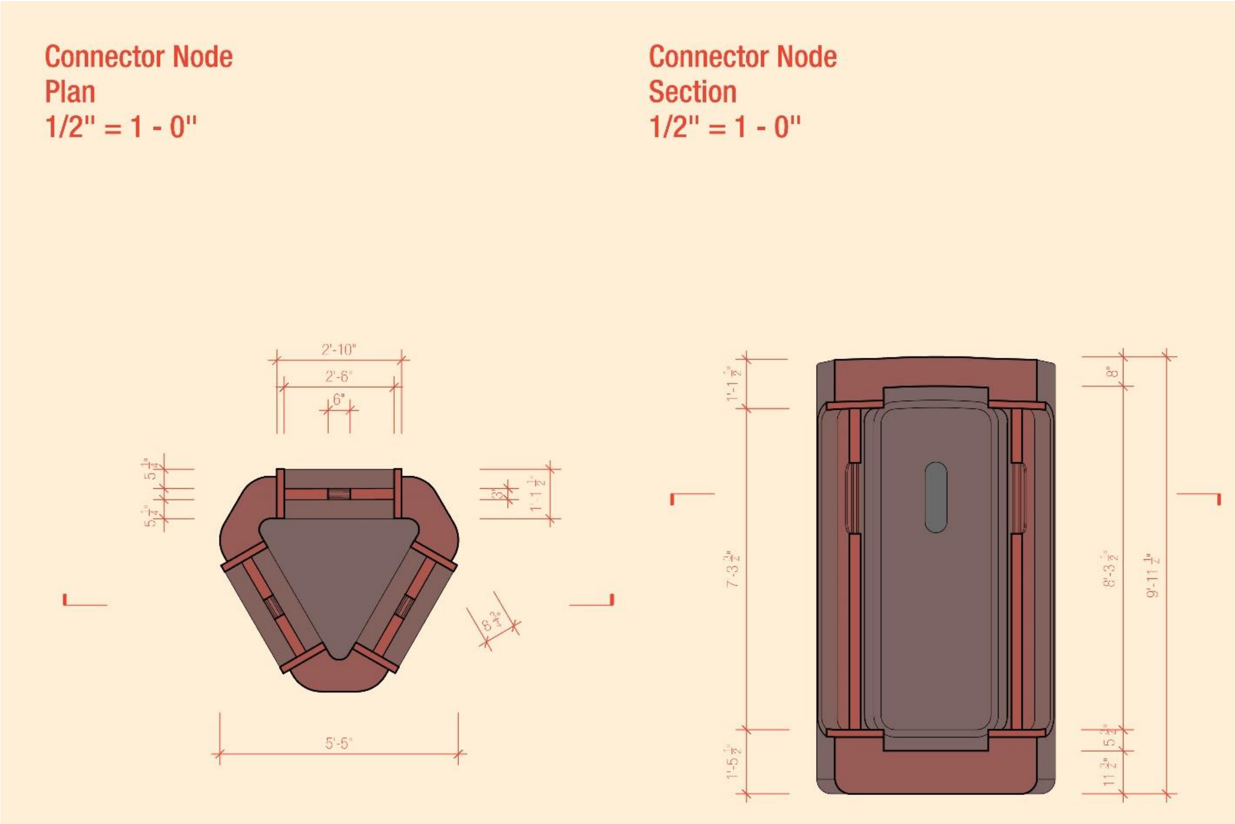

Figure 19 Connector Node Orthographics

Figure 20 Connector Node Axonometric

Sub-Chapter 3 Silo

The silo is the structural framework that the LLRUs mount to before placed inside the rocket. A maximum of six LLRUs and three connector nodes can be loaded onto one SLS 1B Cargo. After reaching the Lunar surface, the units and nodes are removed from the silo and panels can be placed to enclose the silo in order for it to be used as raw material storage (water, rare earth metals, helium-3, regolith, etc..).

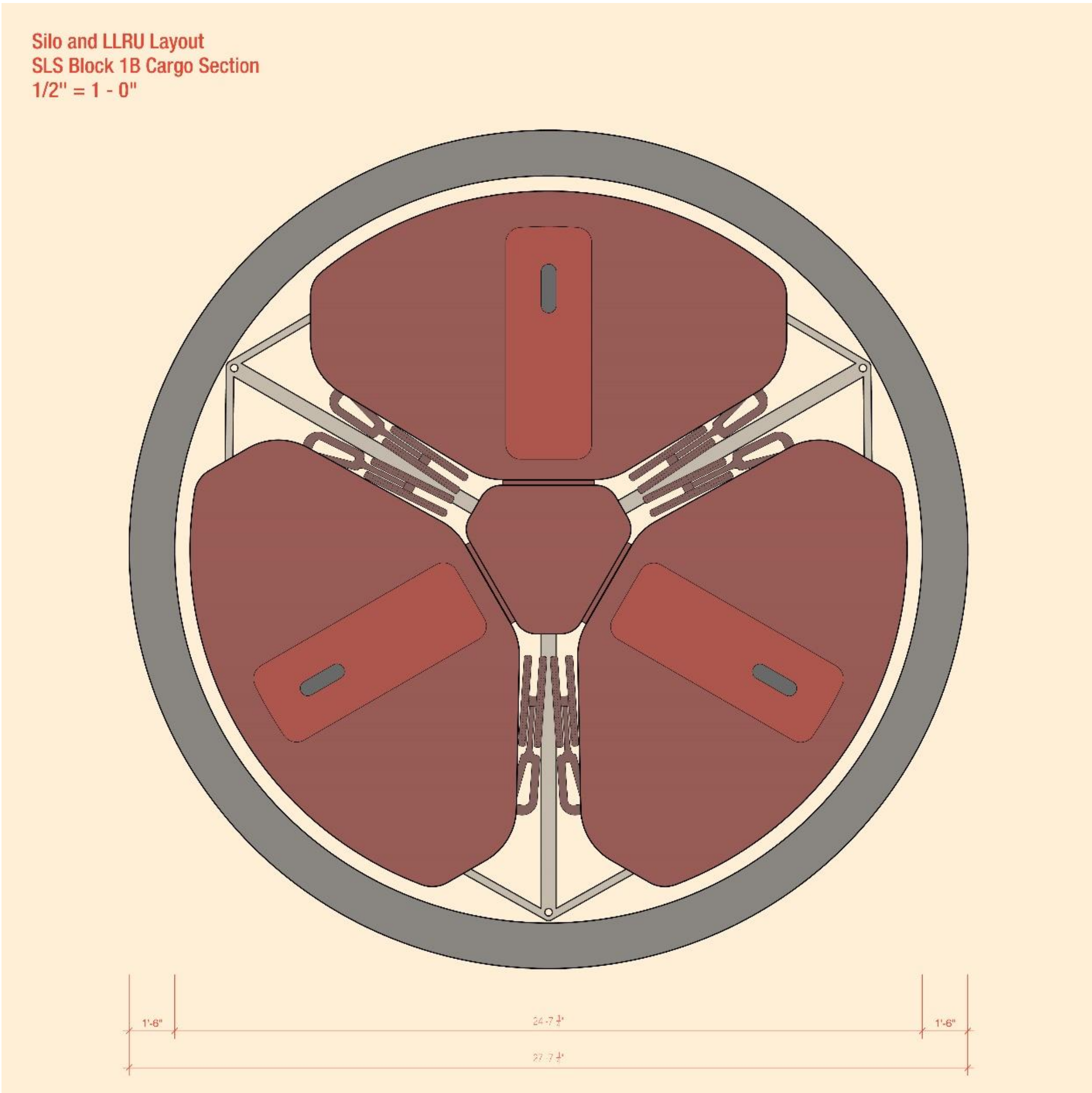

Figure 21 Silo and LLRU Layout

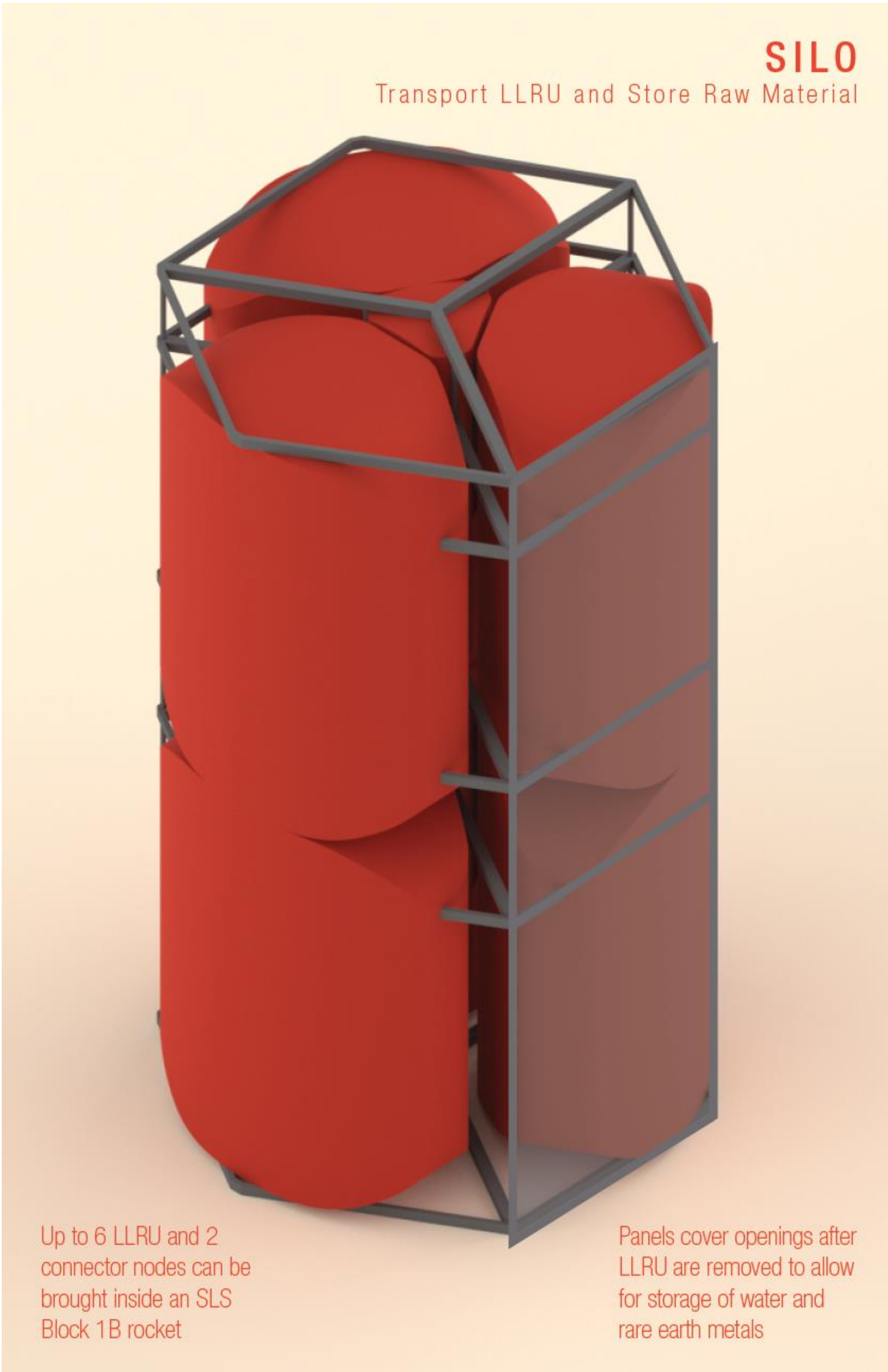

Figure 22 Silo Axonometric

Figure 23 LLRU Massing in Rocket

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