Pit
of
the
Moon

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A Modular Departure to Lunar Colonization

a final study by

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Dedication

To my grandfather, who gave me the opportunity to pursue the years I have in architecture.

To my family, who always encouraged me and were always intrigued by the many projects that I have created over the years.

To Clara, who always helped me through ideas when I got stuck and for helping me through the truly stressful times of life.

To my roommates, who through all the insanity of studio, always found the time to take a break for us to spend together.

To my classmates, who through the six years of college, became my friends and will always remind me of the fun of studio.

Mission Details

Introduction

With renewed interest in space exploration and the ongoing Artemis missions from NASA, lunar colonization is nearing ever closer. Designs from pop culture media and common design concepts tend to be small confined spaces, usually in some dome like structure. This project aims to be a departure from these ideas. Through use of modular design, we are able to create large, open interior spaces that adhere to constraints of rocket storage capacities. Truly melding the architecture and engineering worlds gives rise to a concept that is not only plausible, but flexible and appealing spaces to the future inhabitants of the lunar surface.

Precedent Analysis

International Space Station

The International Space Station (ISS) is the single biggest instance of collaboration amongst the various space agencies. The ISS serves as an on-going orbital research lab, as well as, a human interaction research experiemnt. Over the many years of its inhabitance, we have learned much about human interactions in such a confined and isolated environment. The information that we are able to extrapolate from this provides a basis for future space stations and colonies.

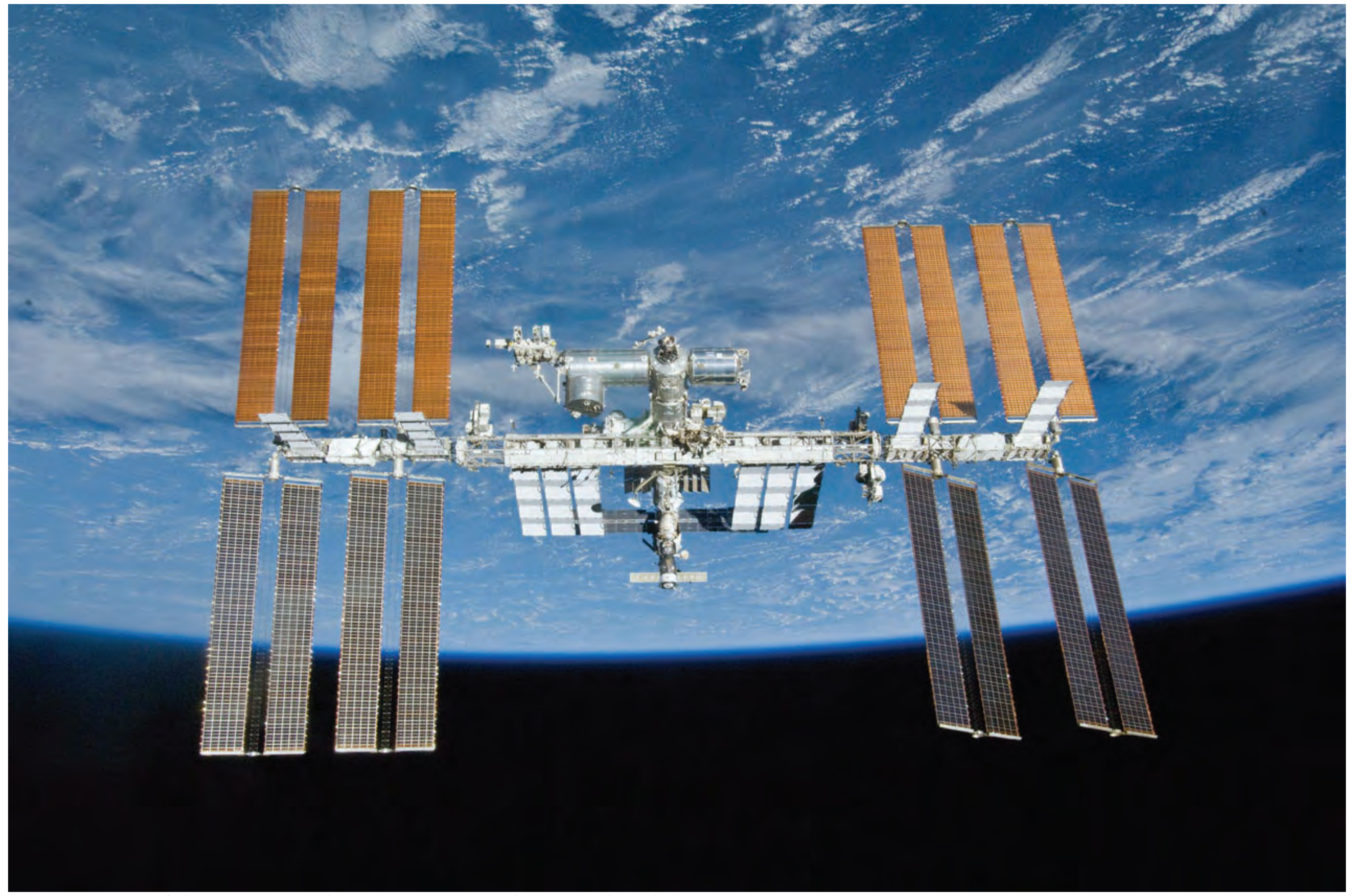


Figure 1 - View of the International Space Station in orbit around Earth

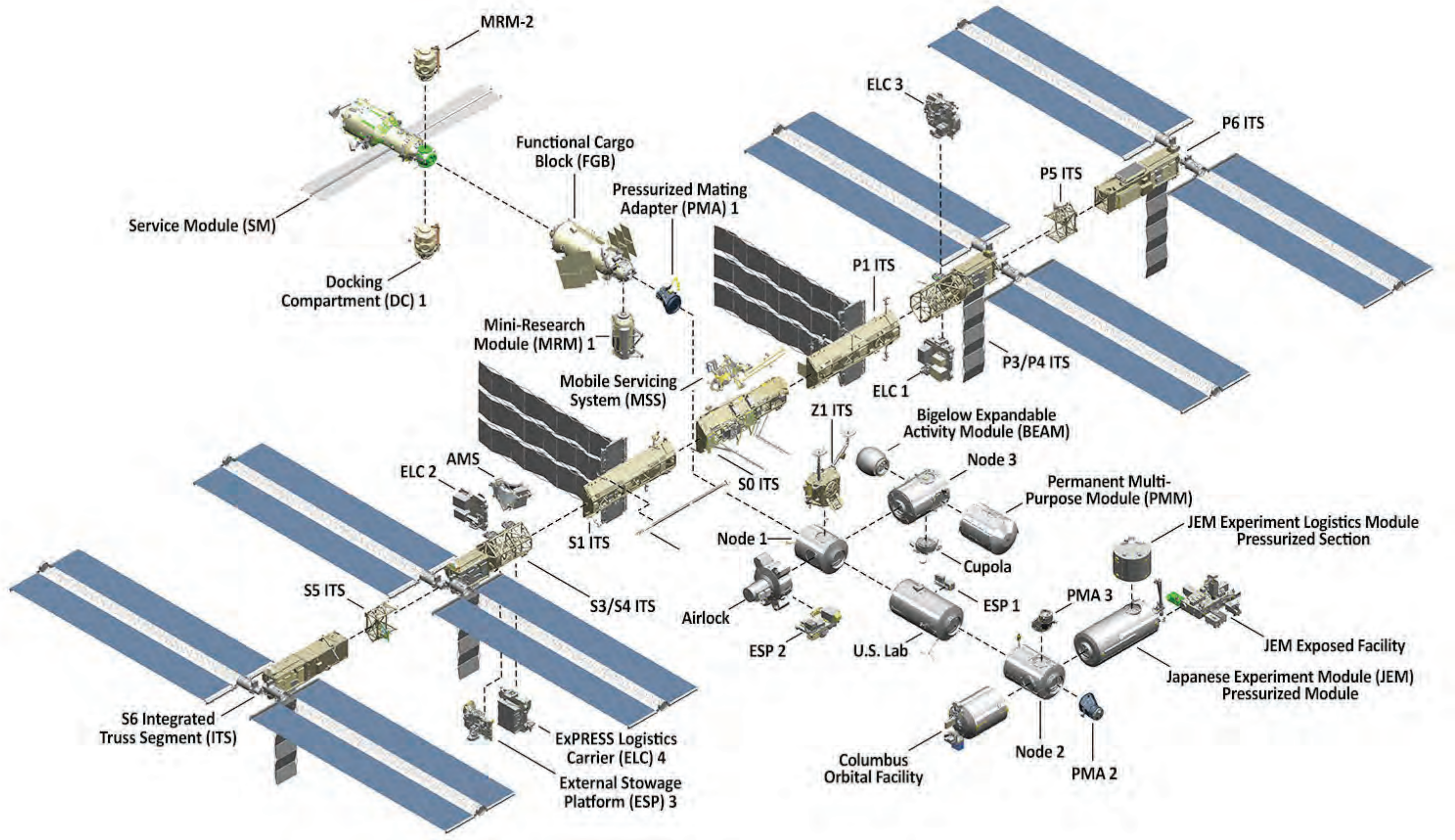


Figure 2 - Exploded axon of the various modular pieces that make up the International Space Station

The modular nature of the ISS (pictured above) provides a method for expansion. Modules are able to be added over time and designed specifically for the tasks that they are required for. Between modules, there are means for sharing and distributing resources (air and electricity) to new modules.

Looking at the interior to many of the modules, the Internation Standard Payload Rack (ISPR) (pictured right) can be found. This standardized storage system allows for components and equipment to easily replaced and stowed away until needed once more or until its eventual decomission.

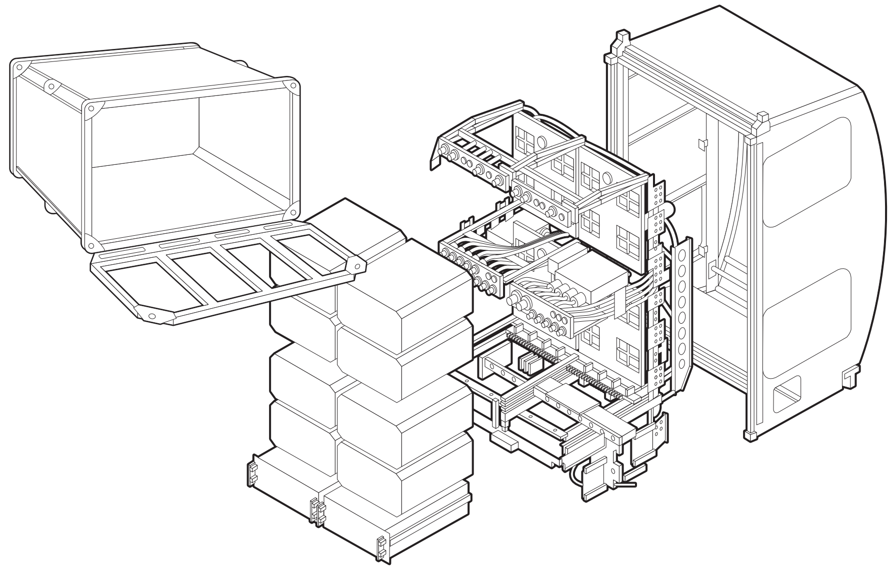


Figure 3 - International Standard Payload Rack

Depolyable Modular Frame

The Deployable Modular Frame (DMF) is a concept for expandable spaces for space station modules. Inflatable modules have larger volumes in comparison to their solid counterparts, suffering only from the lack of a reliable storage platform. The International Space Station's ISPR does not lend itself to use in such an application due to its inability effectively utilize the newfound larger space of inflatable modules. Vittorio Netti's DMF project seeks to provide a solution to bridge the gap between inflatable space modules and a new and efficient storage platform.

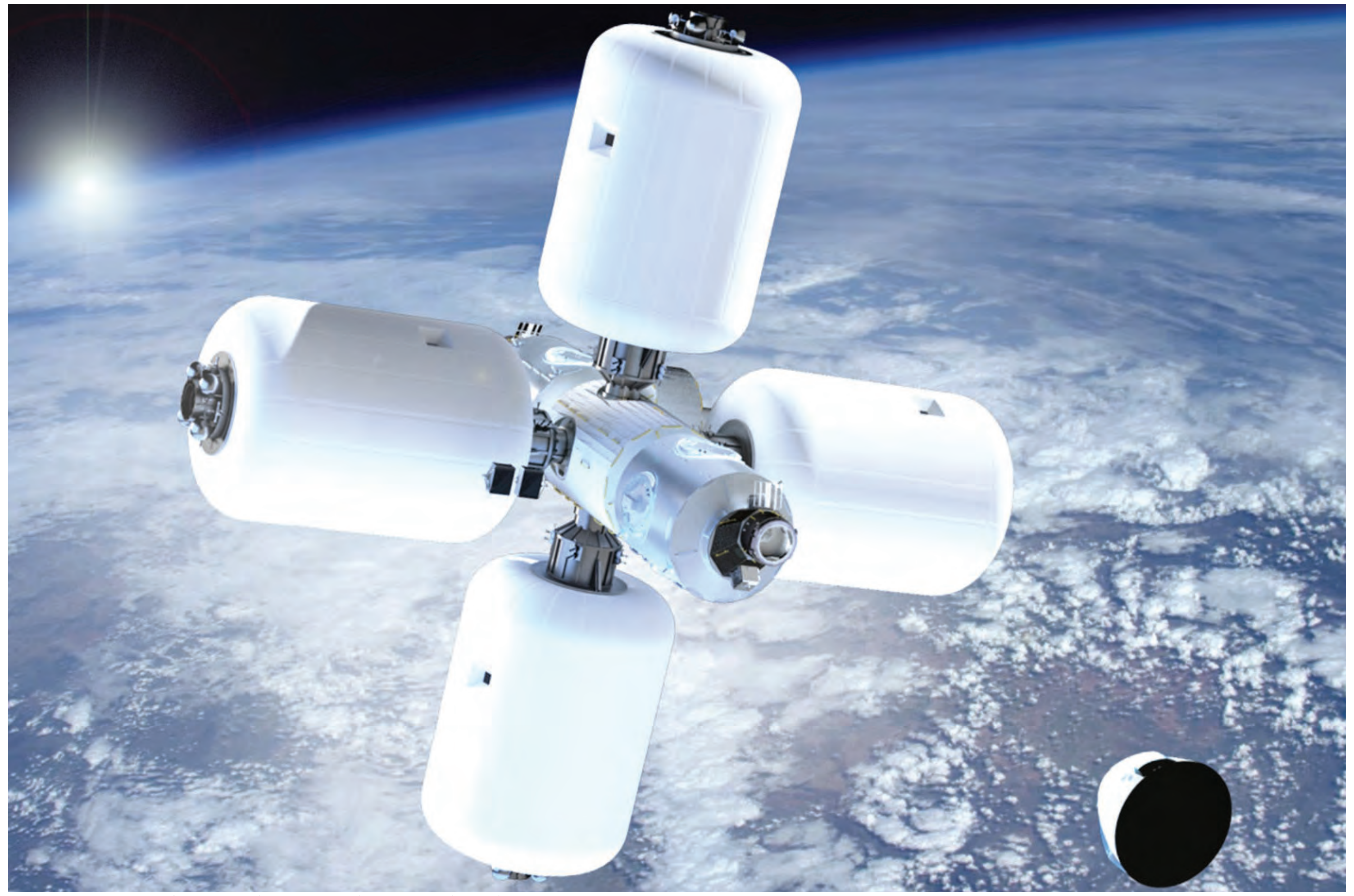


Figure 4 - View of a DMF cluster in orbit around Earth

Figure 5.A - DMF in stowed configuration

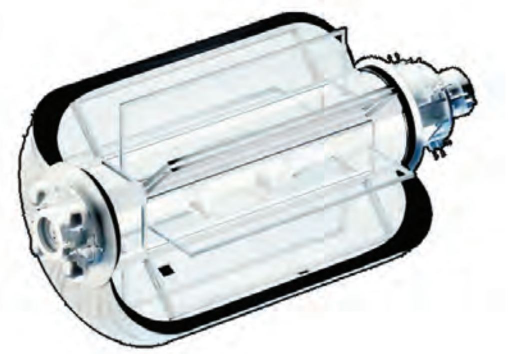


Figure 5.B - Deployable Frame (DF) deployment

Figure 5.C - Modular Rack (MR) configuration

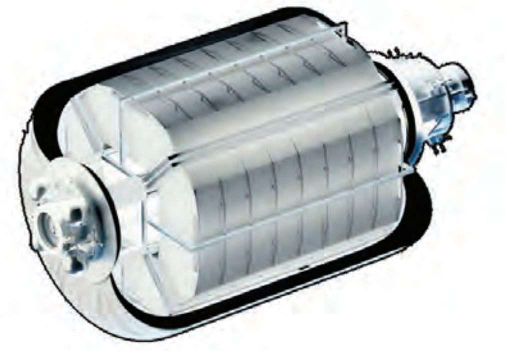


Figure 5.D - Rack enclosures outfitting

The DMF consists of multiple layers. First, we have the inflatable membrane that incases the useable space, attached to a rigid support frame for connecting a series of modules. Second comes the Deployable Frame (DF), which expands and provides the structure from which to hang the next layer, the Modular Racks (MR). The final layer composing this system are the individual submodules. A single submodule (pictured below) is composed of two (2) modular racks. Figure 3 (pictured left) depicts the deployment and assembly process of the interior once the membrance has been inflated.

To accomodate the needs of varying spaces, different configurations of submodules, and their contents, can be laid out. Completely filling the DF with submodules provides for a cargo storage configuration. Omitting a few submodules allows for that space to be used as a workstation, out of the way of the typical flow of traffic throughout the module. Having removed submodules also allows for submodules to slide back and forth on the DF, easily stowing and reveiling the necessary equipment for the tasks at hand.

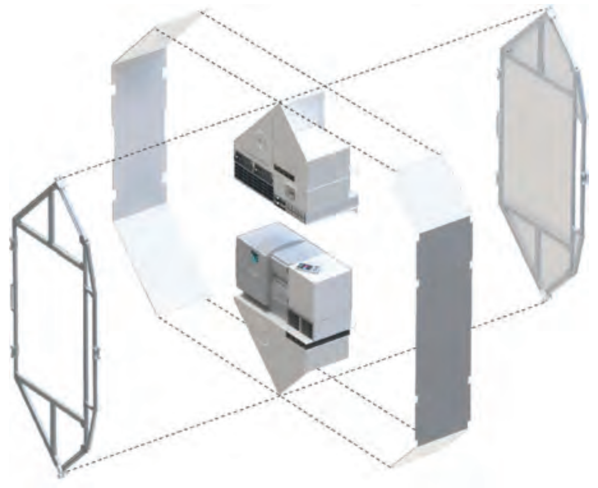


Figure 6 - Exploded view of a submodule

Biosphere 2

While this Arizona research facility ultimately failed, Biosphere 2 integrated elements into the design that are beneficial to alternate project applications. Biosphere 2 was meant to be an experiment about closed ecological systems on Earth and on other planets. The failure of this project resulted from multiple factors. The system wasn't fully closed, leading to an invasion of CO^2 producing bacteria. For a time the project was kept a secret, before the public ultimately found out and turned the facility into a zoo for the public to visit.


Figure 7 - View of the Biosphere 2 facility

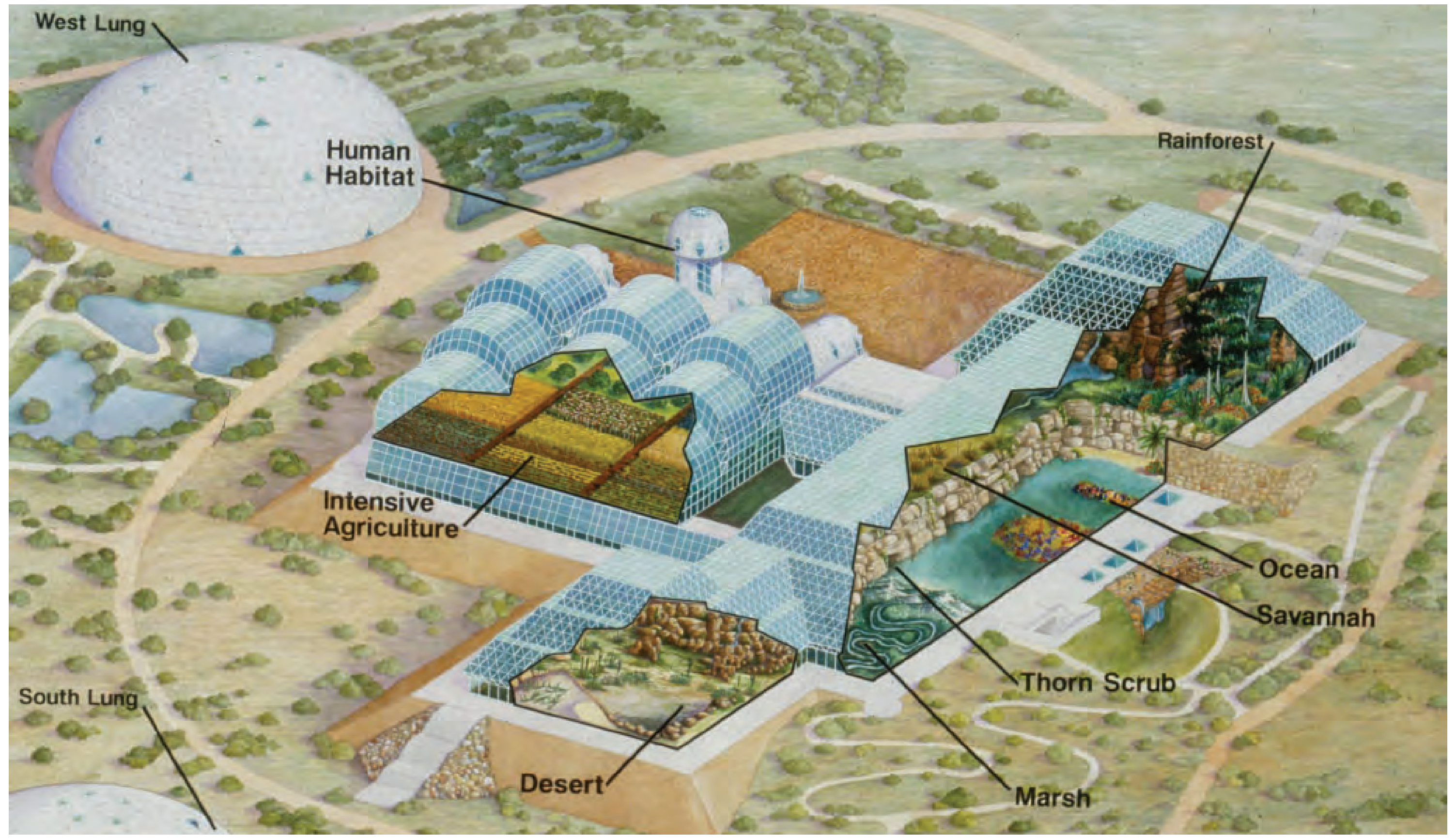


Figure 8 - Reveal cuts of the various parts of the Biosphere 2 facility and what the spaces are.

Biosphere 2 contains a series of environments and creatures that were deemed important to maintaining a stable ecosystem. Figure 5 (pictured above) shows the all of environments that make up the facility and their connections to one another, with a designated area for human habitation.

The applicable portions of Biosphere 2 come from the atmospheric control system, the double-layered, air-tight exterior and the lung structures located further away from the core facility. These combined system (pictured right) provided a means for maintaining a stable atmosphere.

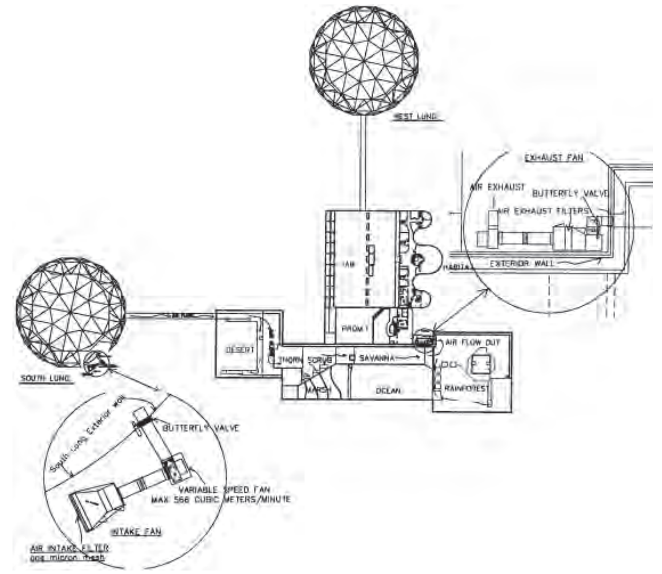


Figure 9 - Functional diagram of the linkage between the lungs and facility

ESA Lunar Outpost

The ESA (European Space Agency) Lunar Outpost concept is a take on developing a lunar colony using inflatable structures, covered with chemically stablized lunar material. This lunar outpost, designed by Norman Foster and Partners, aims to solve the issue of sending a larger inhabitable structure within the tight restrictions of rocket cargo capacities. These inflatable habitats expand out of the landing module allowing for the module to serve as an entrance or expansion point to connect future modules.

Figure 10 - View of a single inflatable habitat and partial view of the proposed rover to used to construct the exterior

Figure 11.A - Packaged Module is set in place

Figure 11.B - Inflatable membrane is deployed

Figure 11.C - Membrane is fully inflated

Figure 11.D - Lunar dirt is pushed up around membrane

Figure 11.E - Hardening chemical added for structure

Figure 11.F - Window modules added

As sending construction materials to space is difficult to manage, having the primary inhabitable space be part of the module that houses it, is an efficient option. Figure 7 (pictured left) shows the process that was developed for this lunar concept. Simply having an inflatable membrane does not withstand the environmental conditions of the moon, namely, the temperature fluctuations and cosmic radiation. To combat these issues, Norman Foster and Partners utilize a mound covering of lunar dirt. A rover, fixed with blade to push material into place and a print head to stablize the loose lunar material into a thick protective covering.

For the interior elements of the lunar outpost, they can be house within the empty space of the landing module. After expansion and final covering, colonists will begin to set up the interior. A downside to this unsupported, inflatable membrane forming the inhabitable space is the inefficient spatial utilization. The sag from the weight of the membrane itself creates tighter areas along the walls that are not able to be effectively used. This pushes most functions to the central area and forces mechanical and electrical systems to the edge.

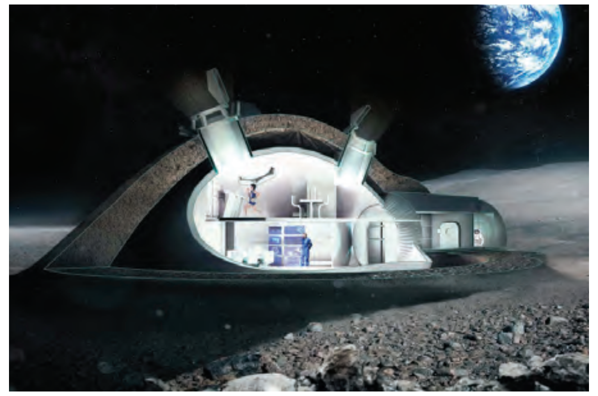


Figure 12 - Section cut of the interior space

Mars X House v2

The Mars X House v2 is a concept Mars colony designed by SEArch+ as part of the NASA Phase 3 3D-Printed Habitat Challenge. This concept structure uses a 3D-printed exterior over a expanding structural frame. While typically pressurized environments are typically round, SEArch+ designed the structure to use a water reservoir to create pressure into a hyperbolic structure. The pressure from the reservoir maintains the inward and outward pressures from the environments for this multi-story colony structure.

Figure 13 - View of a series of completed Mars X House v2 modules

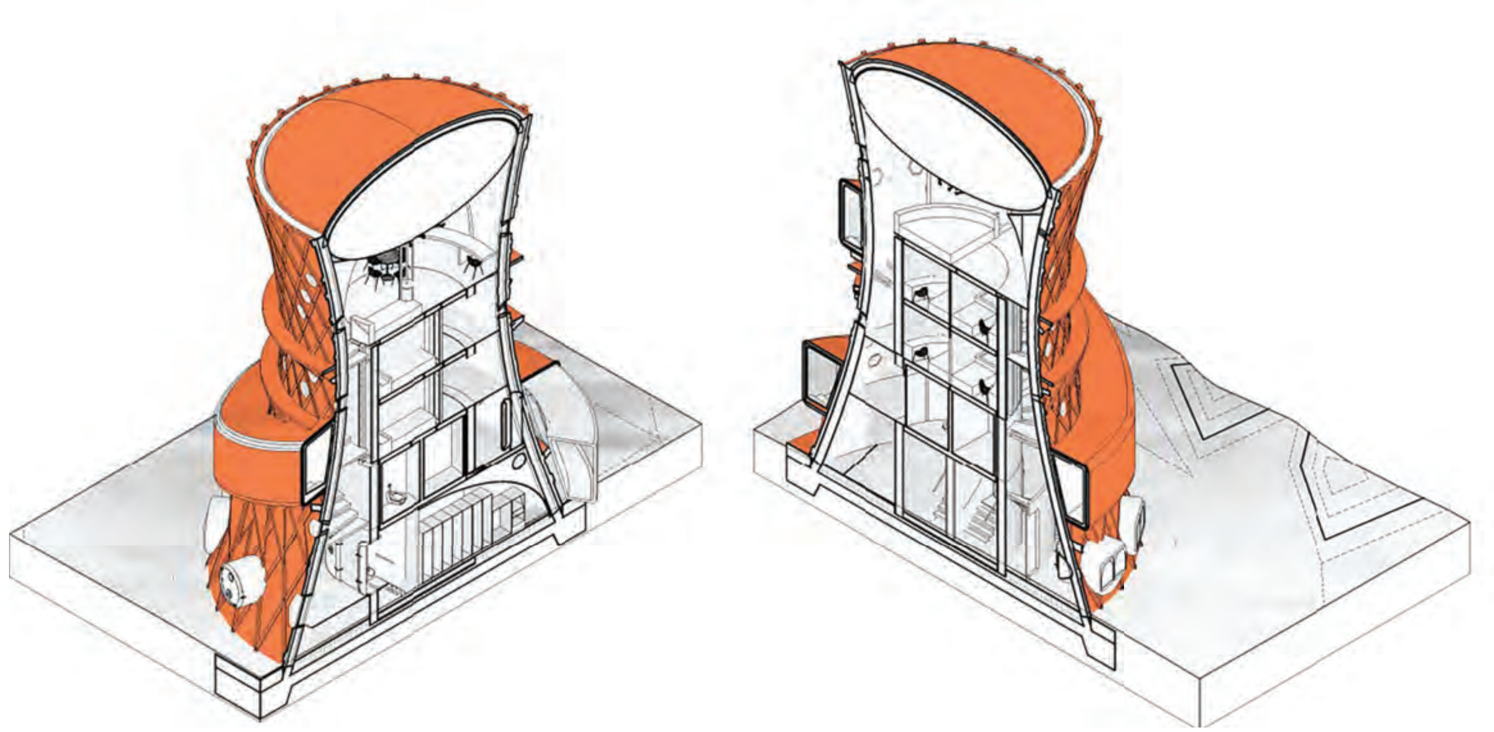


Figure 14 - A pair of section cuts in either direction showing the vertical series of interior spaces and means of egress.

To solve the problem of vertical egress, an external staircase was created. In the middle floors, the living spaces can be found while in the lower levels the systems and some research spaces can be found. At the top of the structure is the water reservoir.

The wall section (pictured right) shows the layers that make up the exterior wall. To help provide strength to the structure a wire lattice is added into the 3D-printing process, along with a layer of insulation and windows.

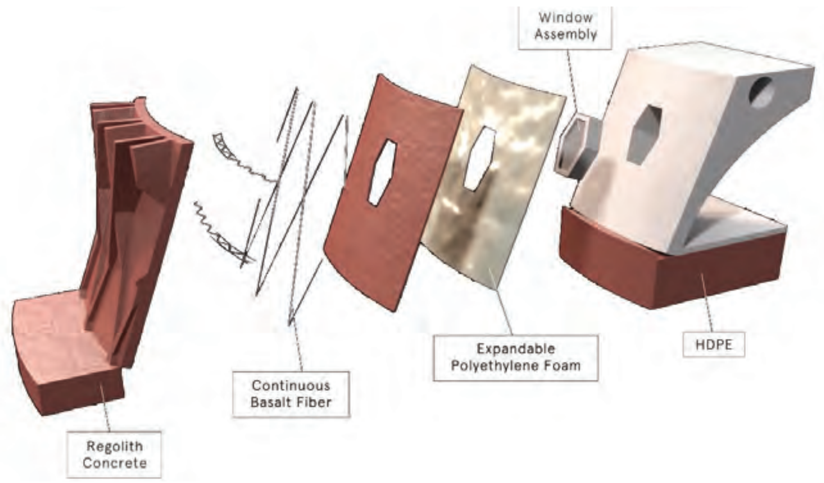


Figure 15 - Exploded wall section detailing what the layers are.

PennState 3D-Printed Mars Habitat

PennState's take on a 3D-Printed Mars Habitat is simliar to that of the Mars X House v2. A 3D-printed habitat, using the martian dirt to create what PennState called "Mars-crete". PennState managed to also develop a functionally graded material by changing the ratios of materials and by adding gradually more heat throughout the printing process to create a translucent material. The conical nature of the structure was developed in a way such that no scaffolding was required to keep the structure from collapsing.

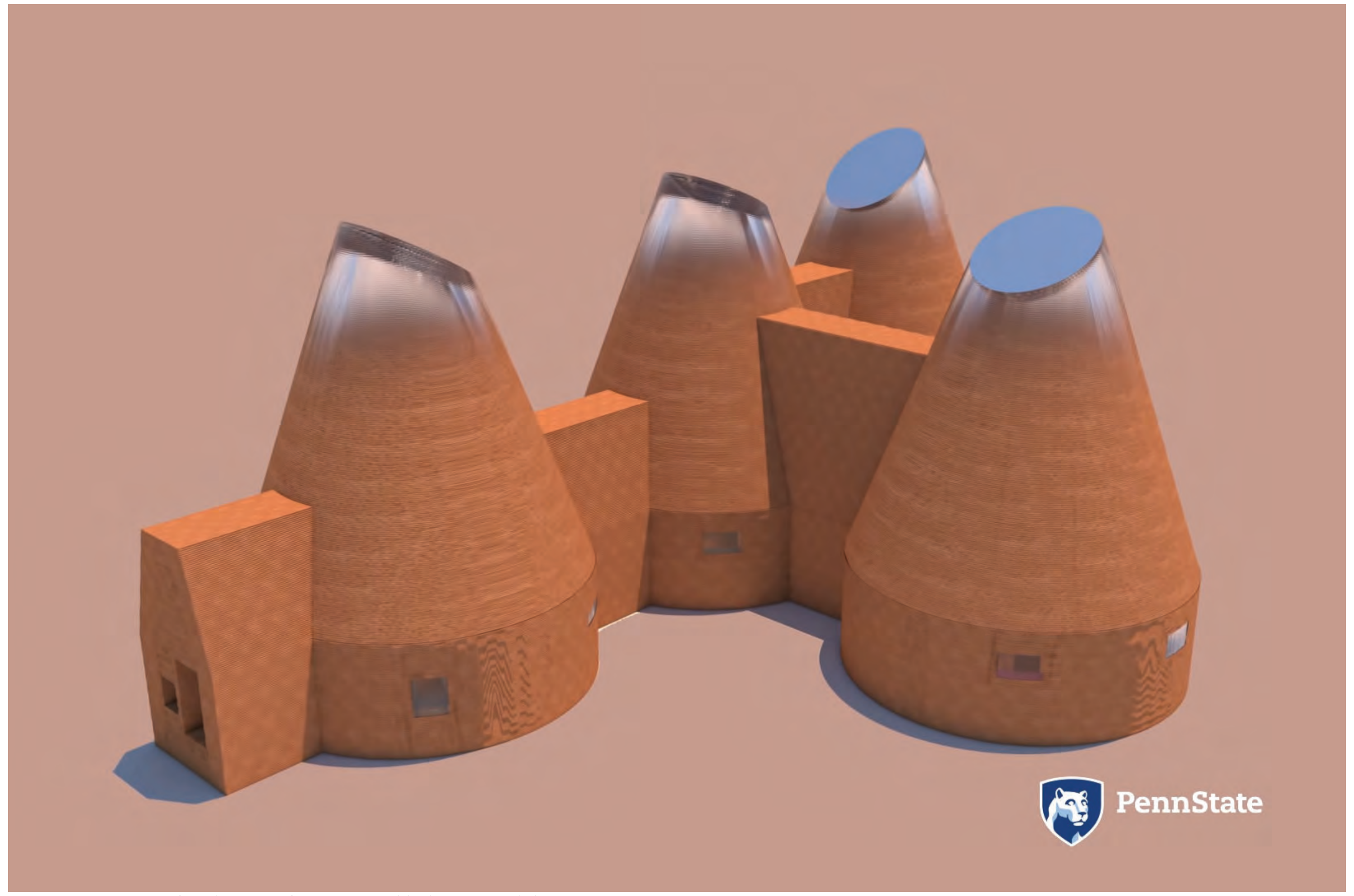


Figure 16 - View of a cluster of 3D-printed habitat modules

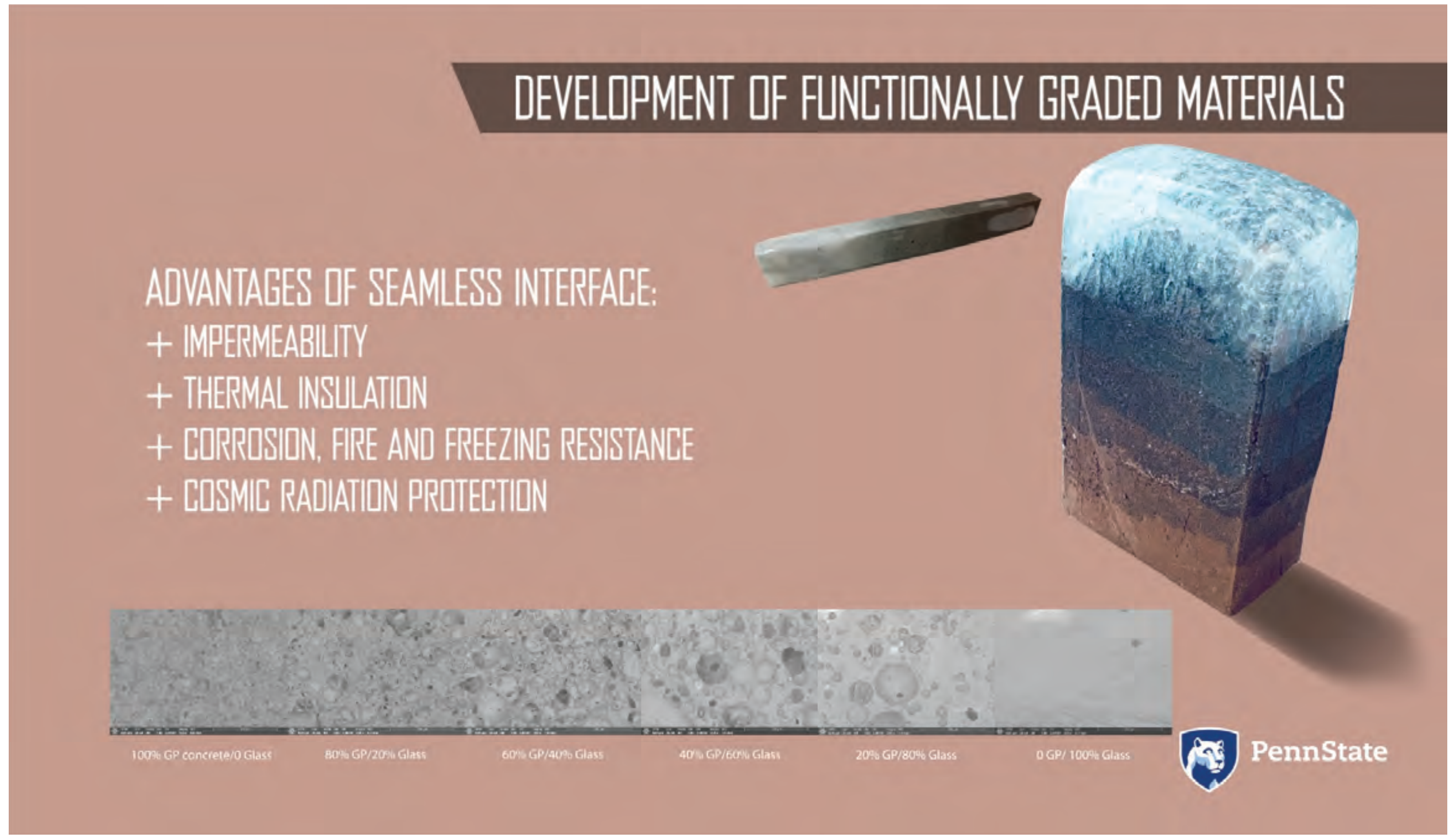


Figure 17 - Detailed look a the advantages and components of PennState's functionally graded "Mars-crete".

The functionally graded material (pictured above) that PennState developed is able to create a gradient from opaque to translucent, while being airtight all the around. This gradiented "Mars-crete" also withstood the harsh effects of the martian landscape, which can be adapted for a lunar colony.

A specially designed rover was created to properly print the functionally graded material. The rover created has a series of tanks with the varying materials required and features an enclosure that, during the printing process, creates the ideal environment for the "Mars-crete" to effectively cure.

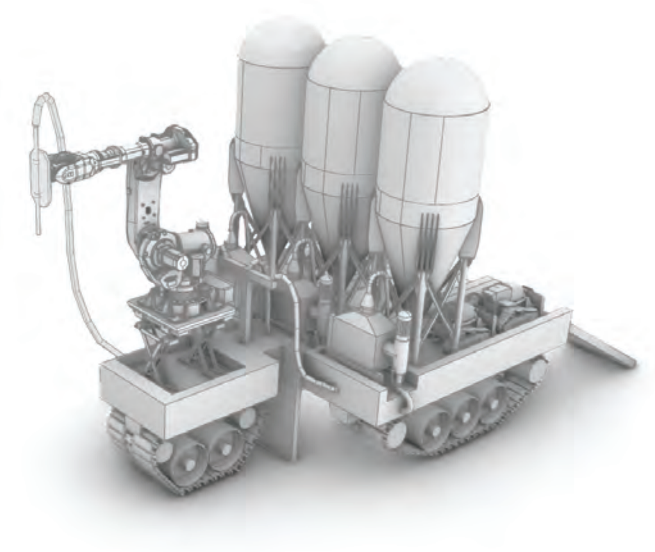


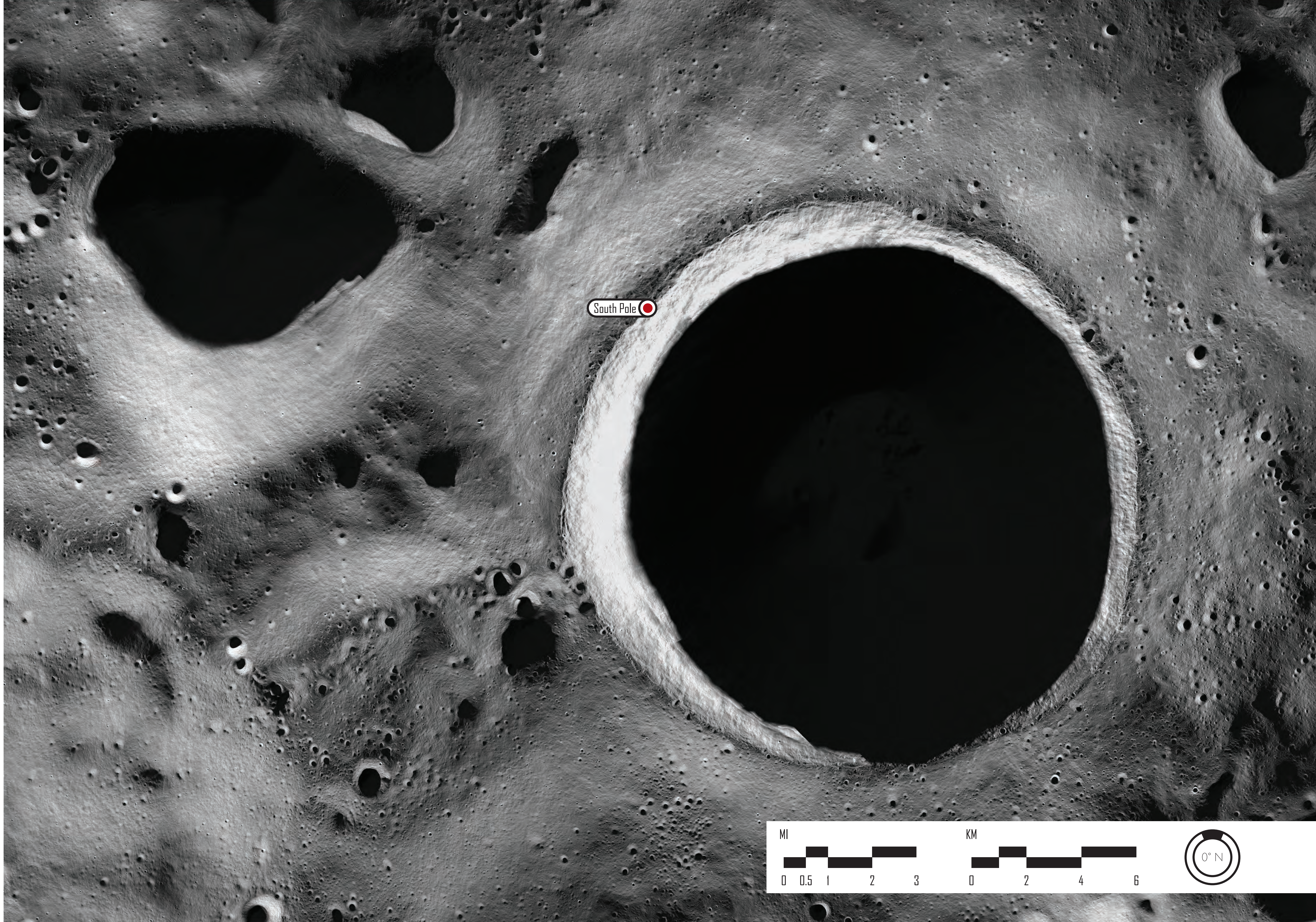
Figure 18 - Diagram showcasing the rover designed for 3D-printing the structures

Site Conditions

Shackleton Crater

Shackleton Crater has been selected to be the site for this lunar concept. The south pole region has been selected as the target for the NASA Artemis missions, with several potential site scattered around the region (see figure 23 in appendix). As the edge of Shackleton Crate intersects the south pole and the moon has a sweeping terminator sun path (see figure 24 in appendix), this provides a prime location for a lunar colony. With the raised rim around the crater, its edge is almost constantly illuminated, providing near constant means for solar energy generation. This location also has a more stable temperature range (see figure 26 in appendix).

One of the reasons in which NASA has selected the south pole region for exploration is the presence of water ice. If this water ice would be able to be harvested, the means for 3D-printed habitat would be much simpler, as the lunar surface already includes all of the necessary ingredients to make a lunar variant of concrete. This water ice could also be used to help sustain life support systems and colonists that will one day occupy the lunar surface.

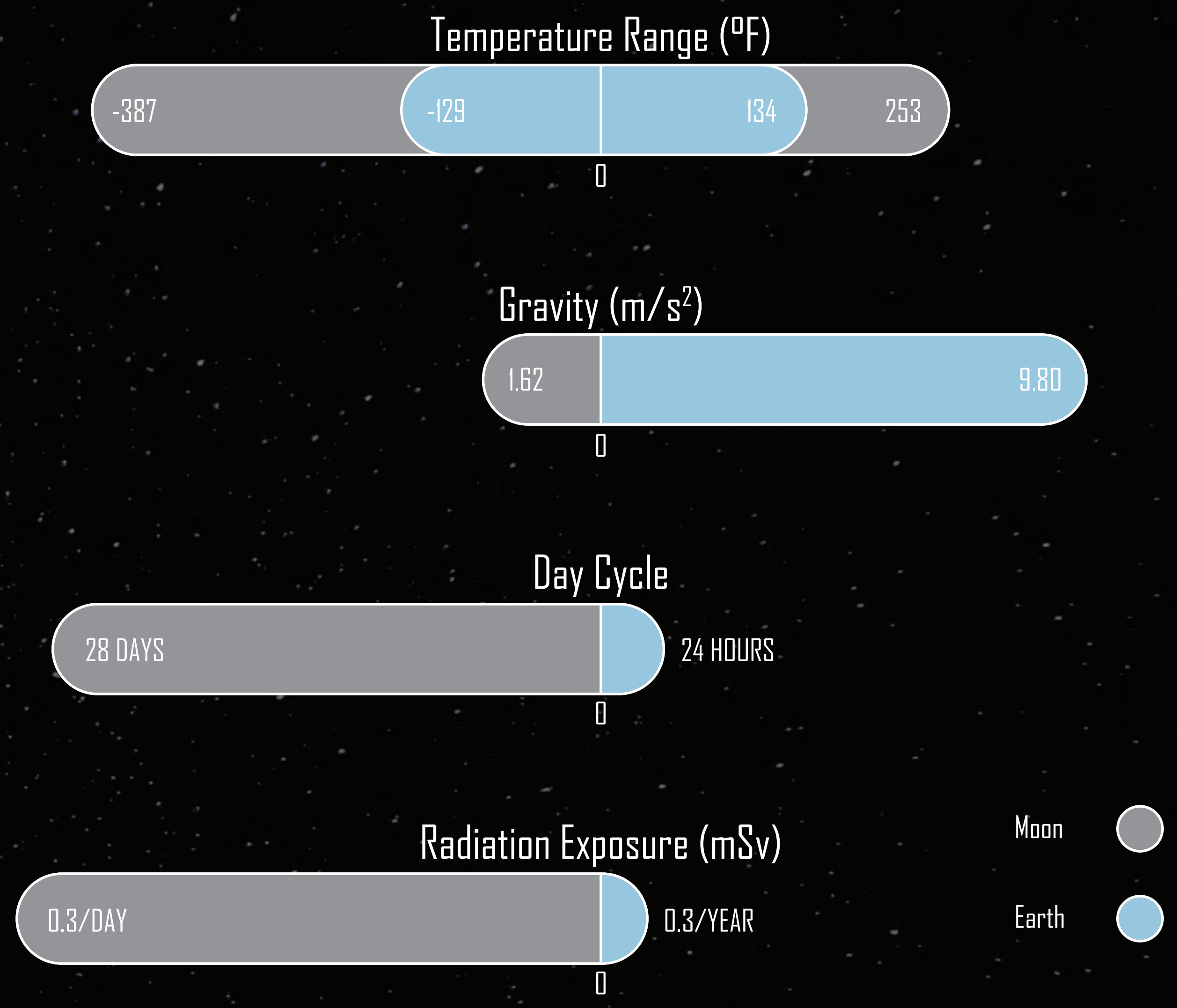


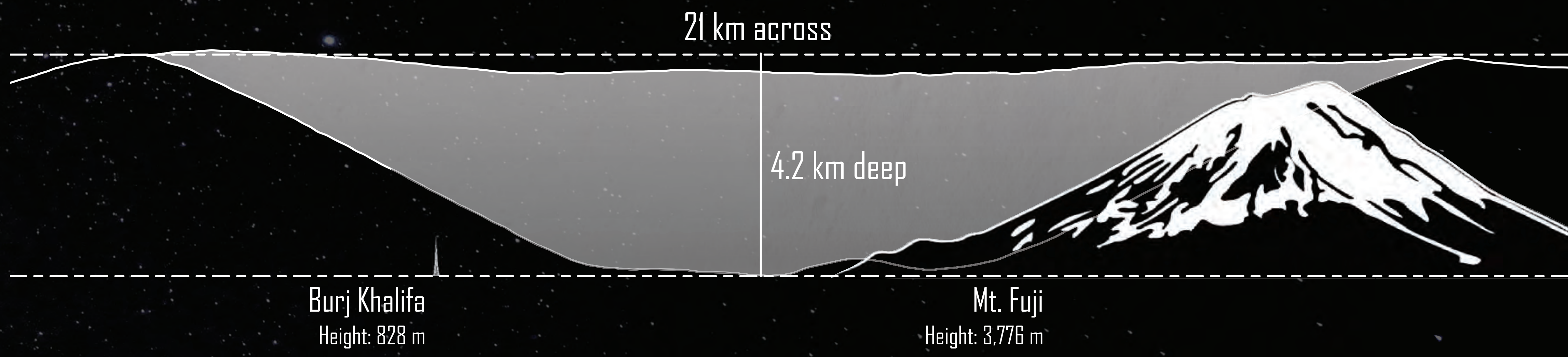
Earth to Moon Comparison

The Earth and Moon are drastically different environments in a wide variety of ways, but a few key ways. The moon is significantly smaller in size, just over a quarter of the radius of the Earth. This smaller size and by consequence, smaller mass, gives the Moon a signficantly lower gravity, about one-sixth the gravity of the Earth. The Moon is tidally locked celestial body. By being tidally locked to the Earth, the Moon itself does not rotate around an axis, but rather the same side of the Moon is always facing the earth, orbiting around as the Earth rotates on its axis. Not being able to rotate itself, the Moon has a longer day-night cycle, which contributes to the higher fluctuations in temperature. Lastly, the Moon does not have an atmosphere, giving no means for sustaining a breathable air or providing protection against cosmic radiation and the heat from the sun.

Earth's Radius:
6,378.14 km
3,958.8 mi

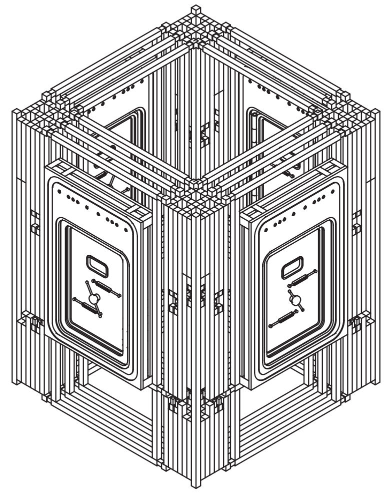
Moon's Radius:
1,737.4 km
1,079.6 mi



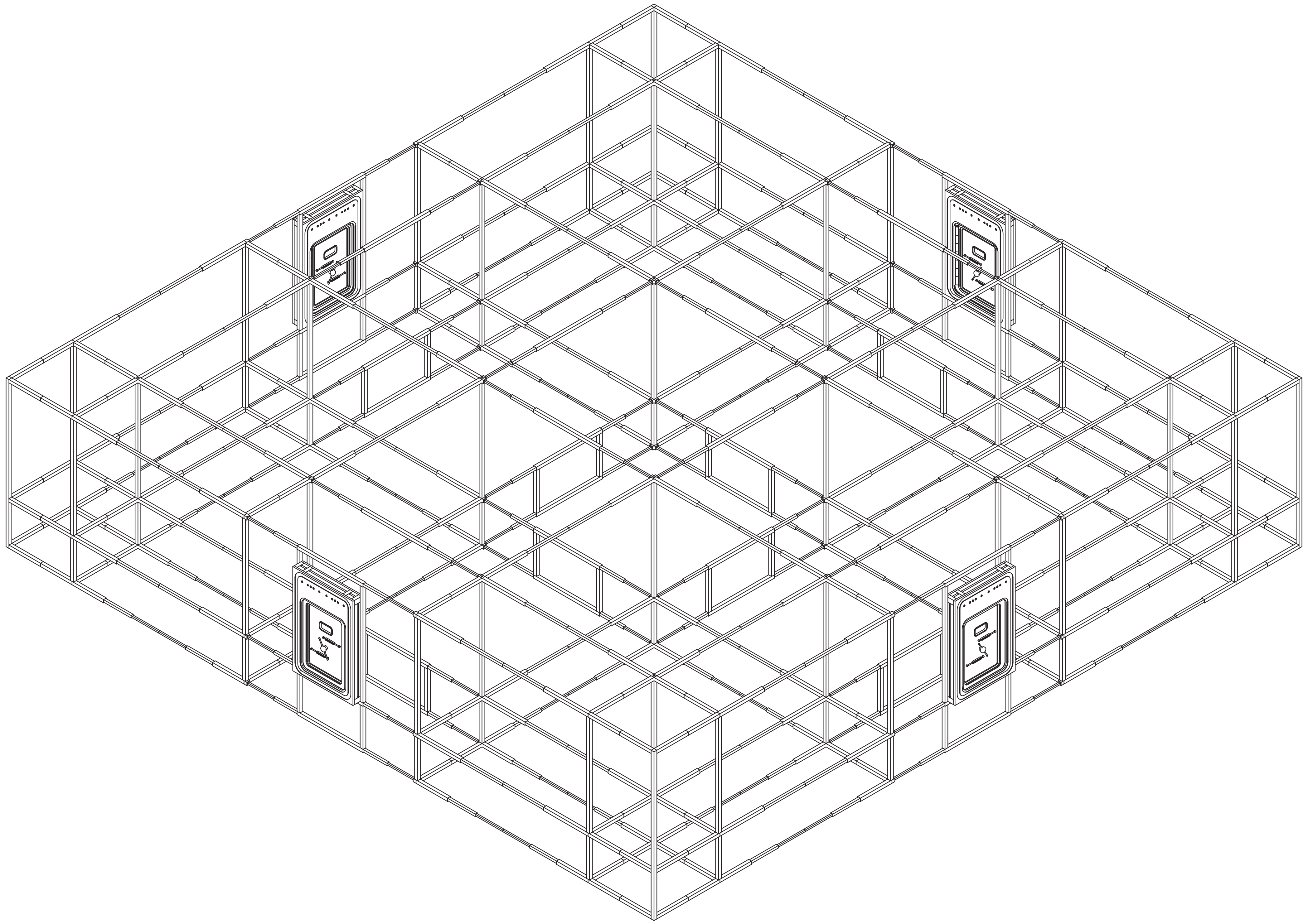


Modular System

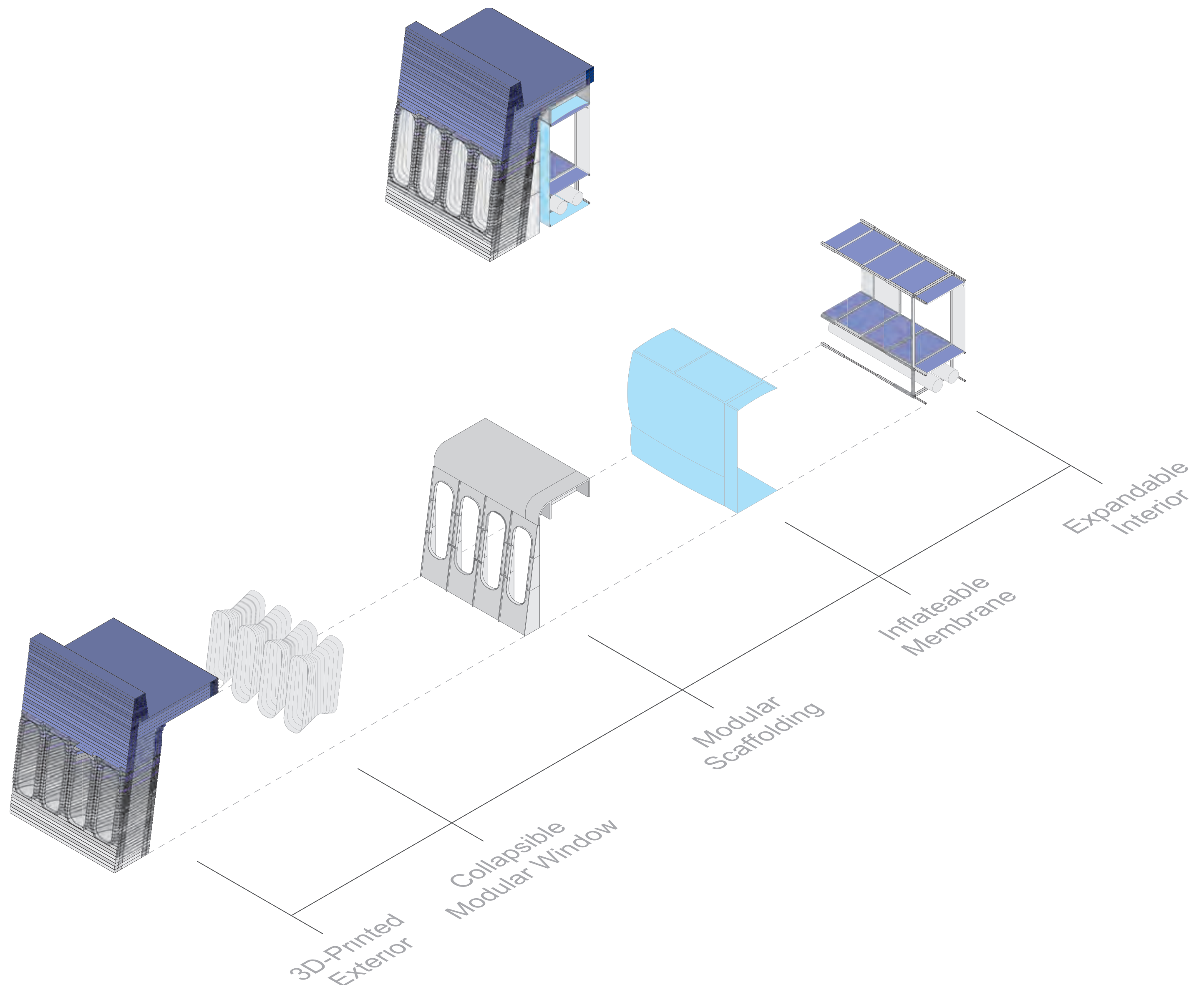
Primary Structural Module



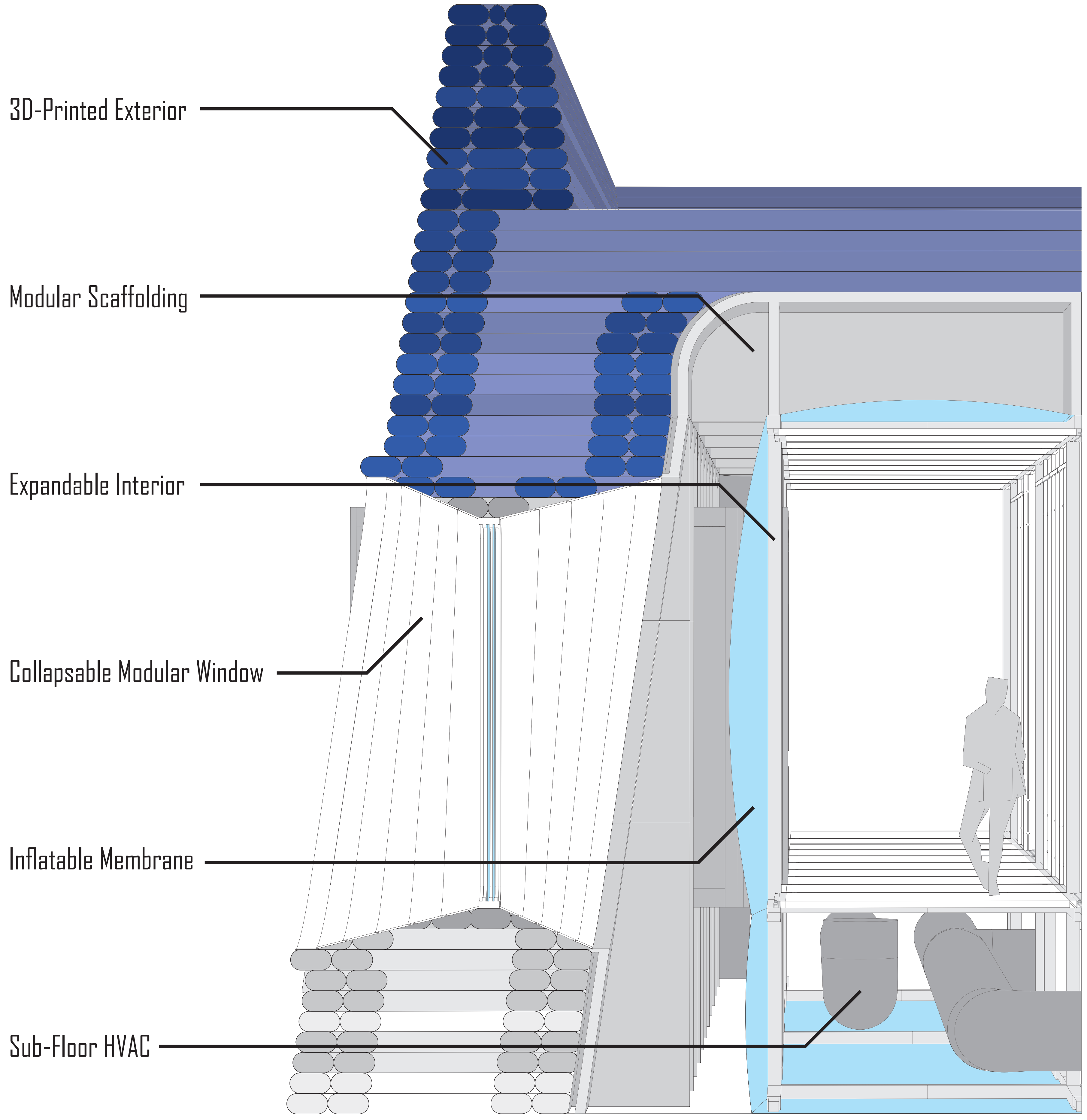
The core to this lunar colony concept is the primary structural module. This expanding modular frame allows for large interior spaces to condensed down and packed within the rockets that would send them to the Moon. With the reduced gravity, the strength and size of structural members is also reduced. This reduced size saves space in the rocket and allows for more weight to added into a single payload. When in a collapsed state, there is a small void within that allows for vital equipment for the expansion process to be housed.



Exterior Wall Assembly

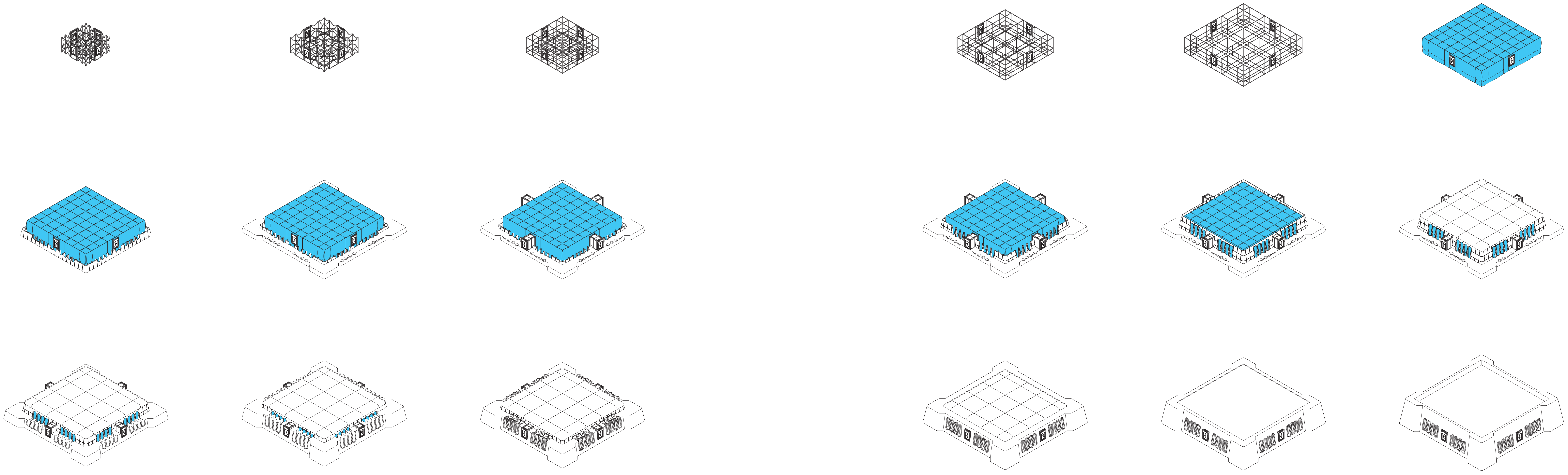


The primary means of environmental protection come from the 3D-printed exterior, encasing the primary structural modules. This monolithic exterior provides the necessary protection from the comparatively high amounts of radiation and the drastic temperature fluctuations of the lunar day-night cycle. The two layers of air-tight protection from the inflatable membrane that is wrapped around the expandable interior and the pairing of the 3D-printed exterior with modular window inserts, similar to that of the Penn State Mars colony concept.

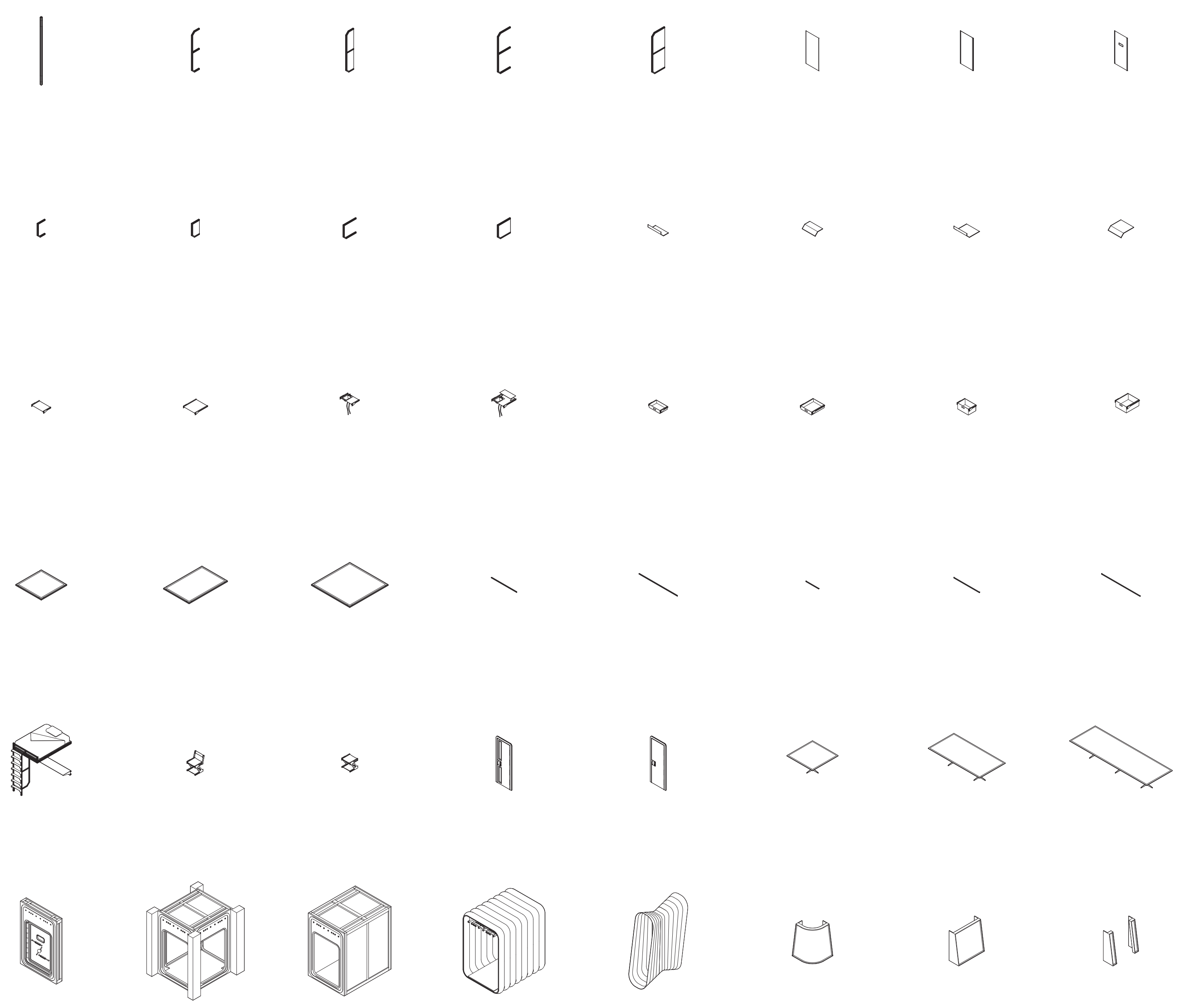


Module Expansion and Exterior Printing

The process of setting up an individual module for habitation is simple. Once a clear and level area has been establish, by means of a rover, the module is set in place and begins expansion. With the frame fully expanded, the membrane inflates. To encase the module and provide support for 3D-printing, the first layer of scaffolding is put in place and then printed around with a rover similar to that of the Penn State Mars colony or ESA lunar colony concepts. Next the connecting airlocks are attached to the exterior, using the first printed layers as support. Once the airlocks are in place, the rest of the scaffolding is placed and printing continues until it is time to insert the window modules. With the windows set in place, the rest of the exterior is printed.

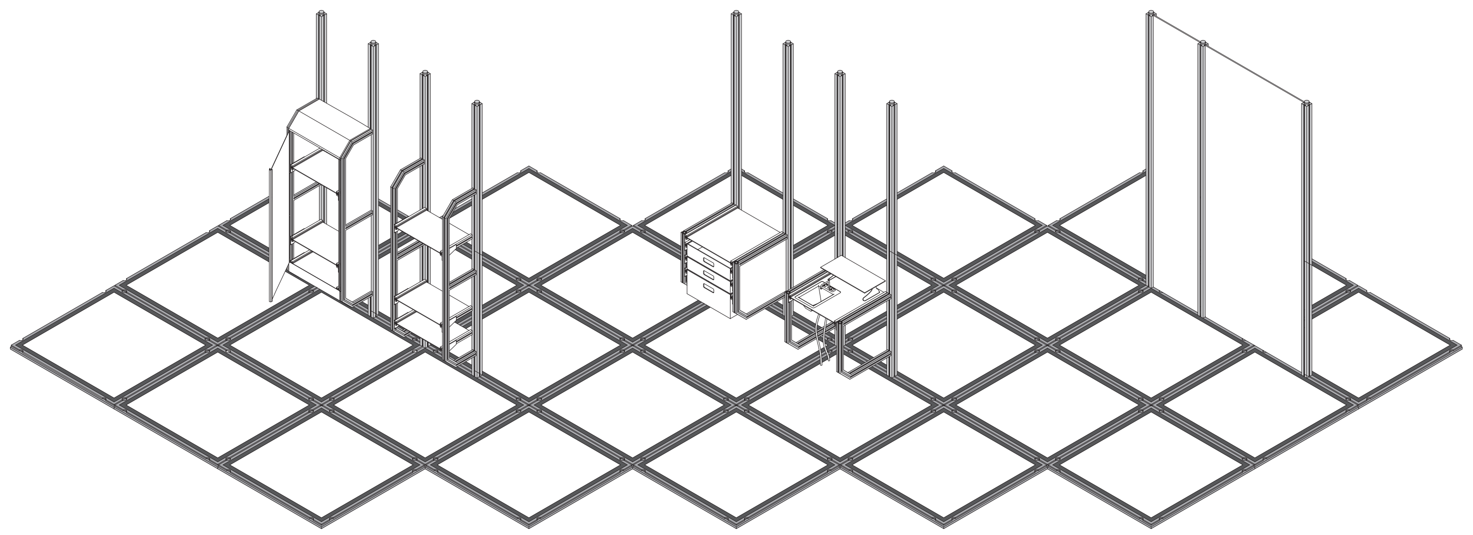


Catalog

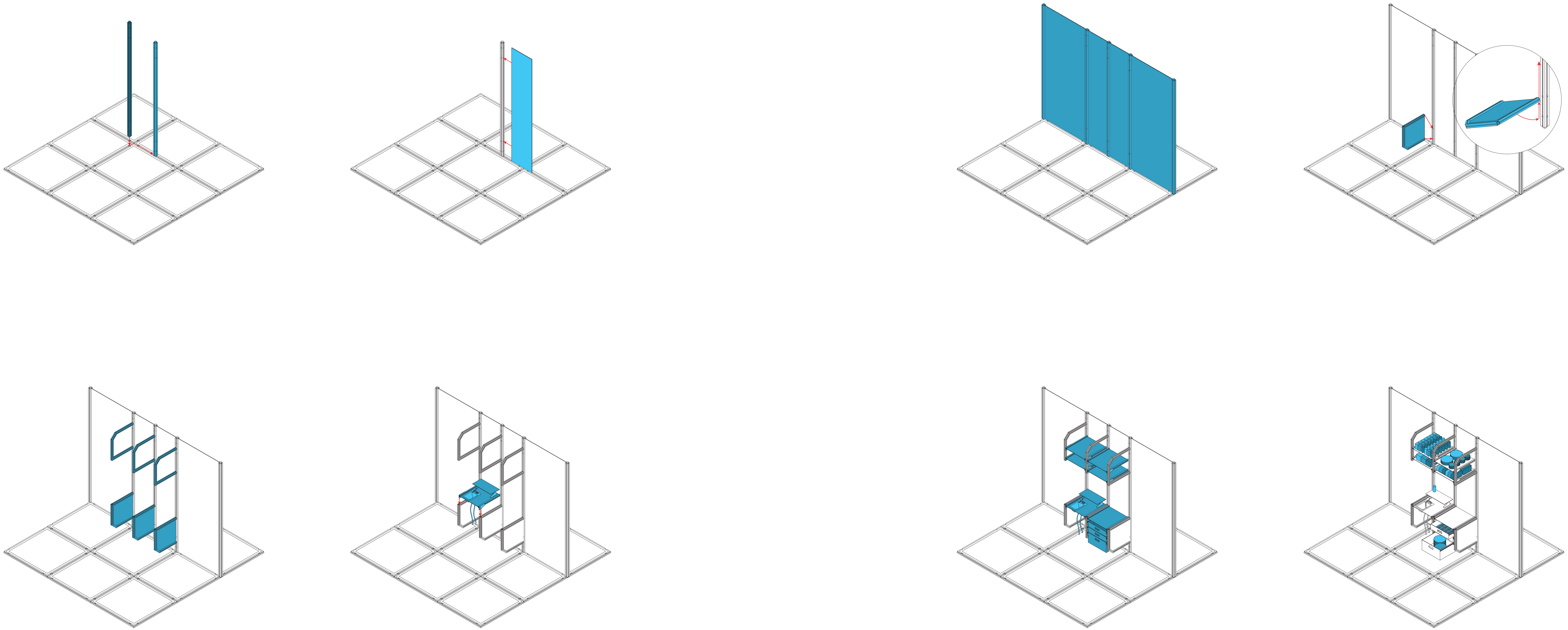


Sample Assemblies

As with most everything in this concept, the interior features a set of modular pieces. This modular assembly features several parts built around extruded aluminum, t-track parts. This assembly method is currently in use in small scale here on Earth, so by scaling it up to the size of a building interior, we are able to create and interior that is easily constructed and changed over time. These parts are lightweight and able to be mass produced for easy replacement and future expansions. The image on the left shows a collection of most of the modular pieces that can be found within this lunar colony concept. By using certain sets of parts, we can achieve a variety of assemblies for walls, cabinets, counters, and more.



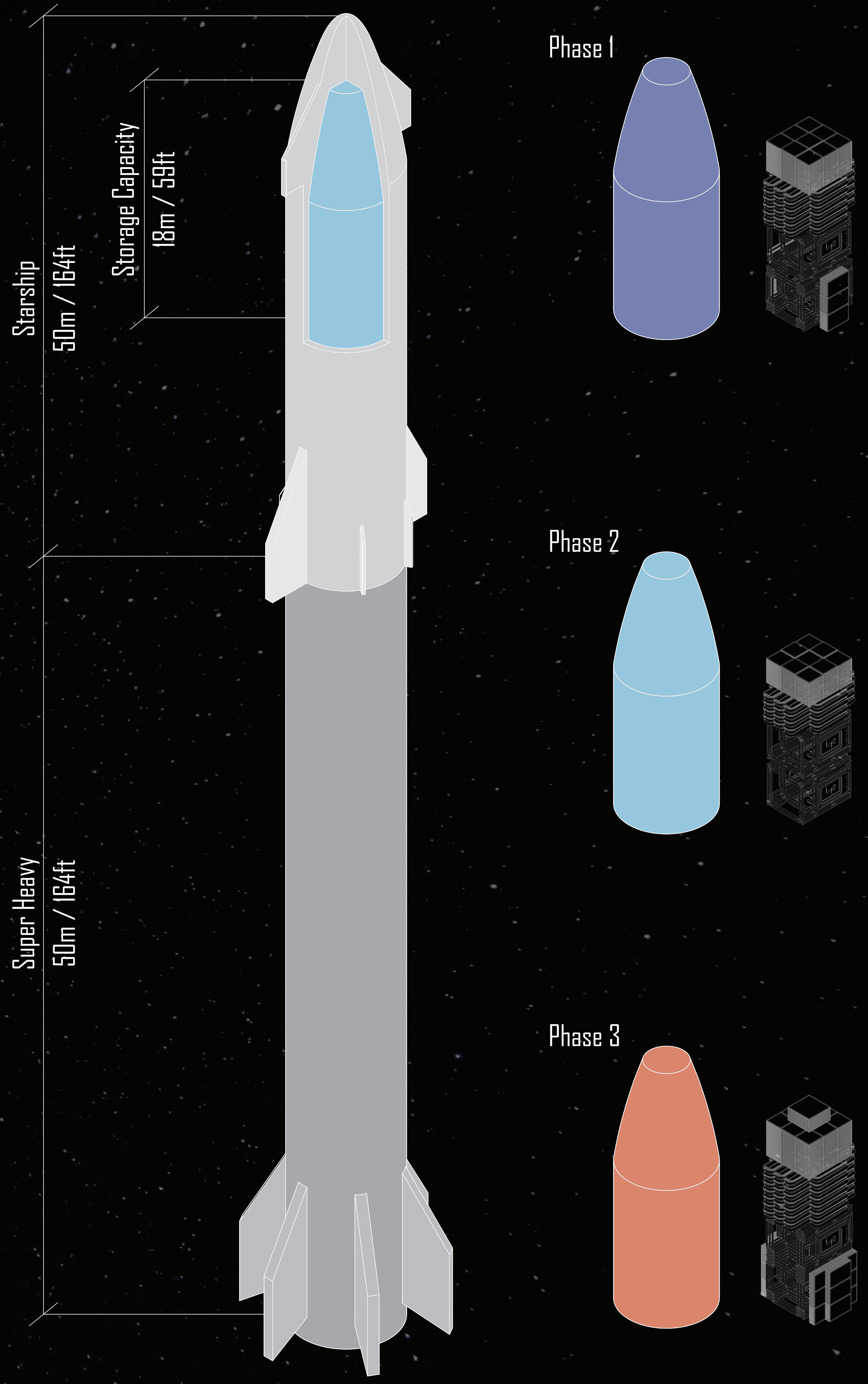
Interior Assembly Process



Design

Multi-Phase Breakdown

The full scale of a true lunar colony cannot be realized a single construction phase. This is largely due to the current limitations on cargo capacities for rockets sending supplies to space. For the sake of this concept, the SpaceX Starship rocket and Super-Heavy thruster system will be used. By using the extended cargo capacity configuration of the Starship rocket, we are able to achieve greater storage capacities in a un-manned launch. Despite the increase capacity, the amount of resrouces required to begin the colony are limited, forcing the initial colony to be broken into three phases. The modular pieces that are part of each phase can be seen to the right in their stored configuration for launch. Since the Artemis missions will already have rovers stationed near the lunar south pole, there will be no need for manned missions to be involved in the initial setup of the colony. Utilizing the existing rovers, we can send different armatures to be used on the rover to aid in the setup of the colony.

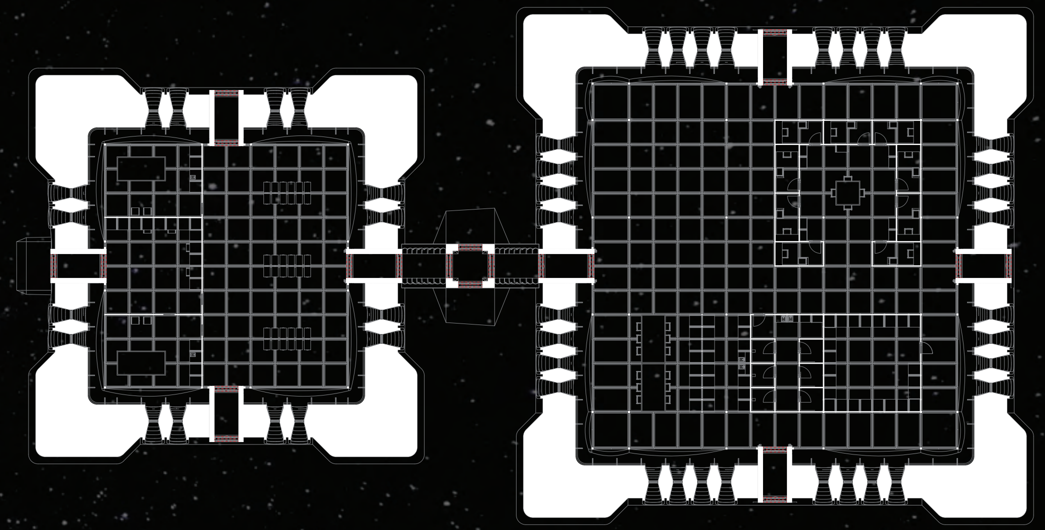


Phase 1

Phase 1 begins with the maximum available space that can be stored in the first rocket. These two modules provide more than enough space than will initially be needed by the colonists that will first inhabit it, but this gives easy areas for expansion for the later phases.

The first of the modules is what will eventually become the control center module. Within this module, living quarters, restrooms, meal preparation, and environmental control systems are housed. The extra space available in this module serves as a gathering and meeting place until further expansion.

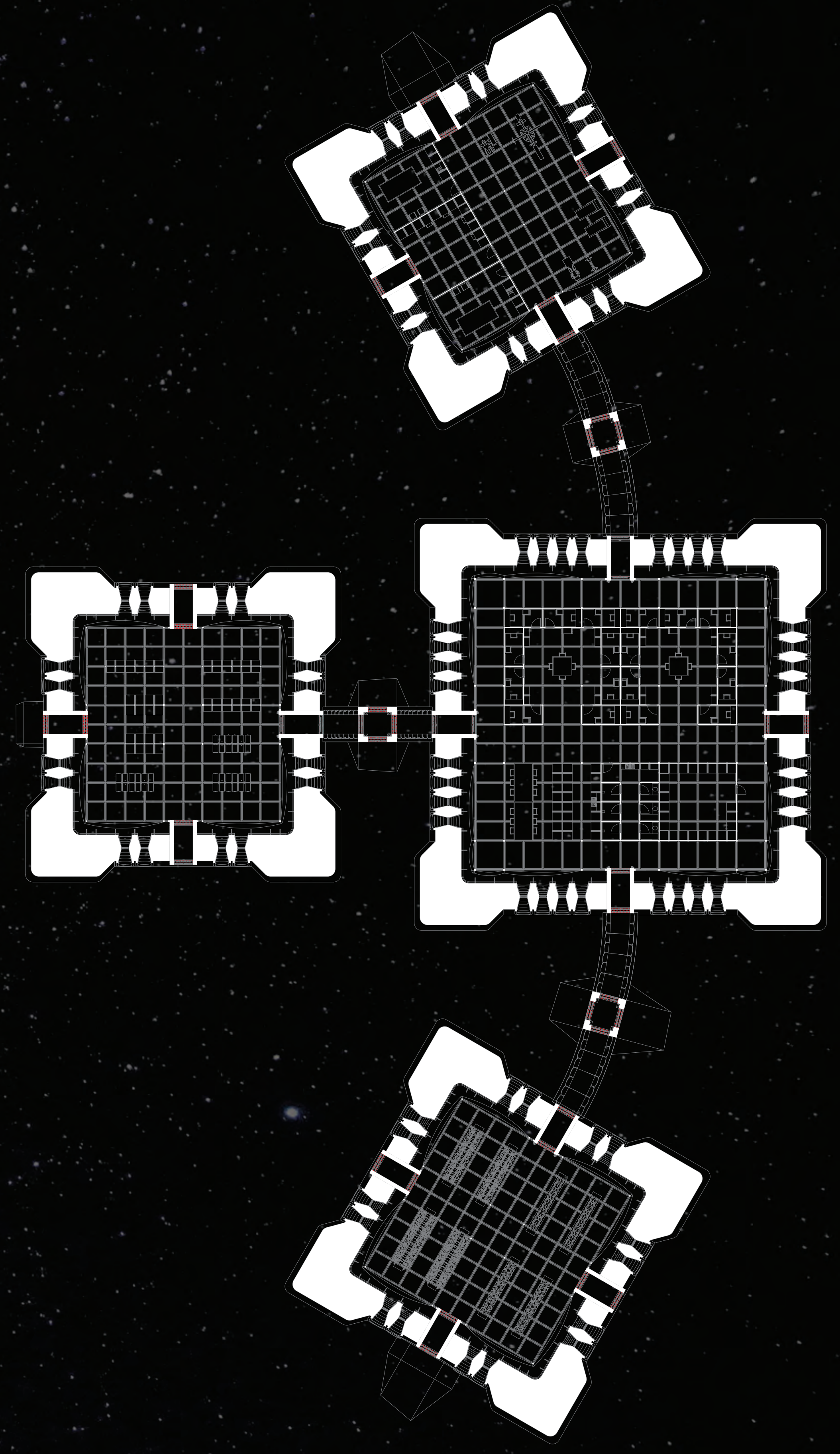
The smaller modules serves as the storage space and temporary research areas until they can be moved elsewhere. In the beginning days of the colony, physiological research will be the primary focus, with minimal research conducted into plant care and surface exploration until more space and personel can be dedicated to them.



Phase 2

Phase 2 focuses on the expansion and dedication of space to the various types of research that will be conducted. In this phase, an entire module is dedicated to the study of plants and how they grow on the moon. The central module doesn't change much except for the addition of more living quarters to fill the increase capacity for research.

The smaller module from phase 1 is converted from research and storage to a work area and storage. This module will be the hub for rover access and servicing. The work area will be geared towards the repair and assembly of mechanical components for either the rover or the various life support systems found in the colony.

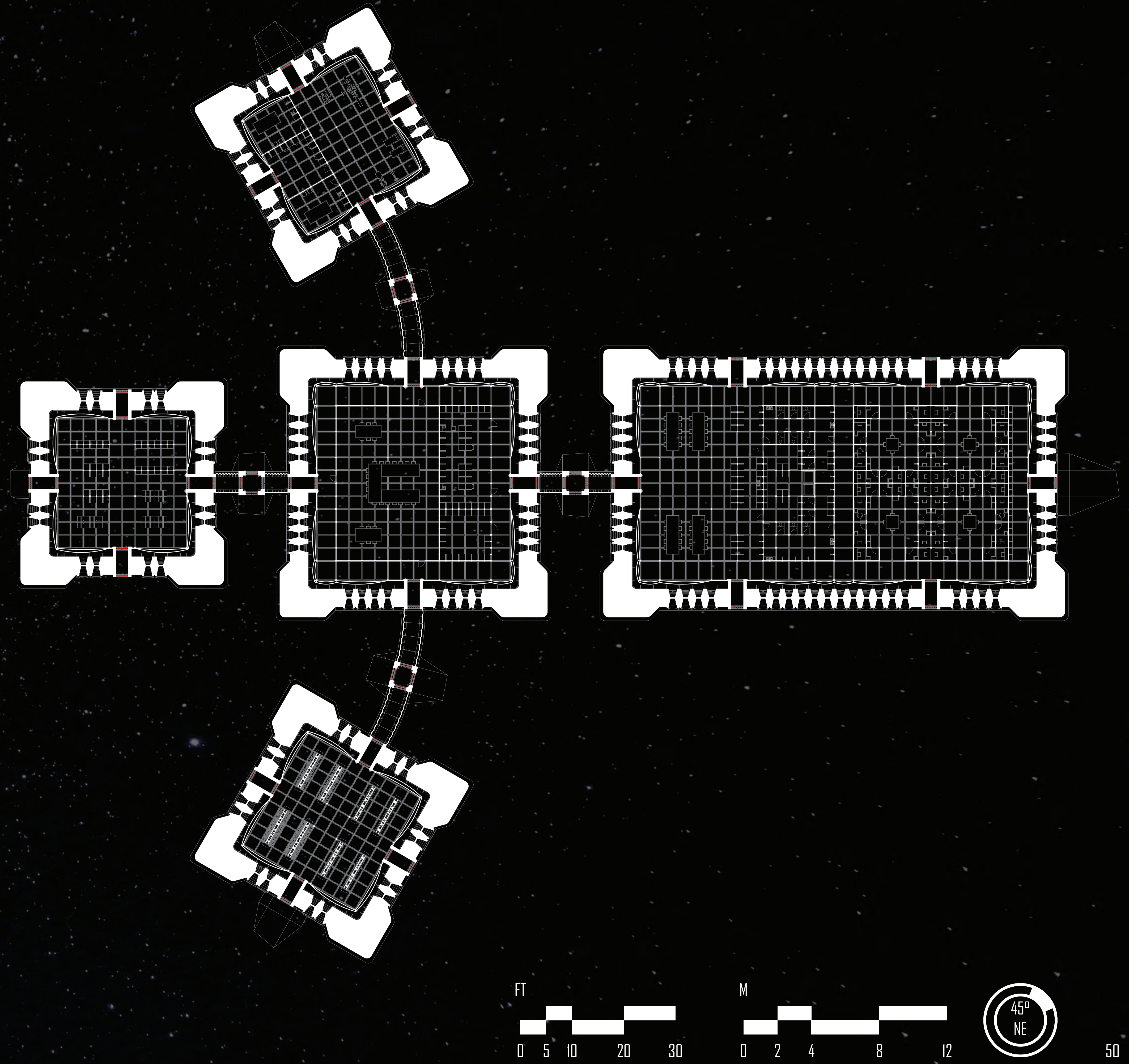


Phase 3

Phase 3 is where the base colony is fully realized. The central module is largely vacated and reassembled to house the new geological research space and dedicated meeting space. The environmental control systems are left where they were originally placed, simply being upgraded to take on the lastest expansion.

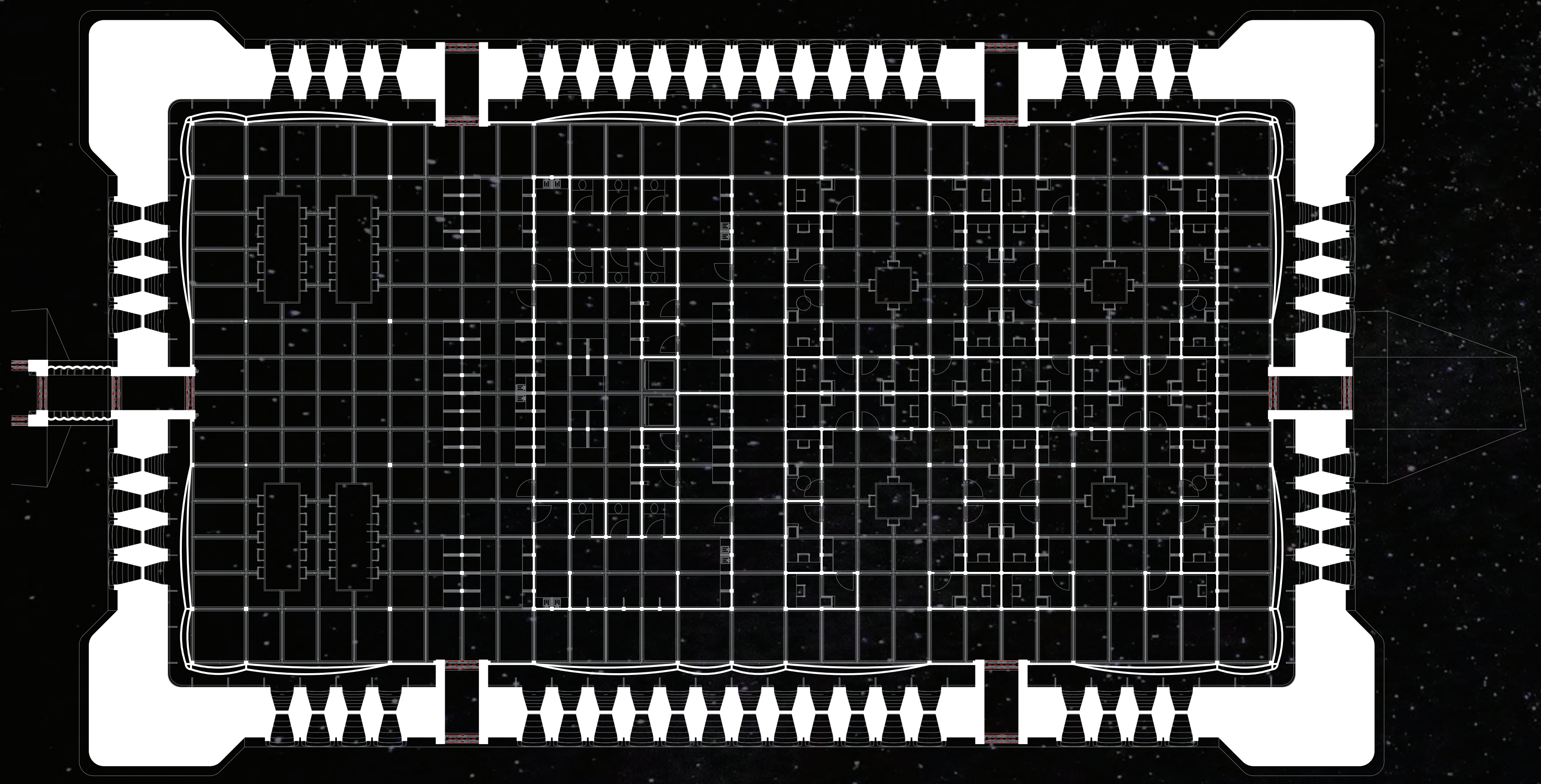
The new large module found on the north end of the now houses all of the living quarters, restrooms, meal prep, gatering space, as well as small active storage space, easiliy accessible for daily use.

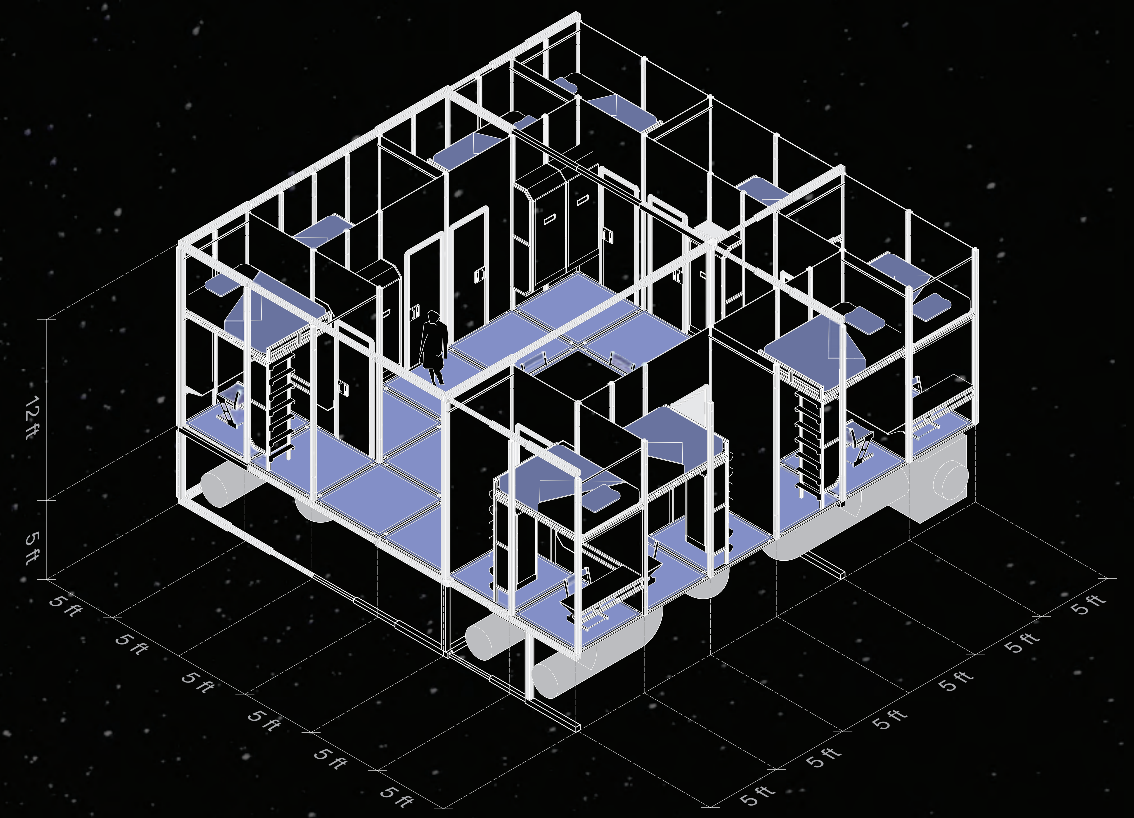
Connecting each module throughout the phases are a series of airlock and flexible inflatable hallways. These airlocks provide exterior access from between modules as well as layers of protection in the event that a module needs servicing and should be vacated.

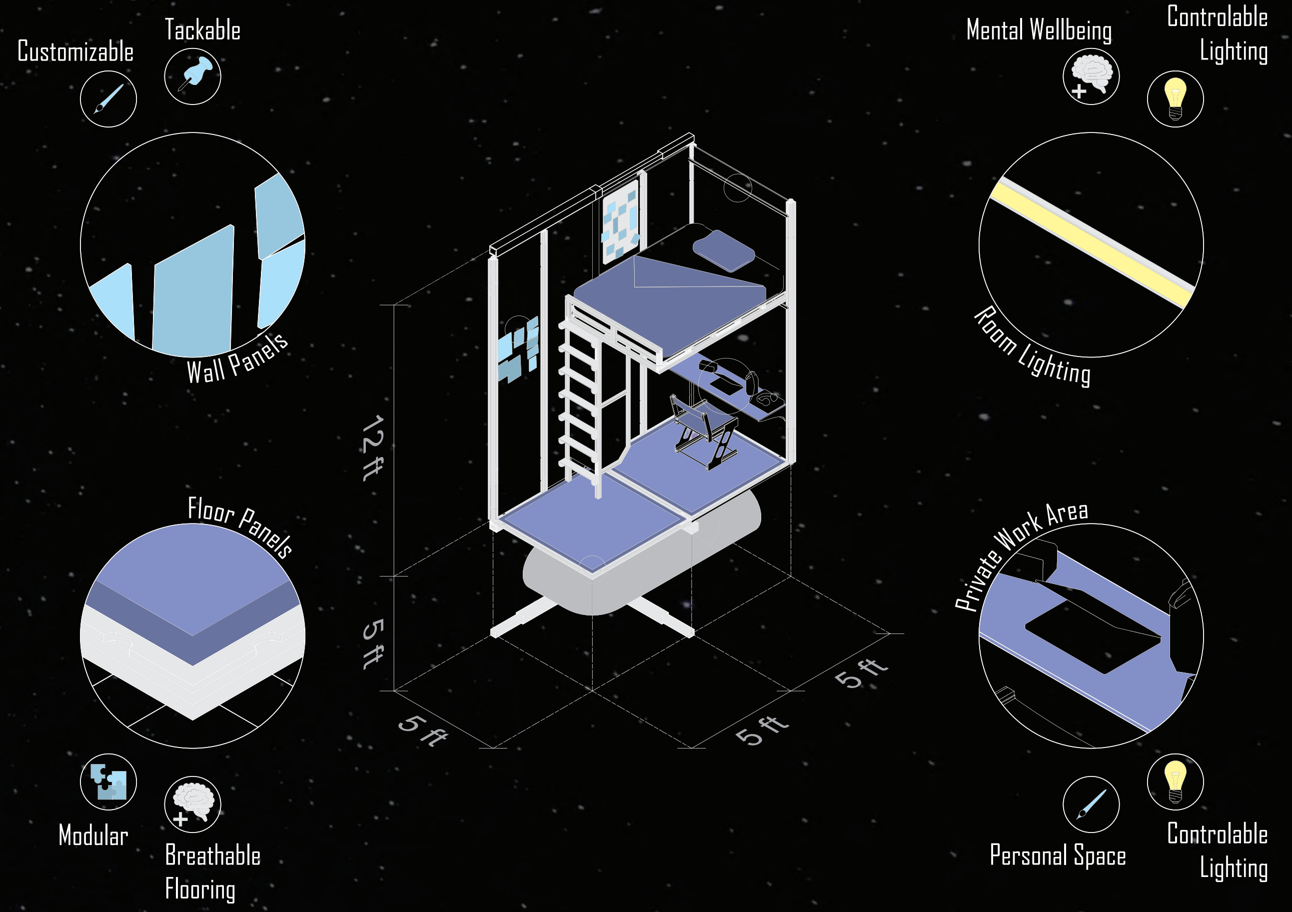


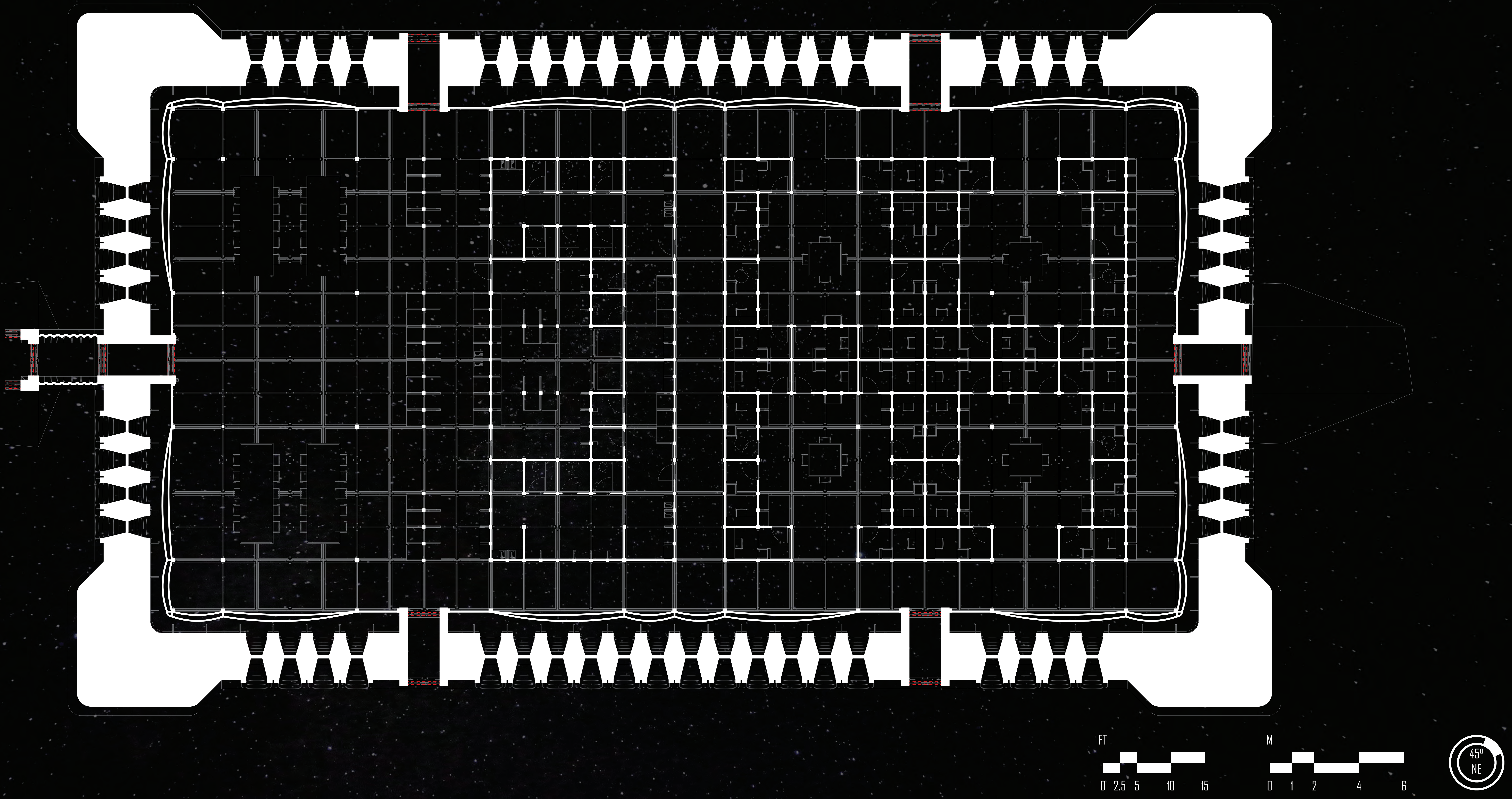
Living Quarters

The living quarters module houses the daily necessities for the life of the colonists. The large open space connects to the meal prep area and restrooms. At this configuration, 36 colonists are able to inhabit the colony. As such, the meal prep area, restrooms, and rooms reflect the needs for such a population. When looking into the individual rooms, there four clusters of nine bedrooms each and a central smaller living room for the cluster. Since space is precious, the individual bedrooms a rather small, although bigger than the sleeping closets found on the ISS. To offset this issue and to account for the lower gravity, a heightened ceiling and a raised bed with personal desk space underneath are created. This provides personal refuge for each colonist when needed.





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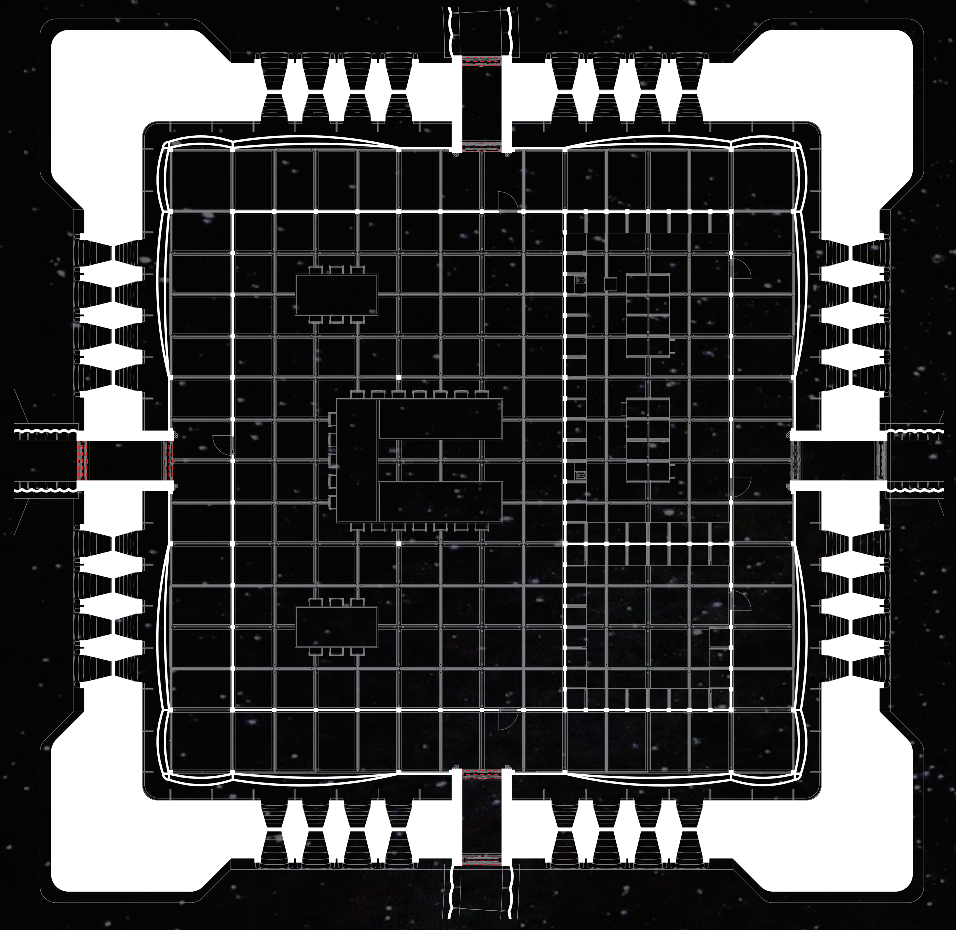
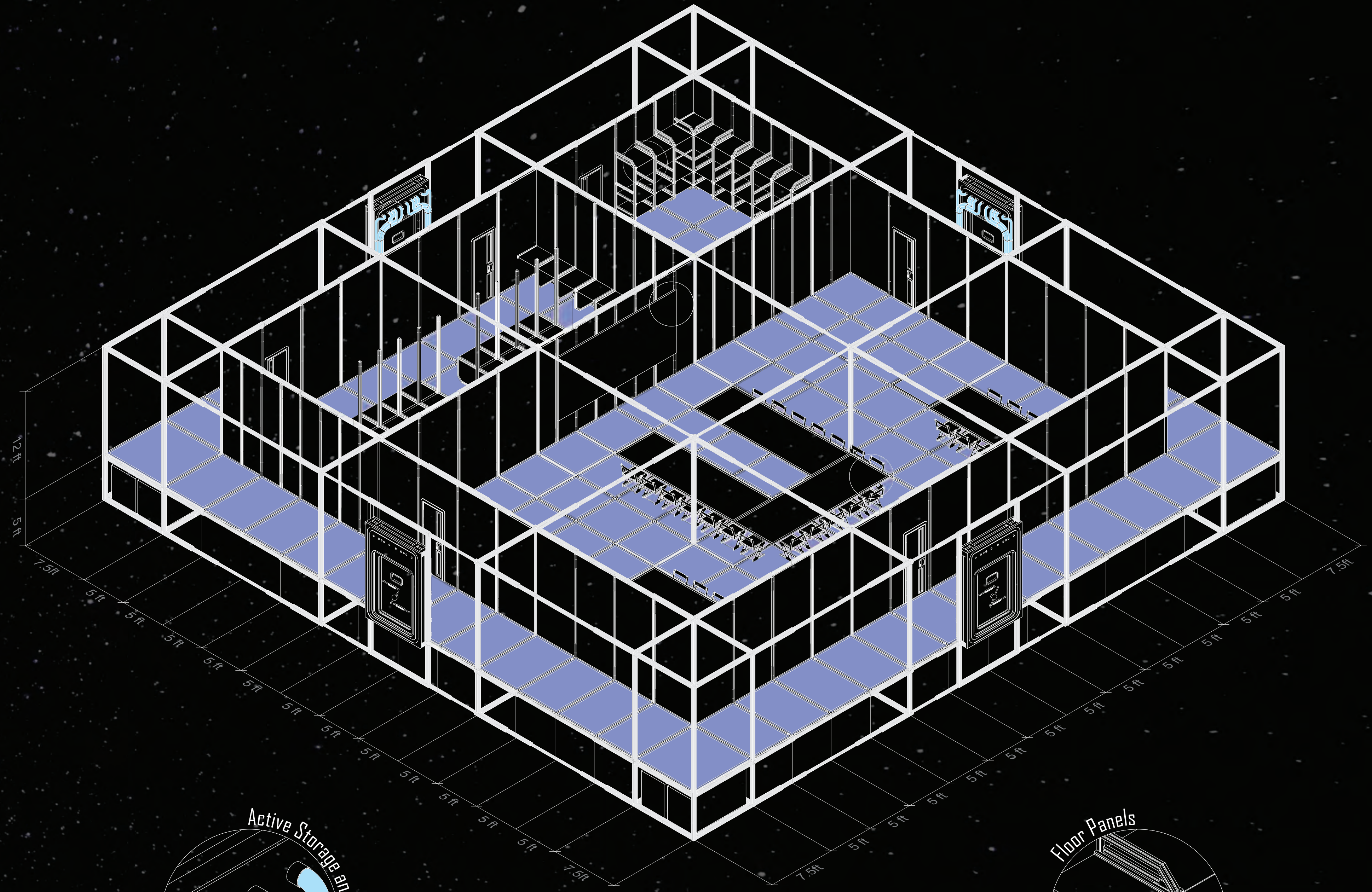
Living Quarters

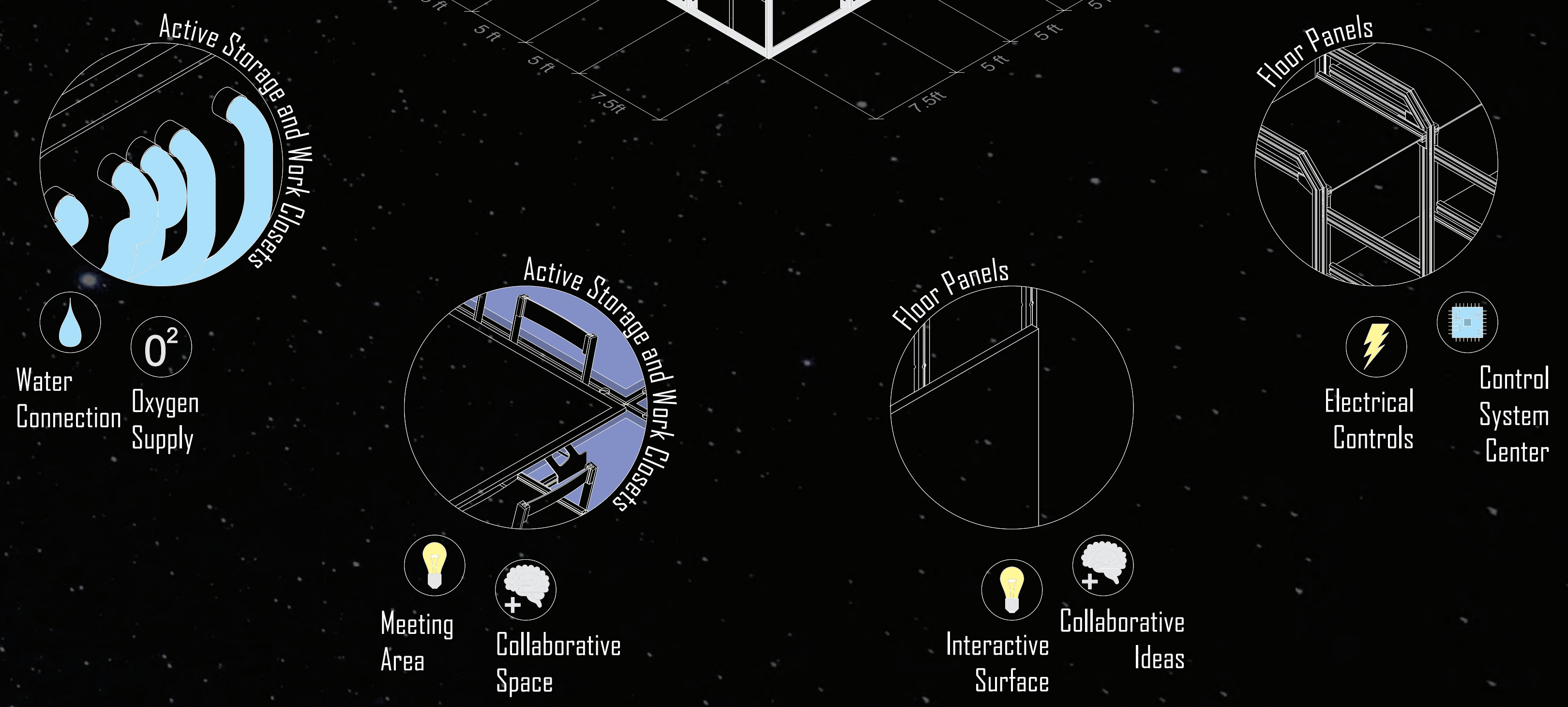
Below you can see the large open space for socialization and meal preperations. Moving all of the enclosed spaces away from the exterior wall gives way to a circulation path around the entire module as a way of being able to have a walking path. Looking to the right, the smaller cluster communal space and individual bedroom space can be seen. Within the communal space, there is space for colonists to come together with others and have smaller gatherings amongst themselves. Each bedroom has a storage locker outside their door for easy access to everyday items that will be used thoughout the day, while the locker within is for more personal items. The walls of the bedrooms have a tackable surface that allows for colonists to put up pictures to remind them of home.

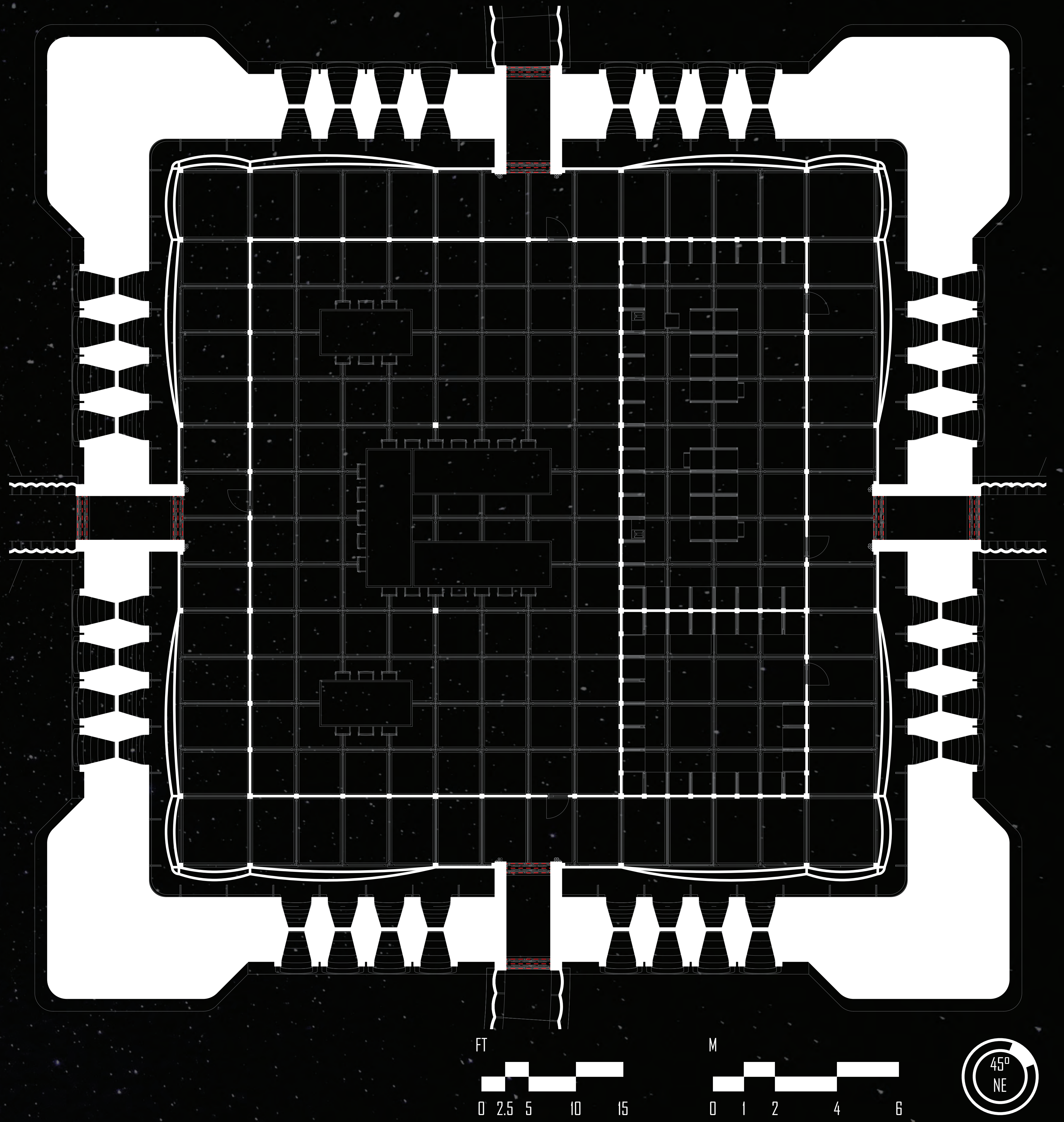
Control Center

The central hub of the colony with the largest amount of traffic with colonists moving between modules to get to their research stations. This control center module houses the brains of colony, with control of all of the environmental systems accessible from a central location along with the environmental controls that can be found in each of the modules. The large central space of this module is utilized for colony wide meetings and for broadcasts back to Earth. The small research area found in this area is set up with plenty of workspace for varying types of geological research experiments. The corridor wrapping around provides access to all modules.





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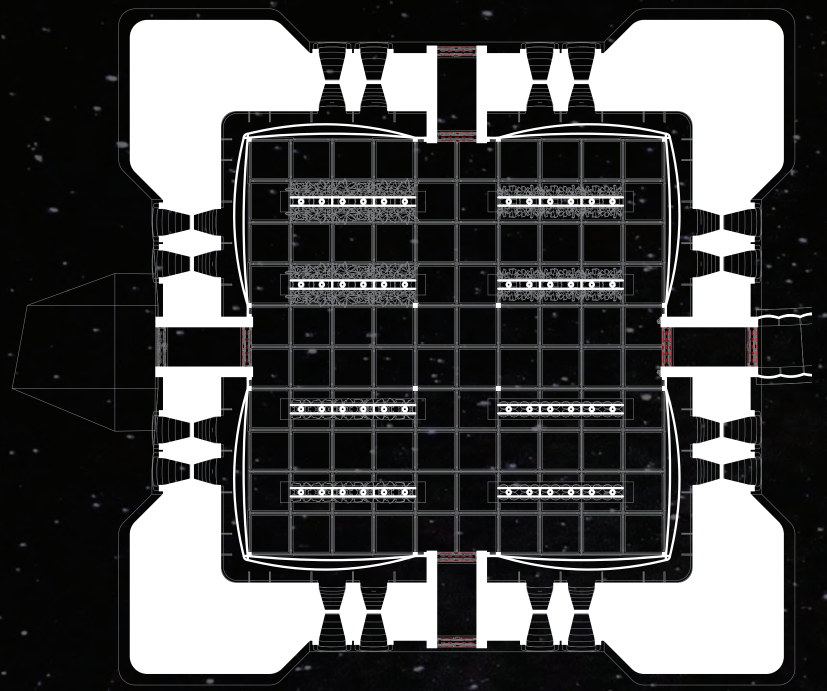
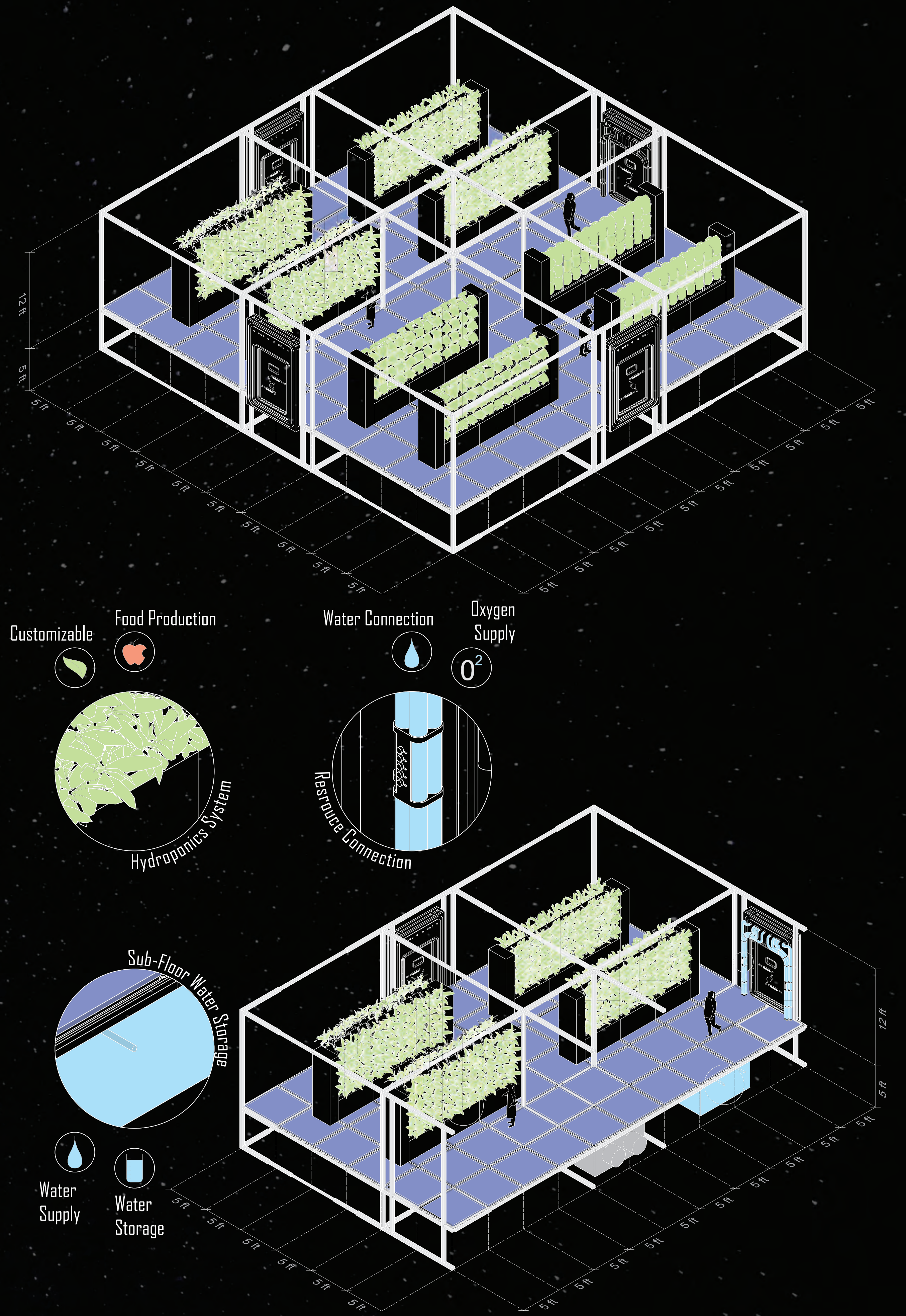
Control Center

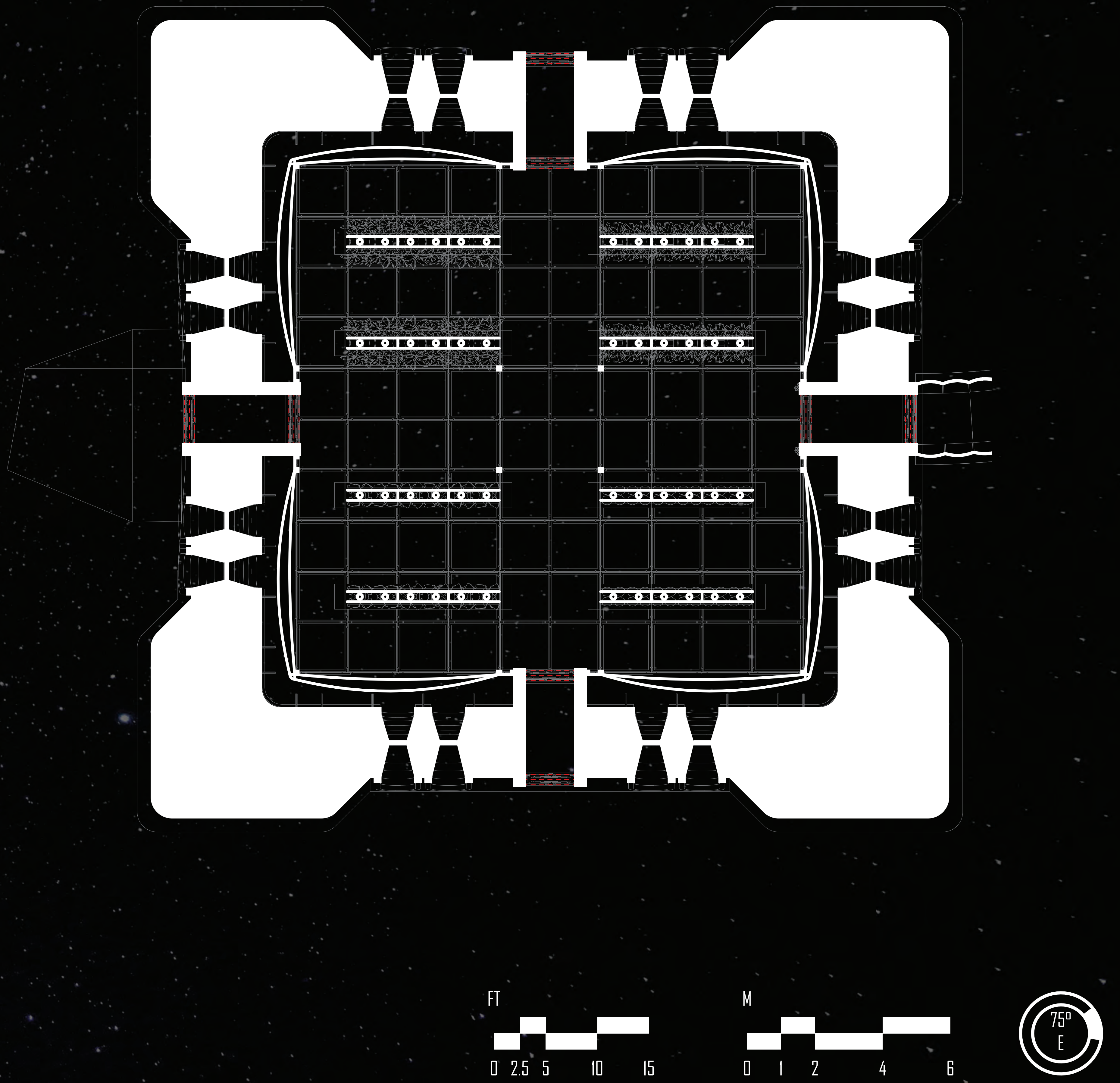
The central meeting space seen below is largely an empty room with seating and tables enough for the whole colony and boards useful for pinning up important information and that can be used as a screen for broadcasts and other media. In the cooridor of the control center module, the module resource connections can be seen. protruding from floor, giving access to a set of controls and then connecting through the airlocks to the next module. This systems allows for all of the modules to share resources and divert them where they are needed most. Lastly, the geological research space is a dense space to be utlized for different geological experiements with plenty of storage for equipment and geological samples.

Garden Center

The garden center houses likely the most important point of research within the colony. Here the hydroponics system can be found, providing a means for a large number of plants to be grown in relatively small space. The garden center is resource intensive, require significant amounts of water that can be sourced from the water ice found within Shackleton Crater. The plants grown in the garden center will provide food for the colonists as well as valuable data in to the effects of low gravity and an artificial atmosphere on plant life.



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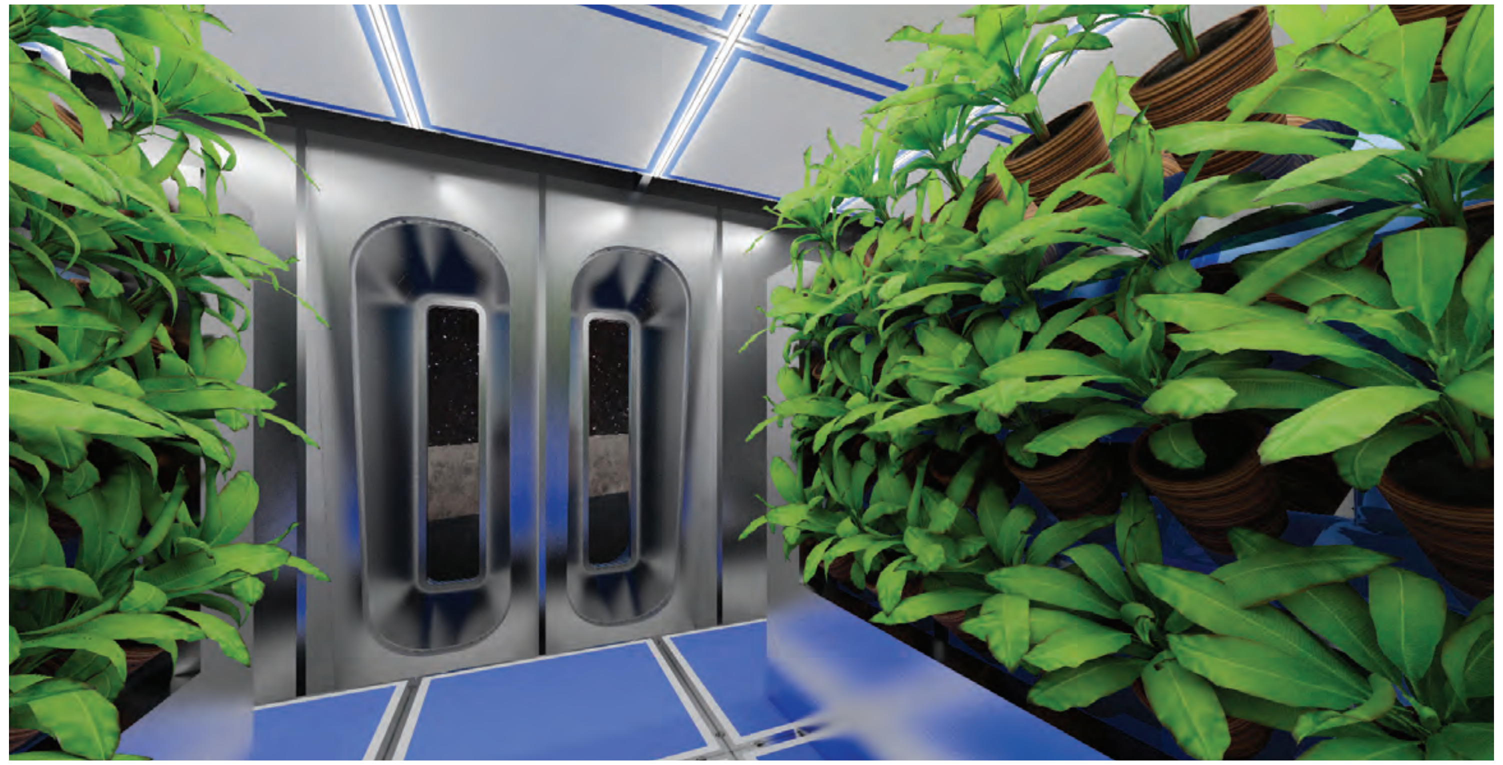
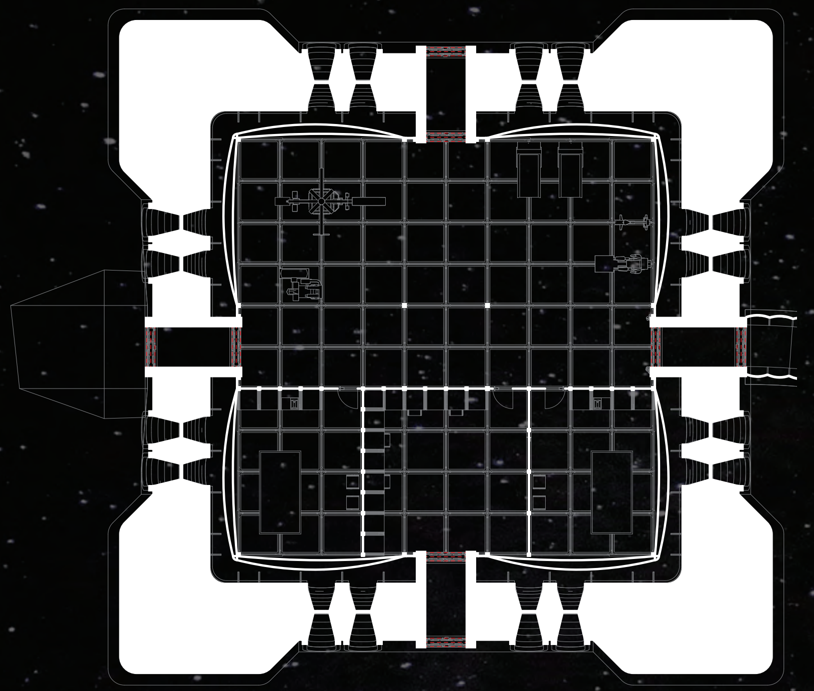
Garden Center

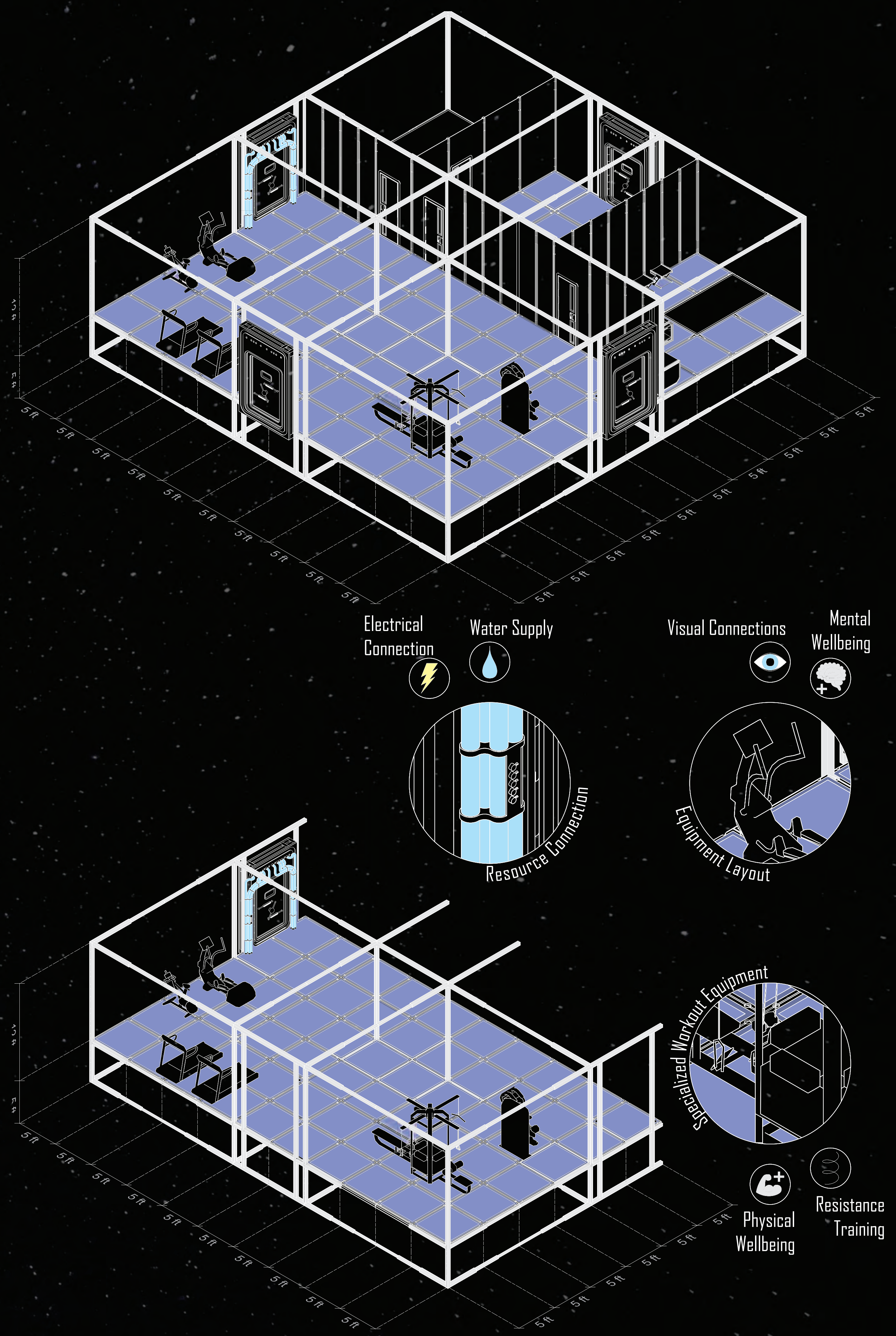
The hydroponics system showcases a dense collection of plants within the small space. Once the plants growing here begin to produce, they will be able to at the very least offset the food consumption in the colony, take the load off of pre-packaged, long lasting meals. The plants in the garden center have access to natural light as well to further study what the effects of natural light through no exterior atmosphere are.

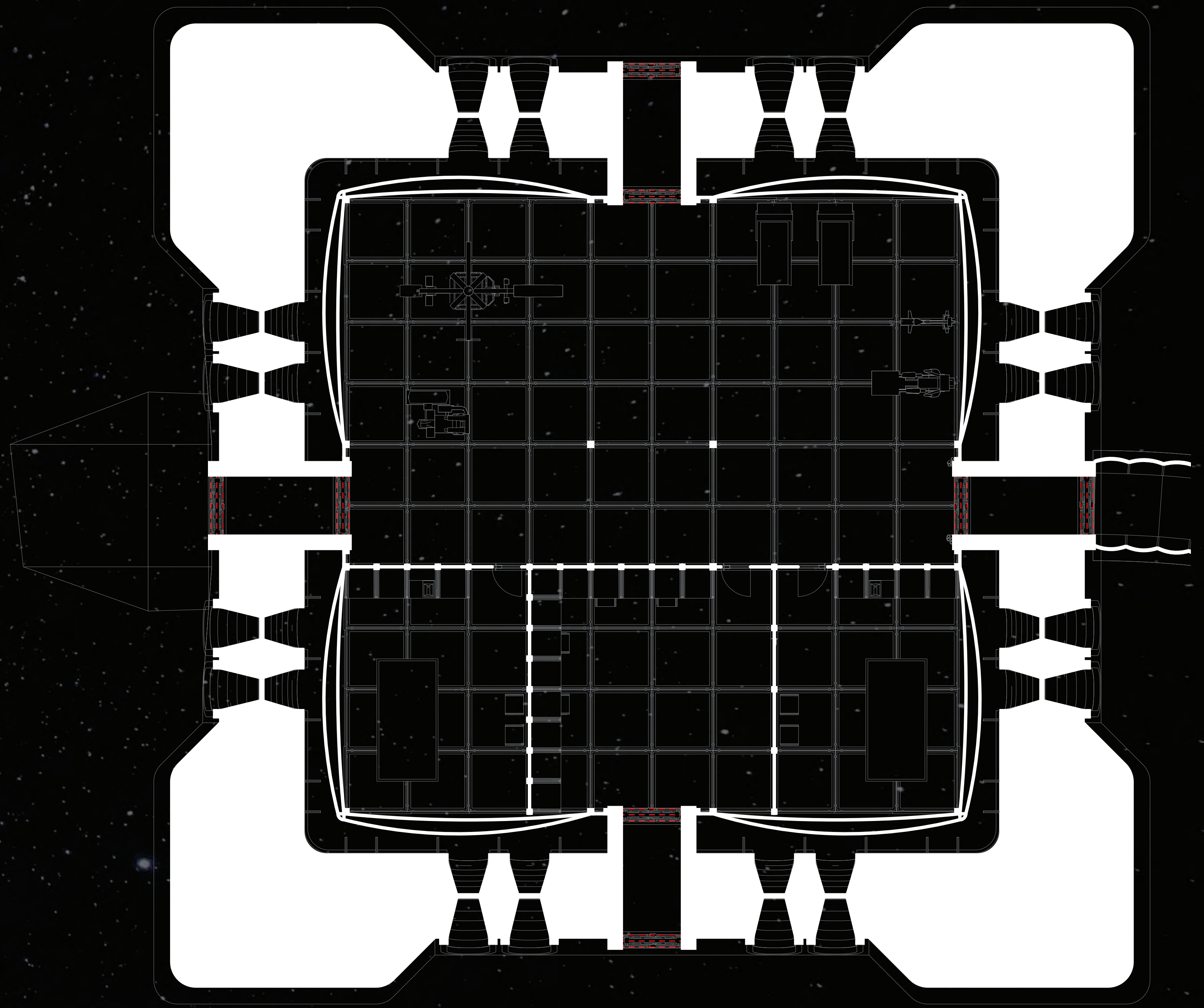


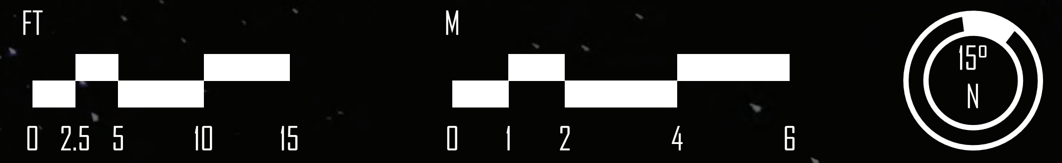
Fitness Center

The primary focus of research in the early stages. With lower gravity, maintaining bone density and muscular strength are vital. Here on-going research will happen with each member of the colony to ensure their mental and physical health is in-tact. In the open space when entering this module, specialized workout equipment can be found, focusing on resistance based training rather than weight based training due to the limitations of cargo capacities. The equipment found here will not be much different than that found currently in use on the ISS.





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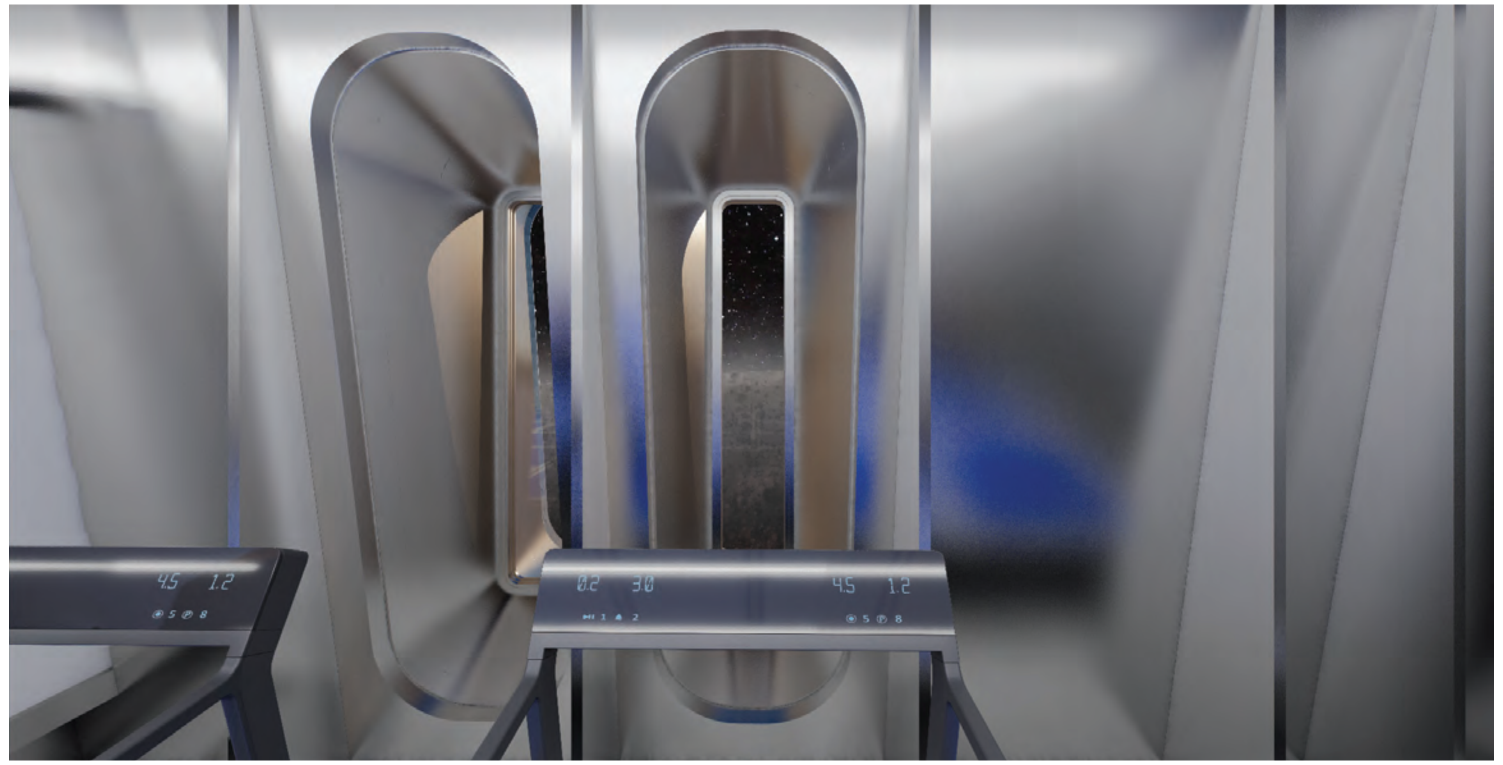
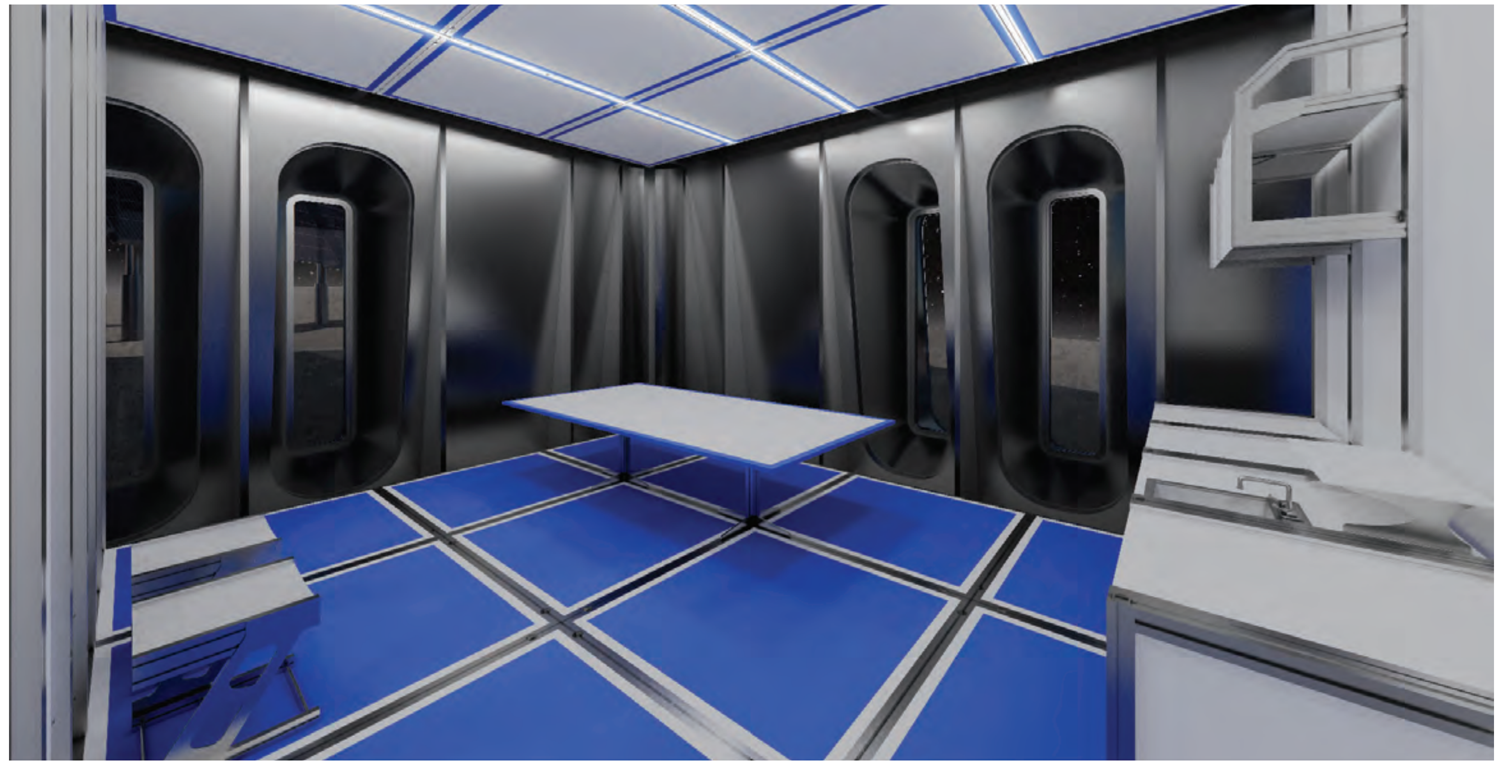
Fitness Center

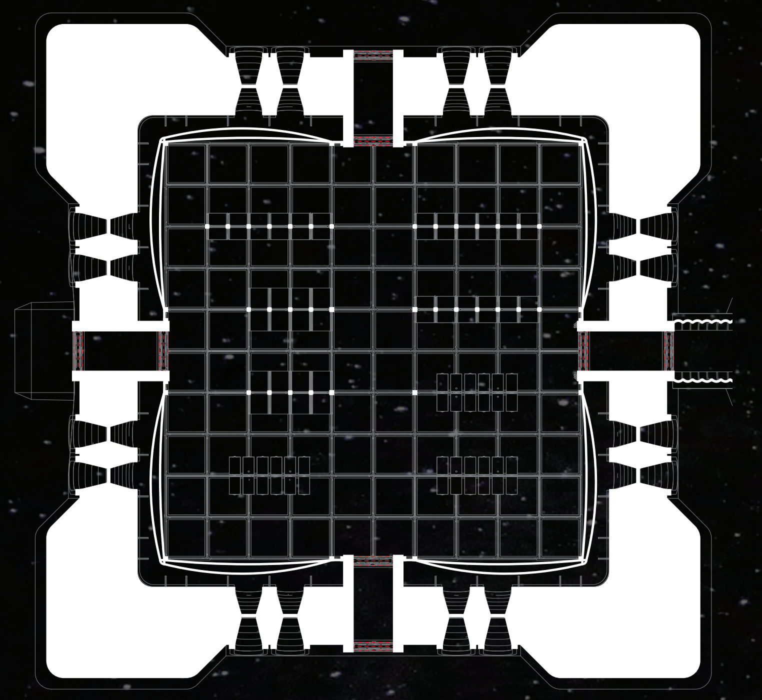
All of the workout equipment can found around the edges of the module facing outwards to the lunar landscape. This gives colonists different views depending on what they are doing and potentially views of the Earth, depending on the time of year that it is. In the private rooms , all of the equipment for health screenings can be found. These rooms are meant to be comforting to those that are getting check-ups .

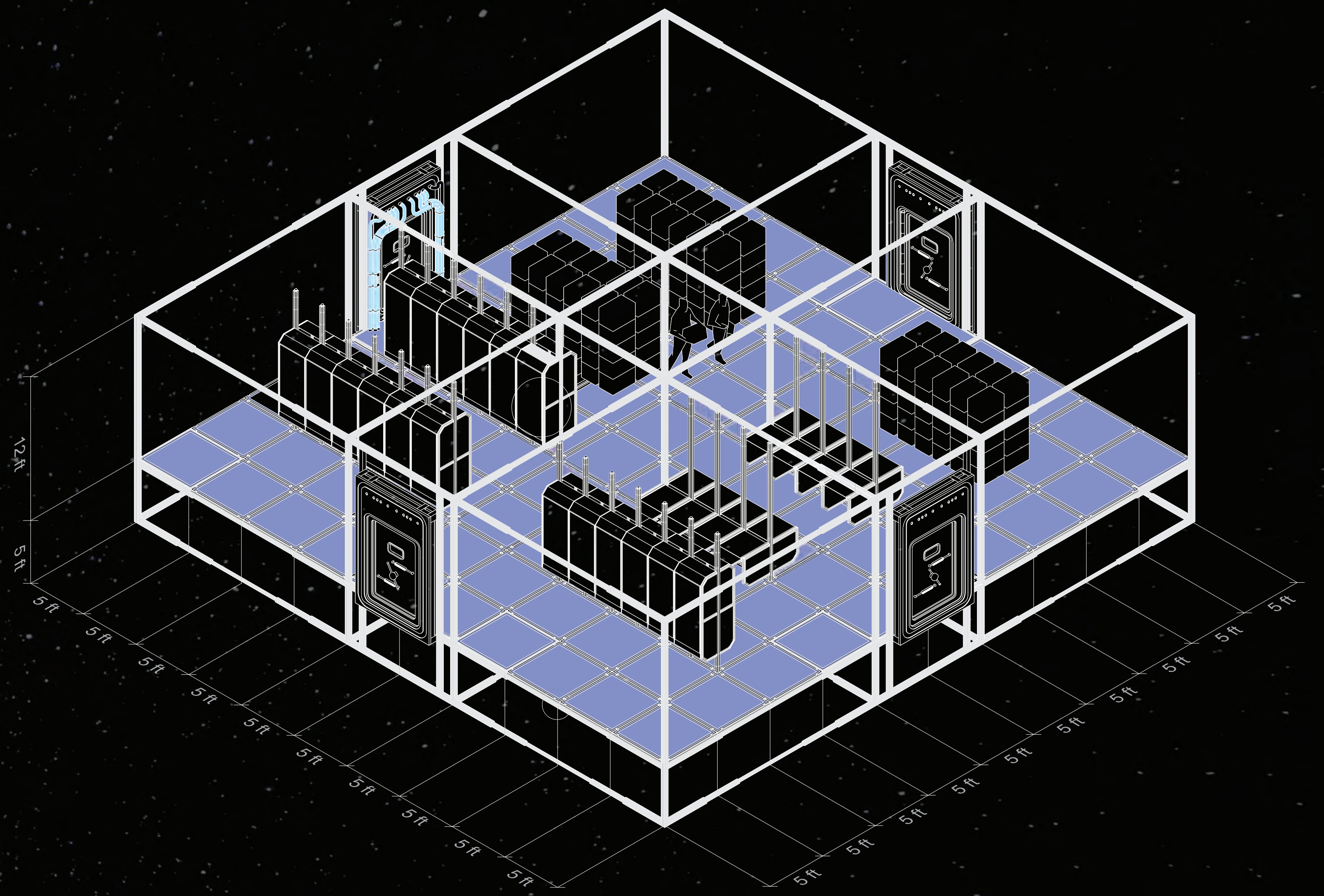


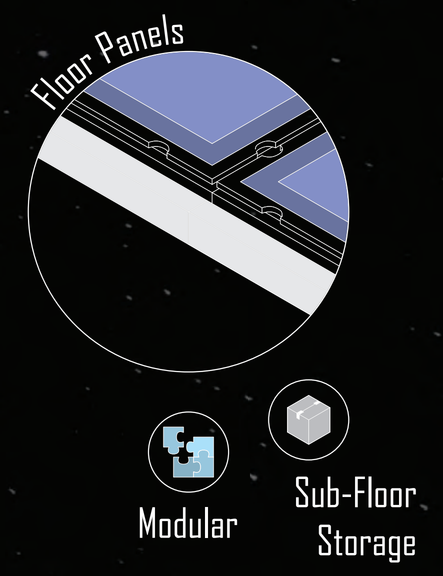


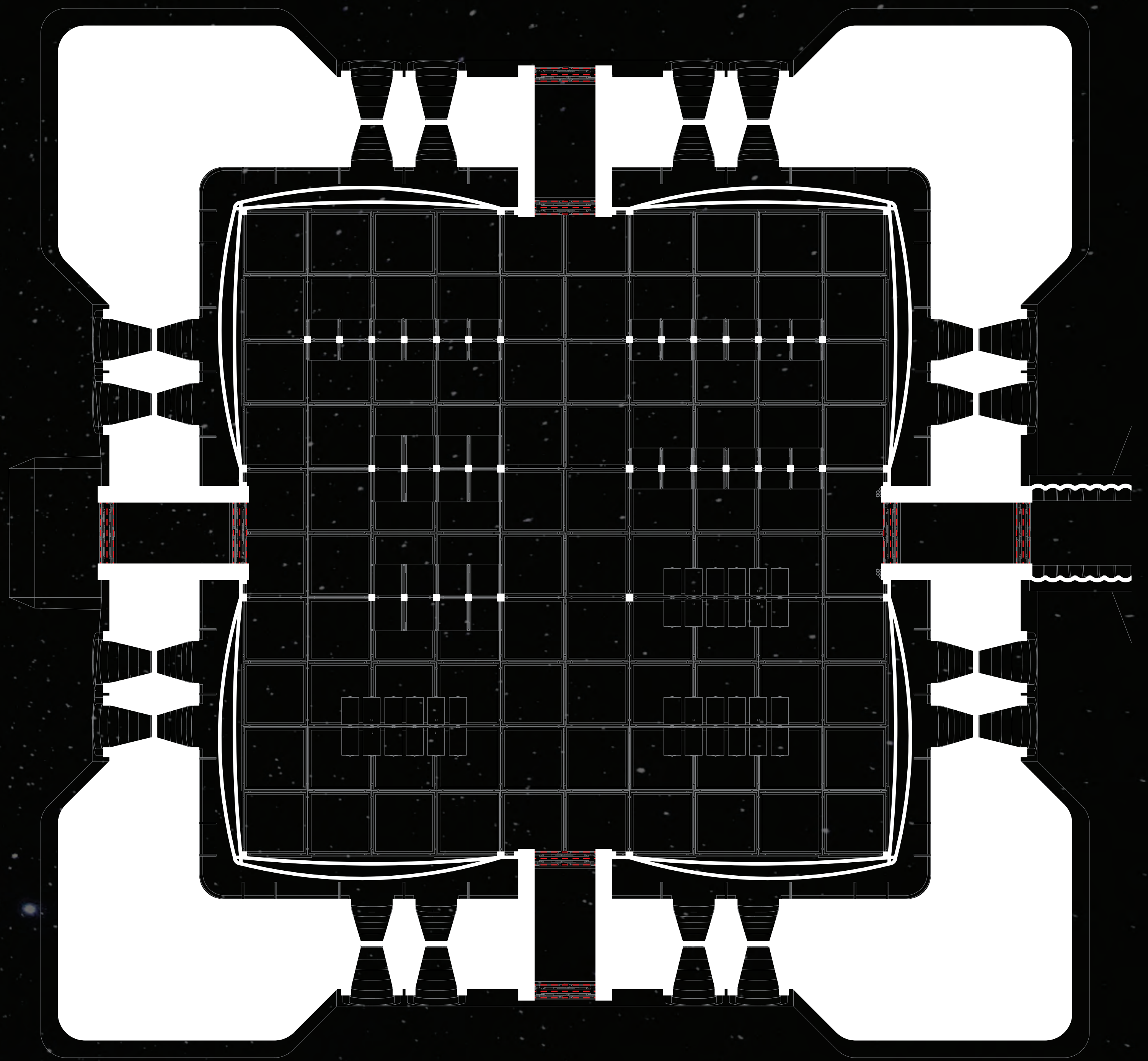
Work Space and Storage

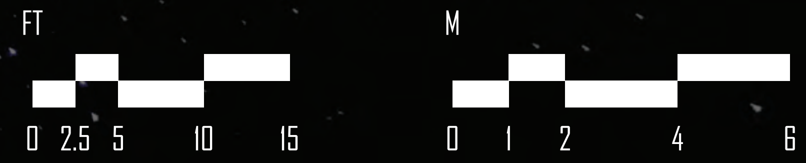
The work space and storage module serves as a service module. Not much in terms of activities take place here. The only function that happens here is the repair and assembly of mechanical and electrical components for the rover or for the environmental systems of the colony. For this there is a small designated space for this to take place along with ample tools and supplies to do so. Outside of this, passive storage is housed here. As with each module, the floor panels are able to be removed to allow access to sub-floor systems, but also be used to store items not needed for the foreseeable future. Once items begin to be needed, they are moved to the main floor for access.







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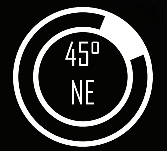
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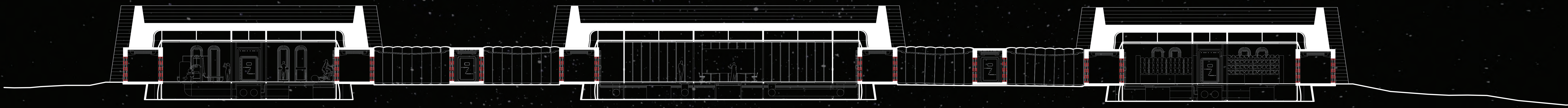
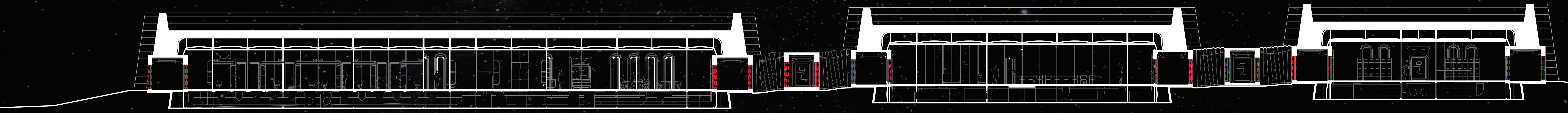
Work Space and Storage

With this module being used as the hub for external access to the rover, all related materials should be located nearby. This means spare parts and spacesuits, among other items. Since a lunar colony is so far removed from the rest of society, there are no cheap means of sending supplies to the colony on a regular basis. This means that stockpiles must be created to have the necessary resources at hand in a moment's notice. Utilizing the relatively empty sub-floor space, several months worth of supplies are able to be kept without added clutter.

Sections

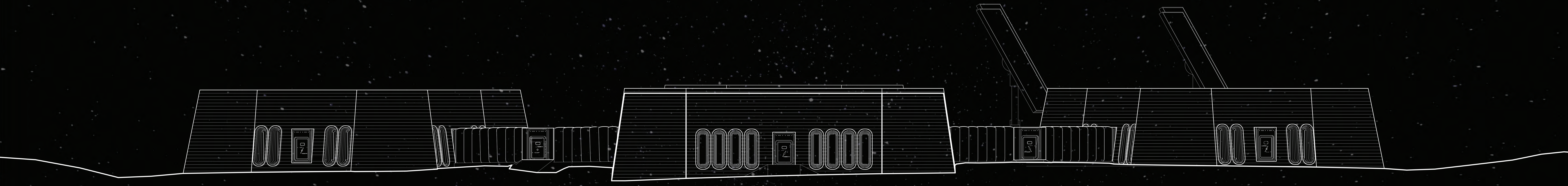


Lateral Section

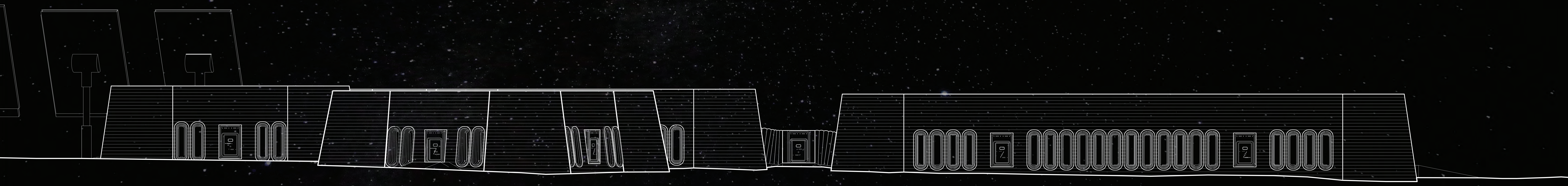


Longitudinal Section

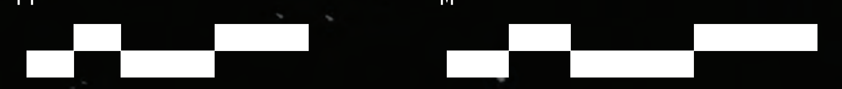
Elevations

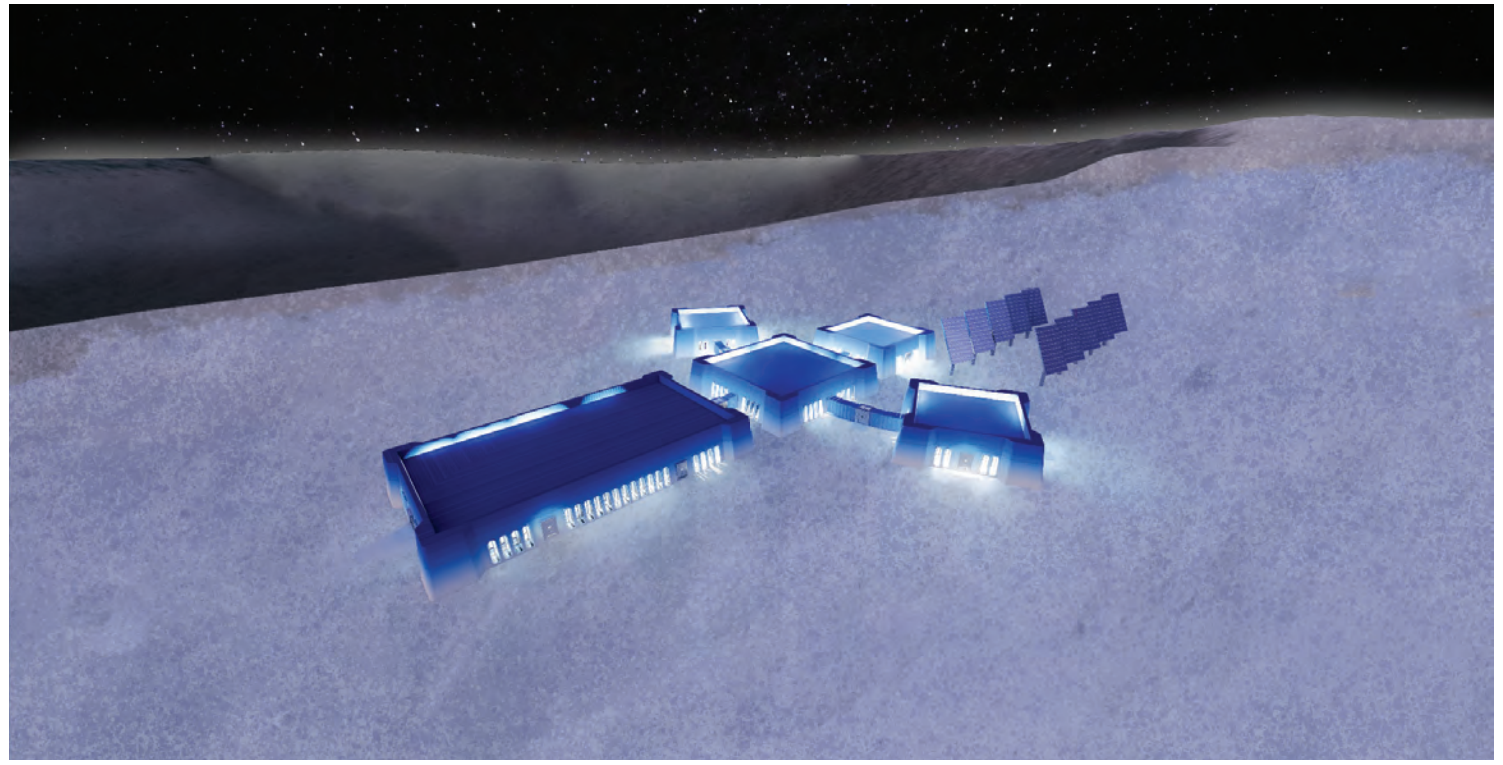


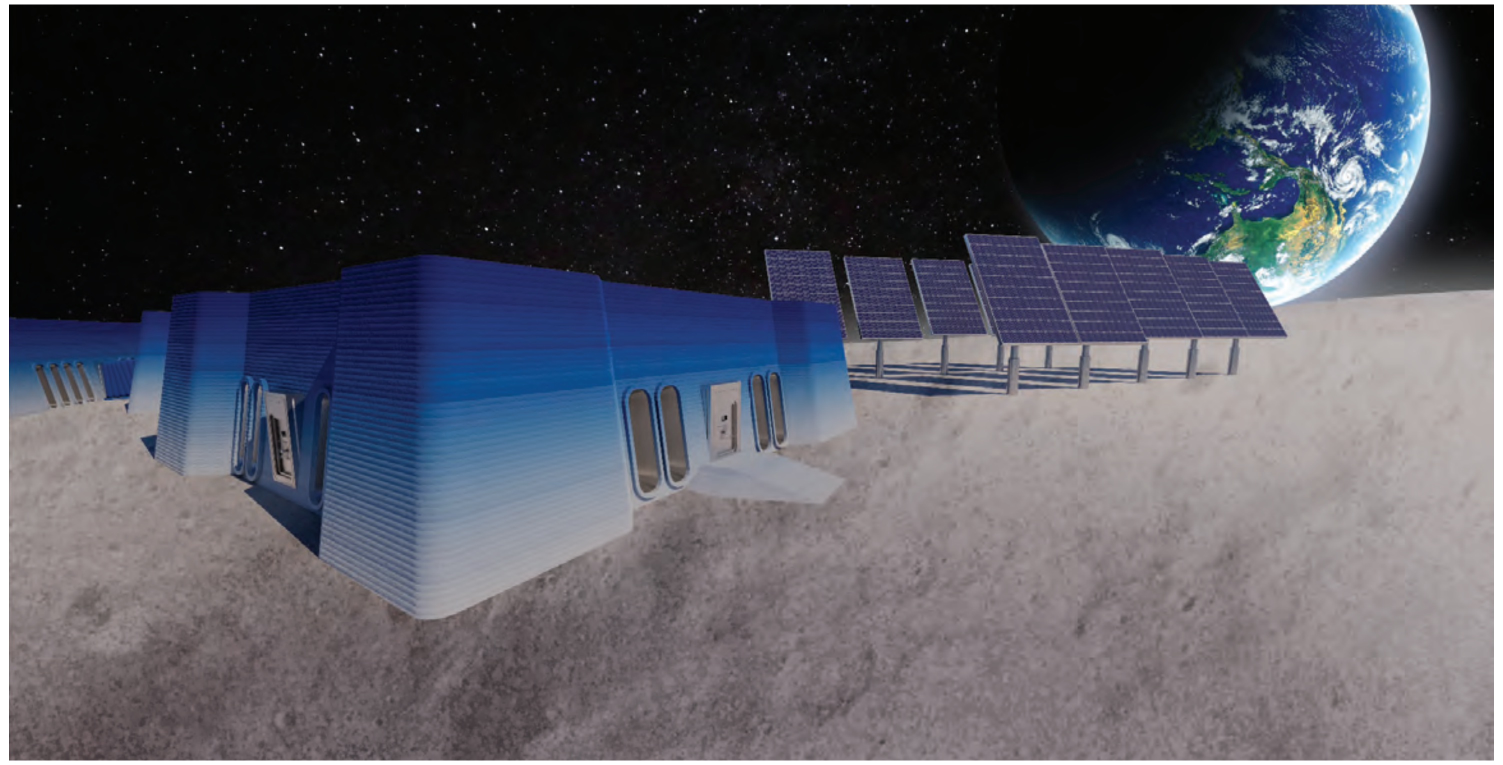
North Elevation

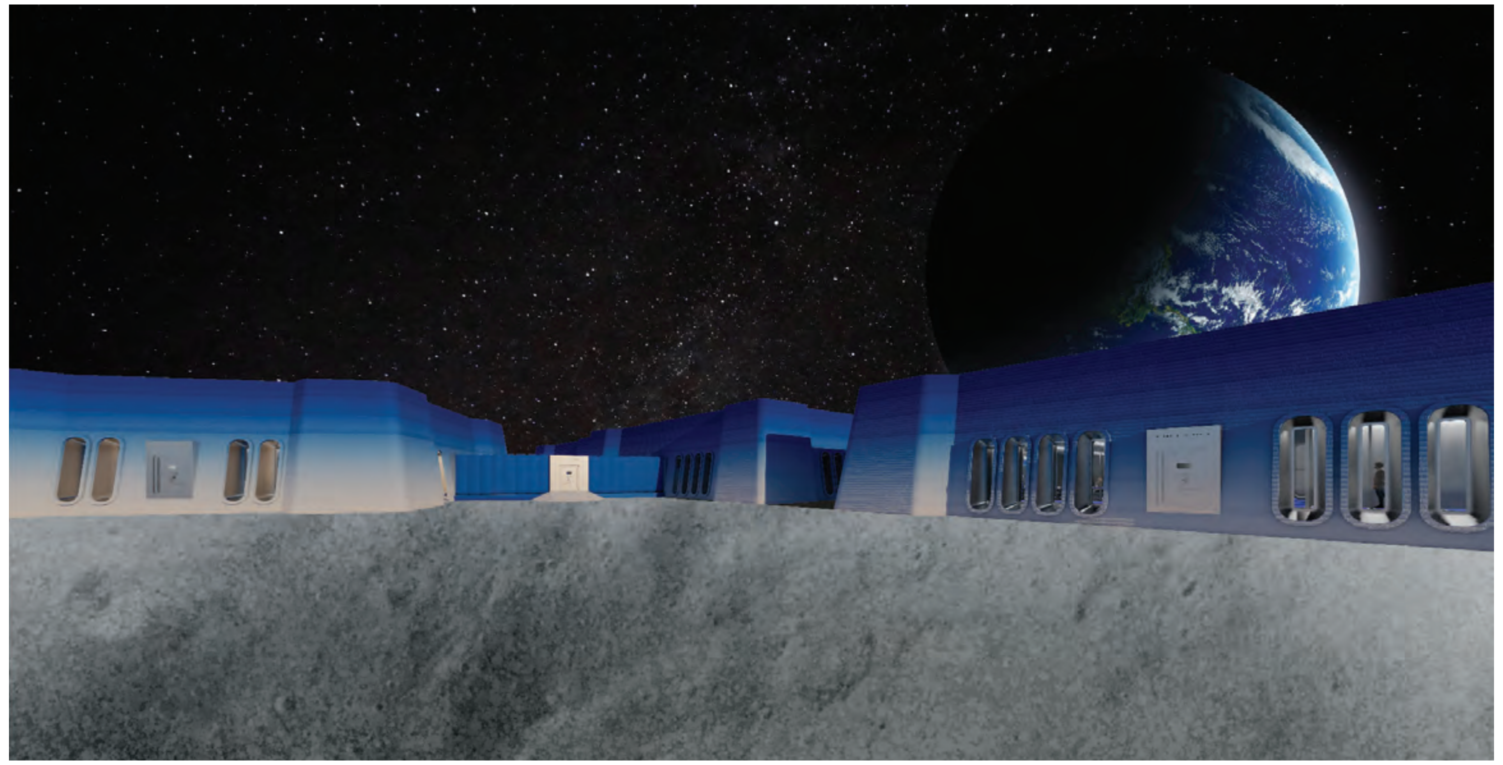


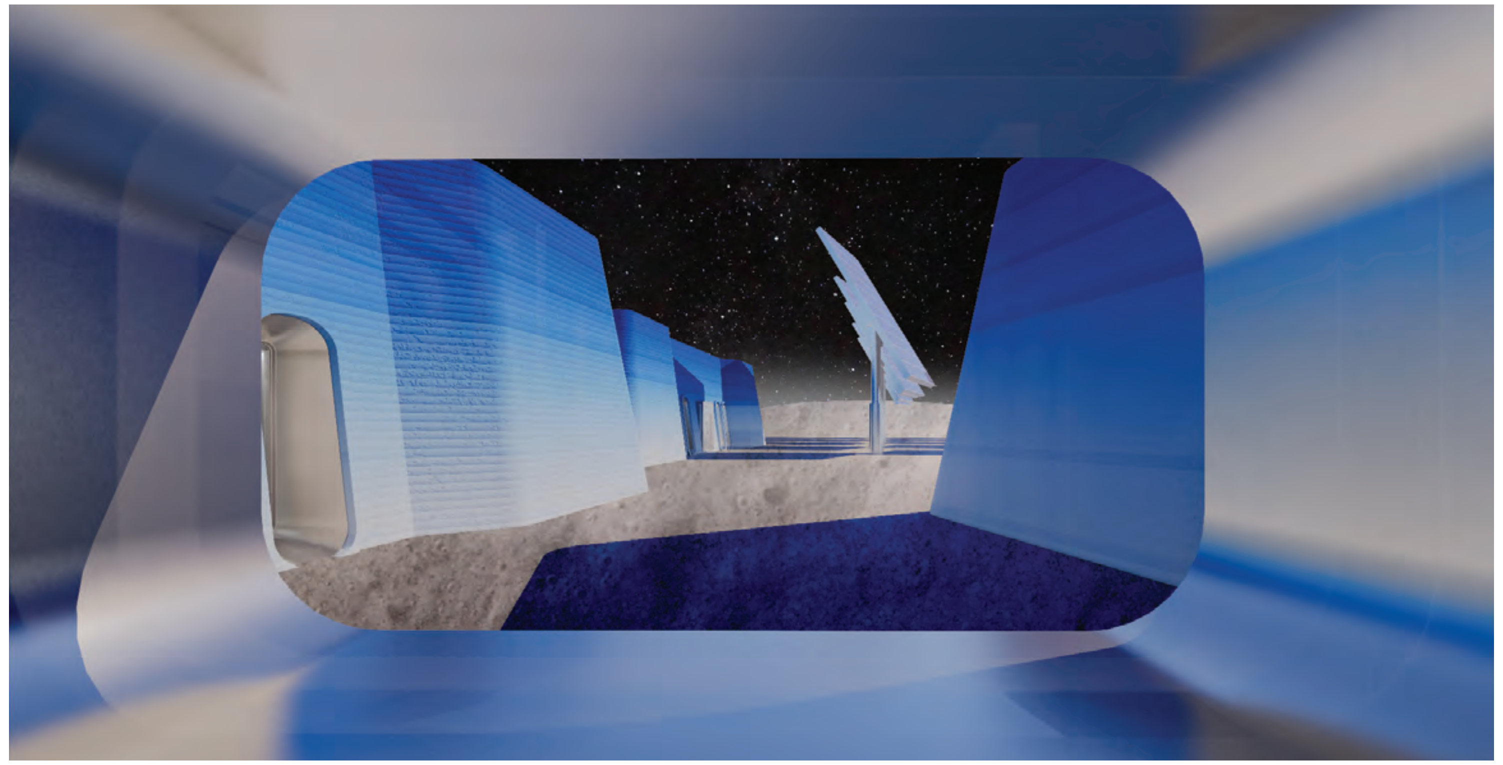
East Elevation









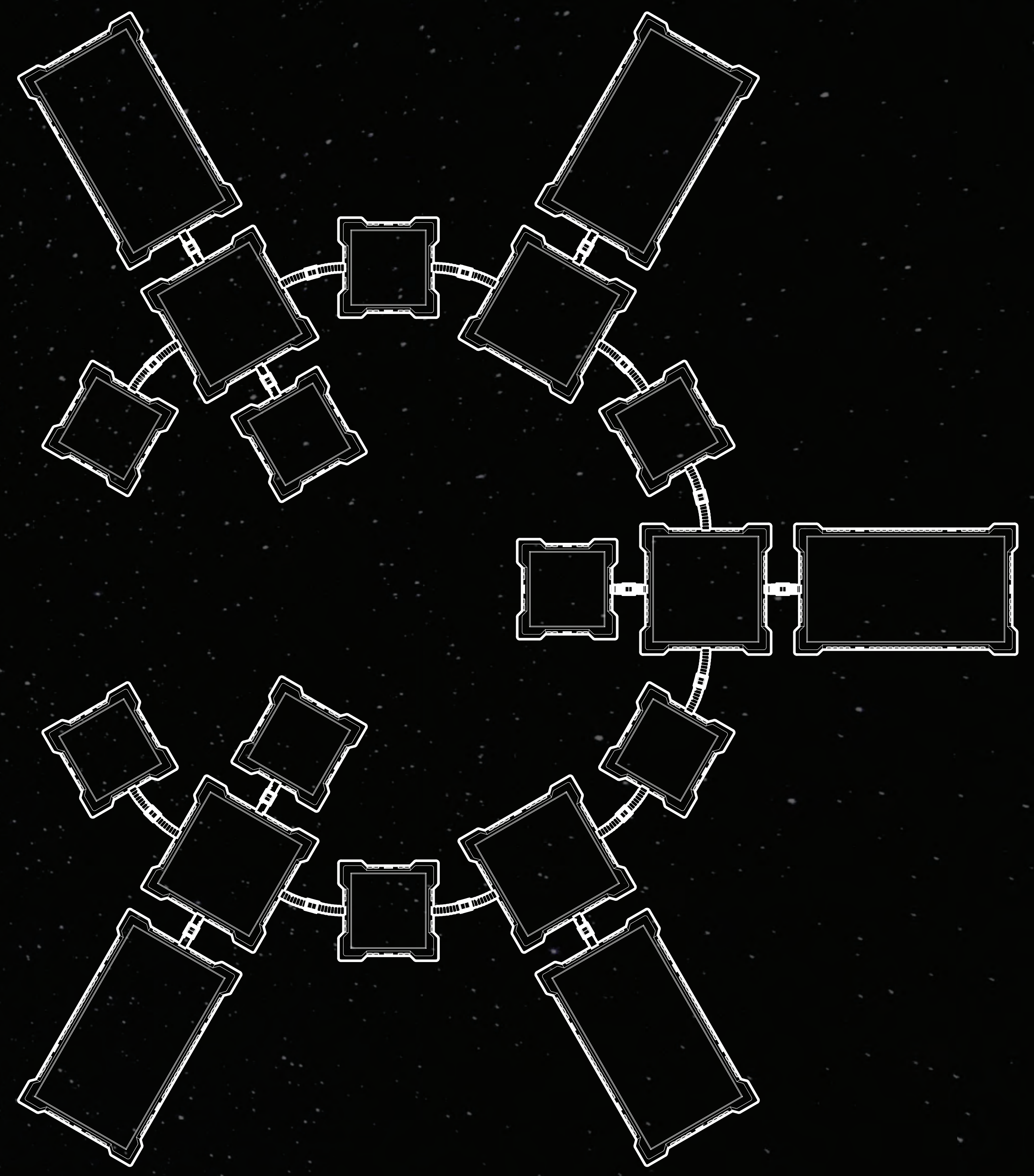


Phase ∞

The final phase of expansion is that of continual expansion. As humanity continues to grow and expand, reaching farther parts of the solar system, the Moon will be used as a hub to help reach the vastness of space.

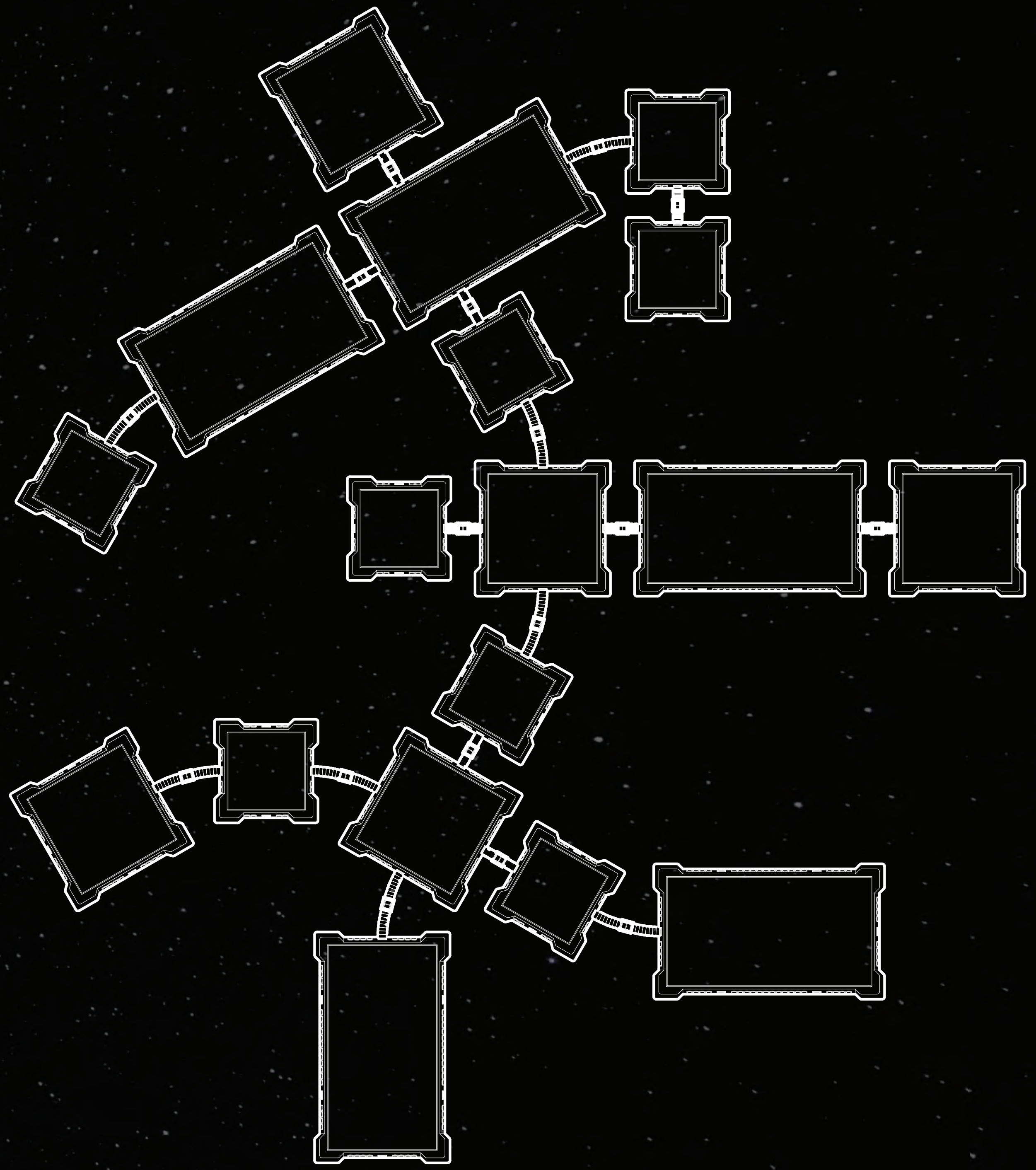
With the expansion into space will come the expansion of the lunar colony. How this happens can be in a multitude of ways. The colony could expand in a radial manner to have a centralized location. There could be a symetrical expansion, having pods of services mirrored in multiple locations. Most likely, there will be an organic expansion. Expanding in a manner than will best serve the needs as they arrise, having multiple hubs spread throughout a chain of modules, each working to serve humanity in its goal of exploration.

Radial Expansion



Symmetrical Expansion

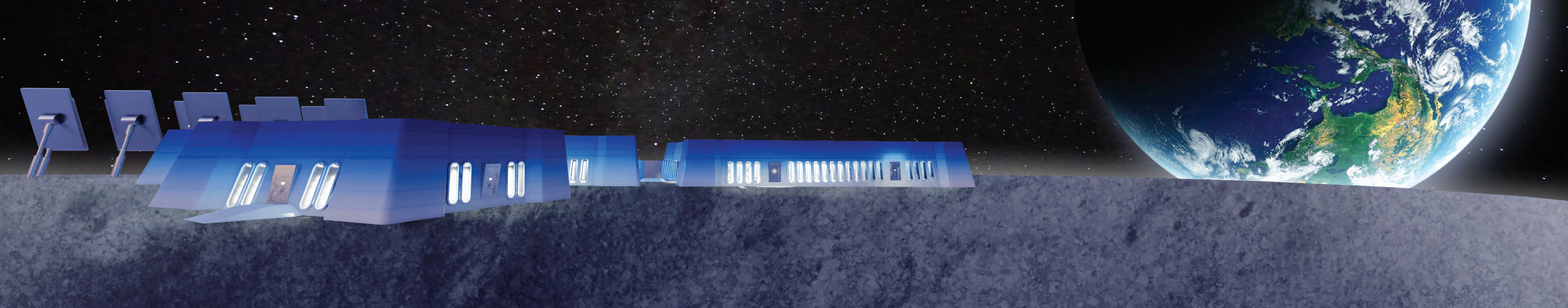
Organic Expansion



Conclusion

Conclusion

The idea for a lunar colony does not need to be a complicated one. Using simple pieces to create a larger collection is as complicated as it should get. Over complication makes the process more difficult. Creating a system that facilitates easy construction means more time can be spent on the design and life safety system. This modular system doesn't just lend itself to a lunar colony, but rather lends itself to temporary structures here on Earth. Using it for terrestrial applications provides a period of testing to ensure that larges portions of the system work as intended. A lunar colony is coming with the renewed interest, a highly modular system may be the way to do it.



Appendix

Maps and images found in the appendix are supplemental material that is either referenced elsewhere in the book or were elements that were used to make informed decisions on the site location, design, or other elements pertaining to the design of this project. These are also generally helpful for understanding the true scope of research

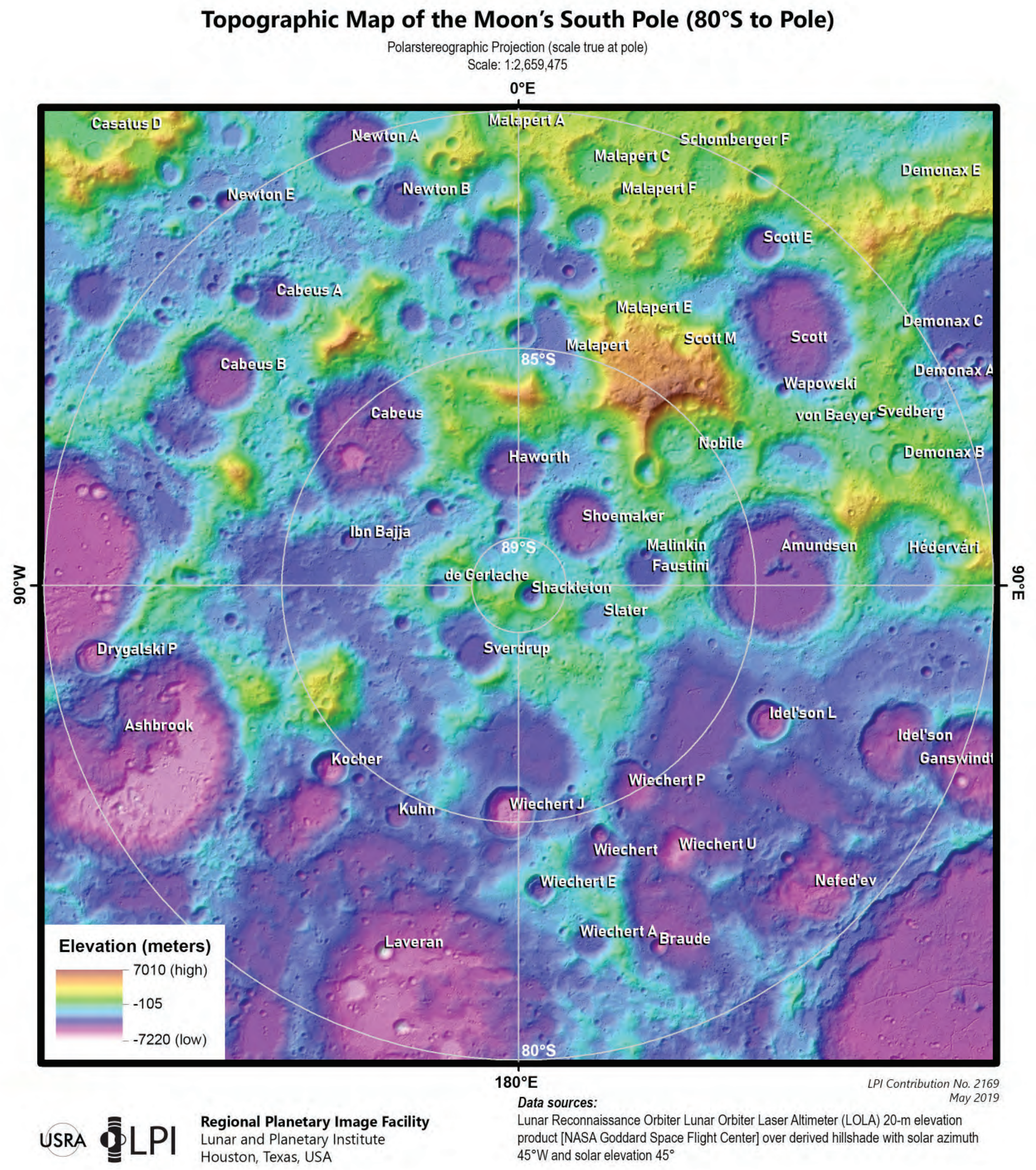
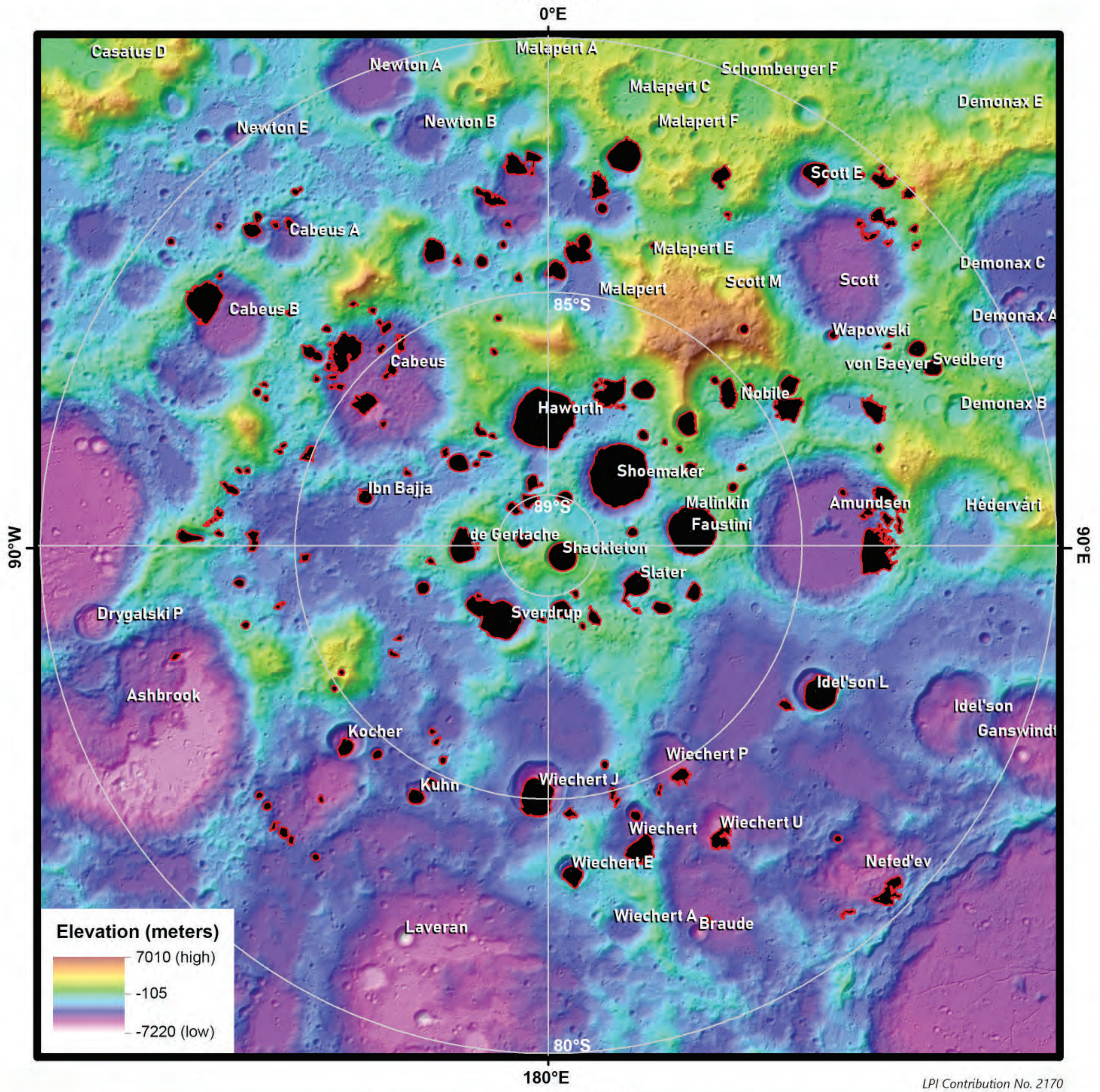


Figure 19 - Topographical map of the wider lunar south pole region

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

Polarstereographic Projection (scale true at pole)
Scale: 1:2,659,475



LPI Contribution No. 2170
May 2019

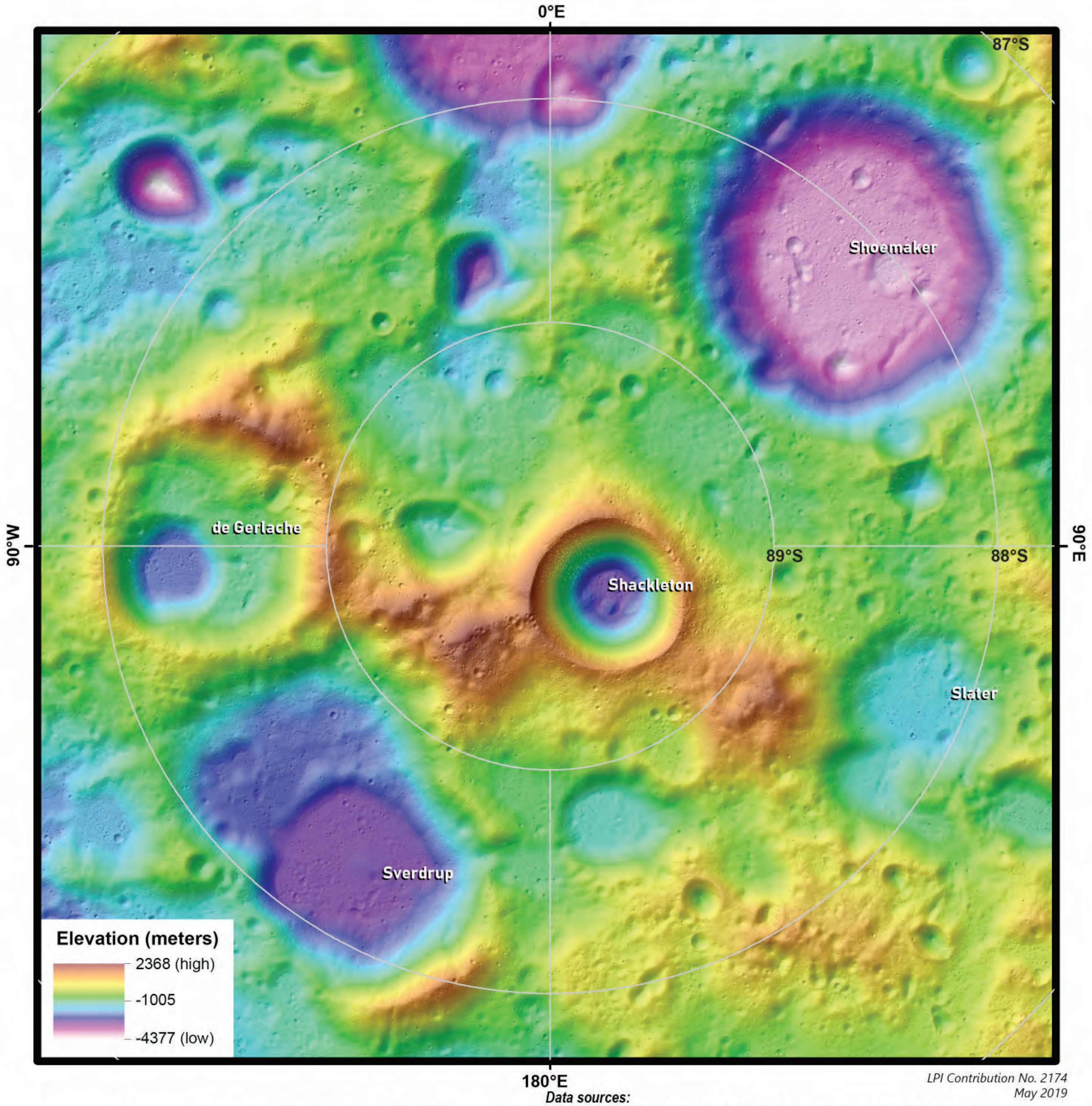
USRA LPI **Regional Planetary Image Facility**
Lunar and Planetary Institute
Houston, Texas, USA

Data sources:
Lunar Reconnaissance Orbiter Lunar Orbiter Laser Altimeter (LOLA) 20-m elevation product [NASA Goddard Space Flight Center (GSFC)] over derived hillshade with solar azimuth 45°W and solar elevation 45°; shapefile of digitized LOLA large PSRs (red outlines with black fill) [NASA GSFC; Arizona State University]

Figure 20 - Composite map of topographical data and PSRs of the wider lunar south pole region

Topographic Map of the Moon's South Pole

Polarstereographic Projection (scale true at pole)
Scale: 1:600,000



LPI Contribution No. 2174
May 2019

USRA LPI **Regional Planetary Image Facility**
Lunar and Planetary Institute
Houston, Texas, USA

Data sources:
Lunar Reconnaissance Orbiter, Lunar Orbiter Laser Altimeter (LOLA), 5-m elevation product [NASA Goddard Space Flight Center] over derived hillshade with solar azimuth 45°W and solar elevation 45°

Figure 21 - Zoomed in topographical map of the lunar south pole

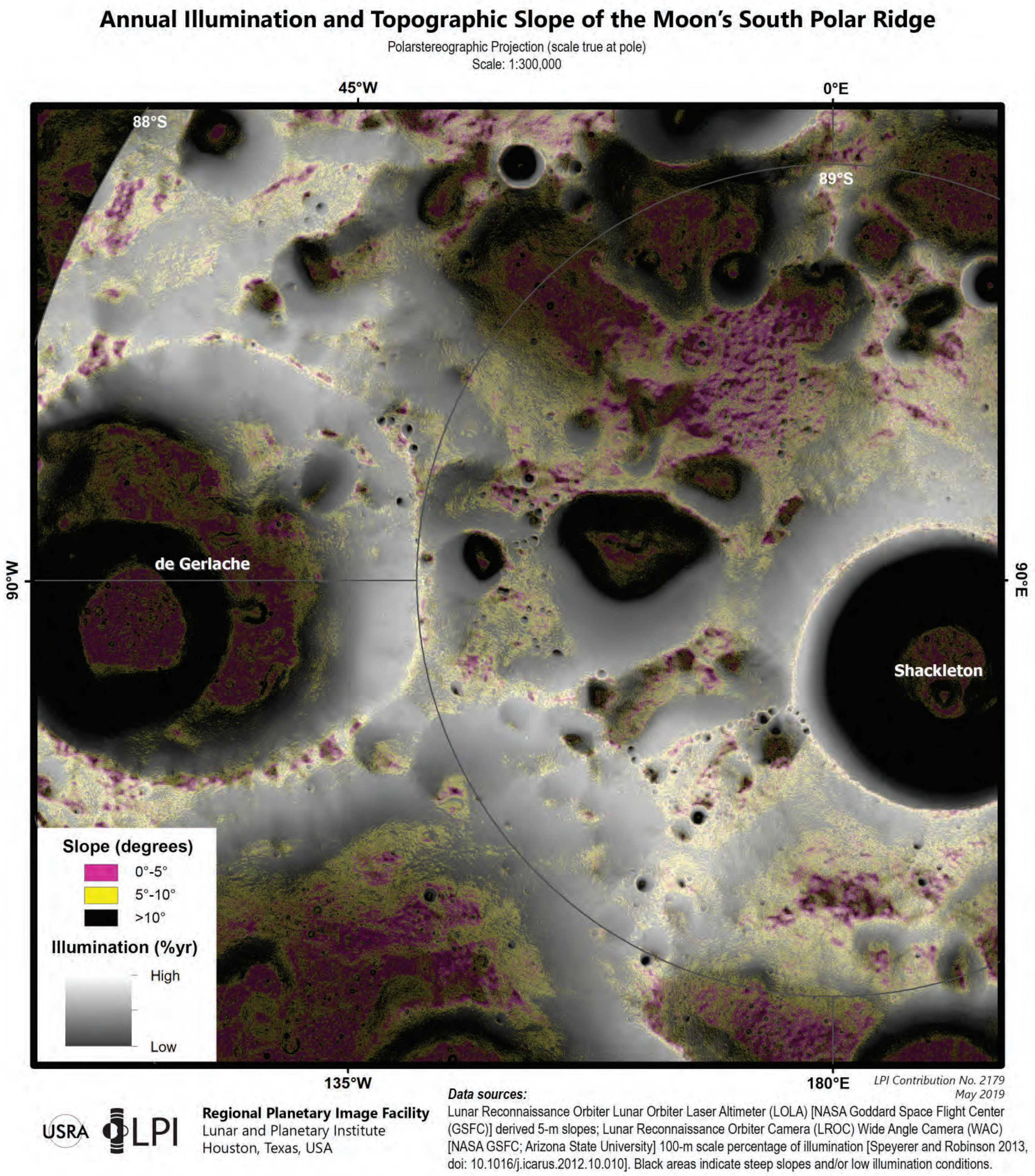


Figure 22 - Composite map of the slope and percentage of illumination per year at the lunar south pole

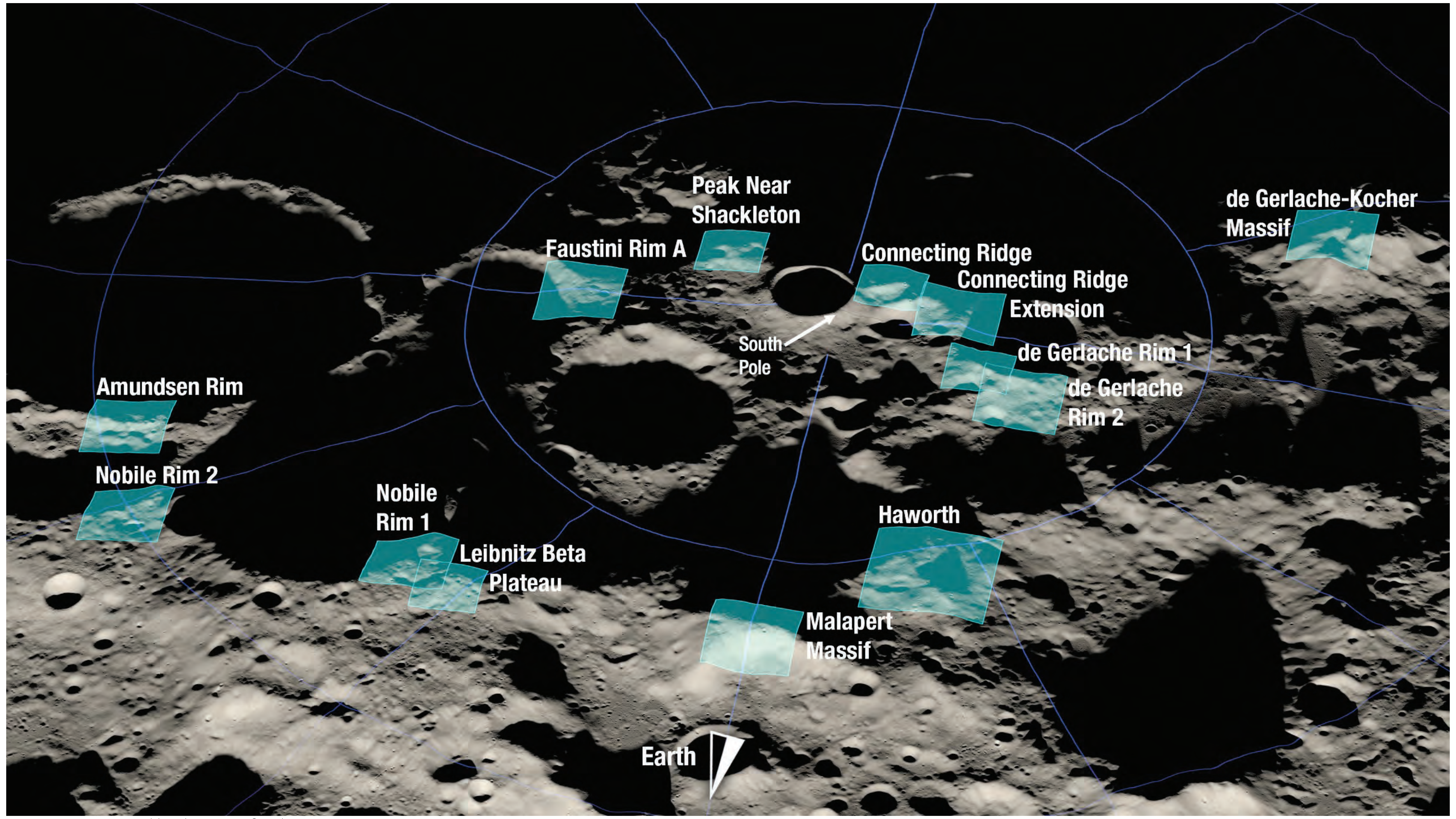


Figure 23 - Proposed landing sites for the NASA Artemis missions

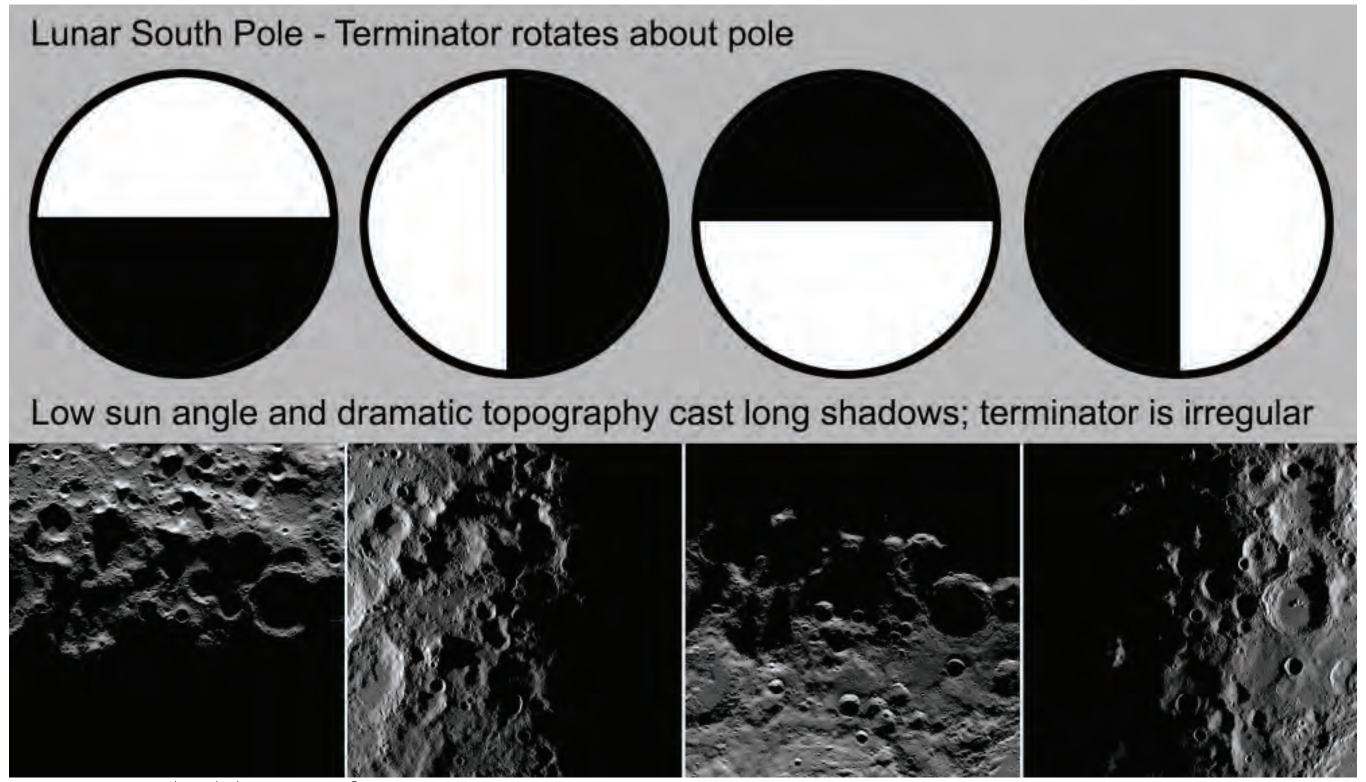


Figure 24 - Graphical depiction of a sweeping terminator

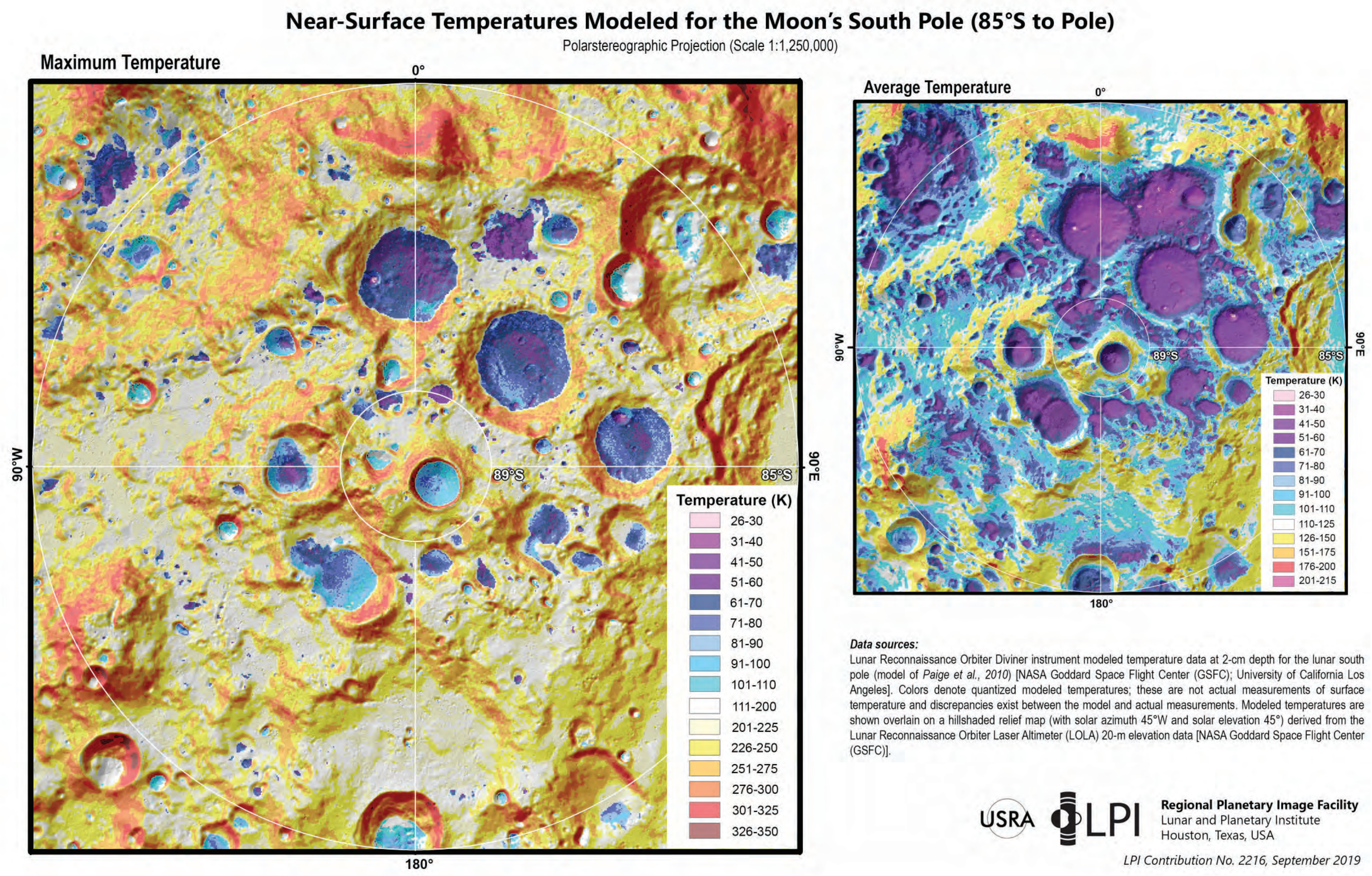


Figure 25 - Maps of the maximum and average temperatures of the lunar south pole region

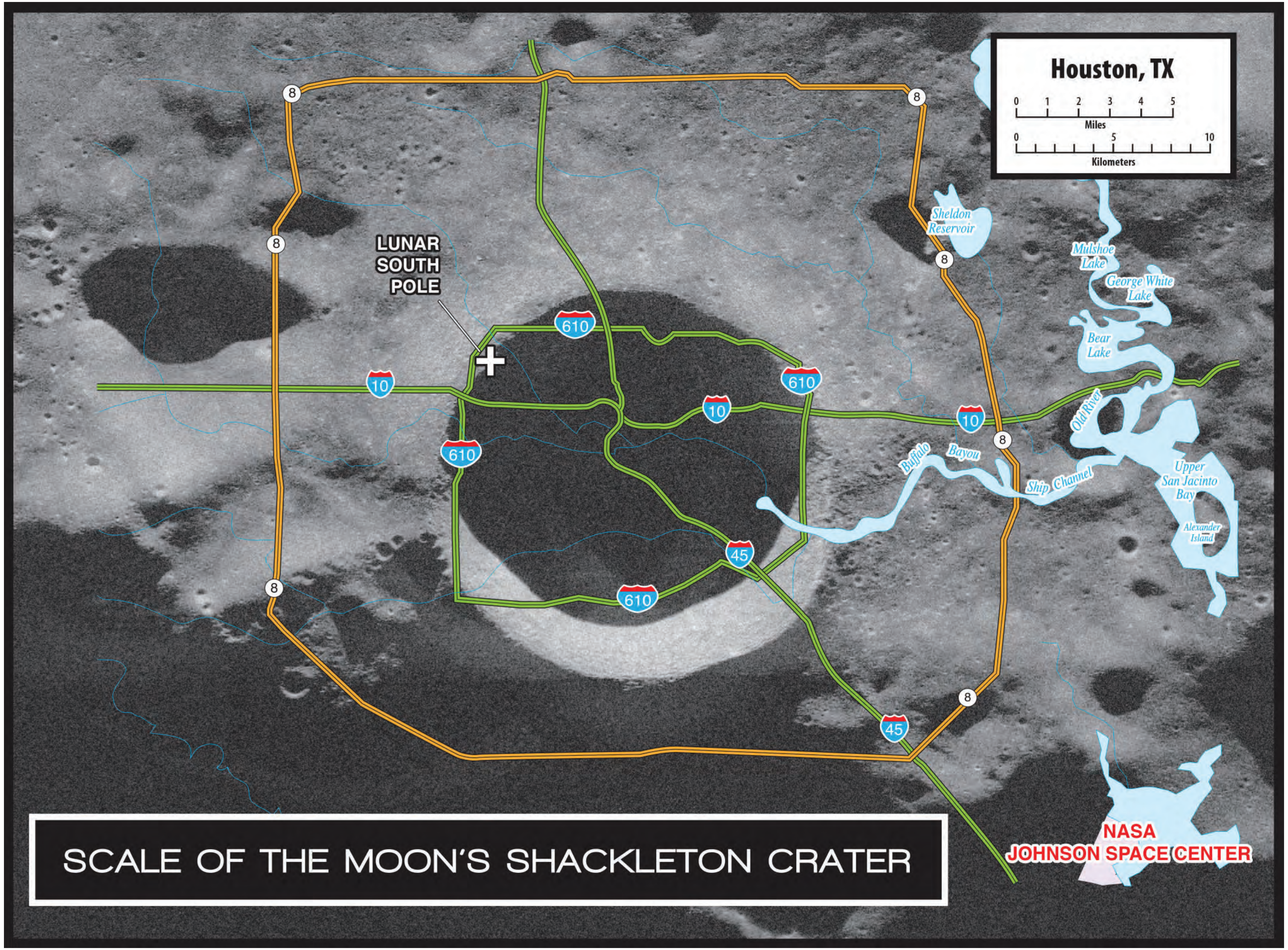


Figure 26 - Area comparison of Houston's major highways to Shackleton Crater

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(Figure 19)
Stopar J. and Meyer H. (2019) Topographic Map of the Moon's South Pole (80°S to Pole), Lunar and Planetary Institute Regional Planetary Image Facility, LPI Contribution 2169, https://repository.hou.usra.edu/handle/20.500.11753/1254

(Figure 20)
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