

Moon Village Reference Masterplan and Habitat Design

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The concept of an international “Moon Village” introduced by the Director General of ESA, Jan Wörner, has been a catalyst for renewed interest in developing a permanent settlement on the Moon. Skidmore, Owings & Merrill is investigating together with the European Space Agency and faculty from the Massachusetts Institute of Technology concepts for the first permanent human settlement on the lunar surface. The European Space Agency is contributing expertise from their research facilities including ESTEC, the European Astronaut Centre, and ESA HQ. This collaboration is strengthened by key input by faculty from the Aerospace Engineering Department at Massachusetts Institute of Technology, including an Astronaut with spaceflight experience. This collaboration aims to demonstrate the potential of an international private-public partnership to advance human space exploration through cross-disciplinary cooperation. The paper presents a holistic approach to planning of a lunar development, centering on the need for habitation systems, designed as adaptive space environments to enable versatile surface operations. The designed multi-functional structural concepts are optimized for performance, safety, and utility, leverage emerging technologies including a combination of structural pressurized vessels, regolith structures for radiation shielding, and adaptive infrastructure planning. Located on the south pole near the “peaks of eternal light”, the development maximizes In-Situ Resource Utilization. Phasing strategies are explored for evaluating the evolutionary steps of the settlement to harness future ISRU-based construction activities.

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Nomenclature

<i>ESA</i>	=	European Space Agency
<i>ESTEC</i>	=	European Space Research and Technology Centre
<i>ISS</i>	=	International Space Station
<i>ISRU</i>	=	In-Situ Resource Utilization
<i>MIT</i>	=	Massachusetts Institute of Technology
<i>SOM</i>	=	Skidmore, Owings, & Merrill LLP

I. Introduction

IN 2015, the Director General of the European Space Agency (ESA), Jan Wörner, introduced the concept of the “Moon Village”^{1,2}. Inspired by the unparalleled level of cooperation achieved by the International Space Station (ISS), the Moon Village represents an extension of this paradigm deep space activities. It is a vision to apply international cooperative principles to exploration beyond Low Earth Orbit (LEO). The concept is opposed to a paradigm of adversarial competition where space faring entities develop capabilities in isolation and for separate programs. The Moon Village envisions a model of development where many players combine resources to deploy a common infrastructure on the Moon that can then support a wide range of activities and missions. The vision has sparked a renewed interest and mobilized creative energies around the world toward returning humans to the Moon to stay.

Renewed interest in the Moon is fueled by the growing evidence that large amounts of water and other volatiles are trapped in the permanently shadowed regions of the lunar poles. The first US robotic mission after Apollo was the Clementine Mission, launched on 25 January 1994 with the objective of mapping the moon at various wavelengths. This mission’s bistatic radar experiment provided evidence of the presence of volatiles in the form of water ice on the Moon’s surface³. More than a decade later, the LCROSS mission was launched in 2008 after the discovery of lunar water by India’s Chandrayaan-1 lunar probe. The LCROSS Centaur upper stage heavy impactor was aimed at one of the permanently shadowed craters, Cabeus near the south pole⁴. The debris plume ejecta from the impact confirmed the concentration of water to be “ $5.6 \pm 2.9\%$ by mass” plus large quantities of methane, ammonia, carbon dioxide and carbon monoxide which would be critical to supporting the future development of a lunar settlement.

In the spirit of the vision to take humanity back to the Moon, Skidmore, Owings & Merrill LLP (SOM) has partnered with the European Space Agency (ESA) and the Massachusetts Institute of Technology (MIT) Department of Aerospace and Astronautics and Media Lab to design the first permanent human settlement on the lunar south polar region. The Moon Village is a long-term endeavor—one with far-reaching goals to envision the acceleration of exploration initiatives that Space Agencies worldwide have set for the coming decades. The project would allow us to build on knowledge and technologies for space applications that will in turn advance our approach to more intelligent methodologies for terrestrial utilization and promise to directly impact how we approach challenges back on Earth. The partnership between SOM, ESA, and MIT marks an important milestone in cross-disciplinary collaboration as an essential element in achieving this vision. Conditions unique to the lunar environment, such as reduced gravity, extreme thermal differentials, high-energy solar exposure, cosmic radiation, high velocity micrometeorite impact, abrasive-electrostatic regolith, zero atmosphere and constrained human systems are influencing the architectural design of an integrated settlement. ESA is providing expertise from their various research and engineering facilities including ESTEC, the European Astronaut Centre, and ESA HQ to enable a holistic approach. Faculty from the Aerospace Engineering Department at MIT, including NASA Astronaut Jeffrey Hoffman bring human spaceflight experience to the team. Together with SOM’s extensive experience in terrestrial applications and expertise in architecture, structural and civil engineering, urban planning, sustainable design, and digital design we will bring real-world scenarios that maximize the potential of the proposed paradigm for lunar architecture.

II. Site Selection

The extensive exploration of the lunar nearside equatorial regions during the twentieth century has established that the lunar surface is extremely dry and devoid of many of the necessary elements to support human habitation. Thus, lunar outpost studies conducted as recently as the 1990s assumed that the first permanent lunar base will be situated in the mid latitudes and that oxygen will have to be derived from the lunar rocks⁵.

In the last two decades, the scientific community has come to the realization that due to the fortuitous alignment of the lunar orbit to the ecliptic, the low-lying areas at both poles are permanently shaded from the light of the Sun. After half a dozen robotic missions, we are now fairly certain that both poles hold large amounts of water and other volatiles. The scientific evidence is still ambiguous about how the water is deposited and in what concentration, but its presence opens up opportunities to use this resource *in-situ*. Additionally, these frozen volatiles hold tremendous

scientific opportunity. The evidence points to the fact that the current conditions at the poles have existed for a very long time and thus this is a treasure trove of stored samples from the early solar system until the present day.

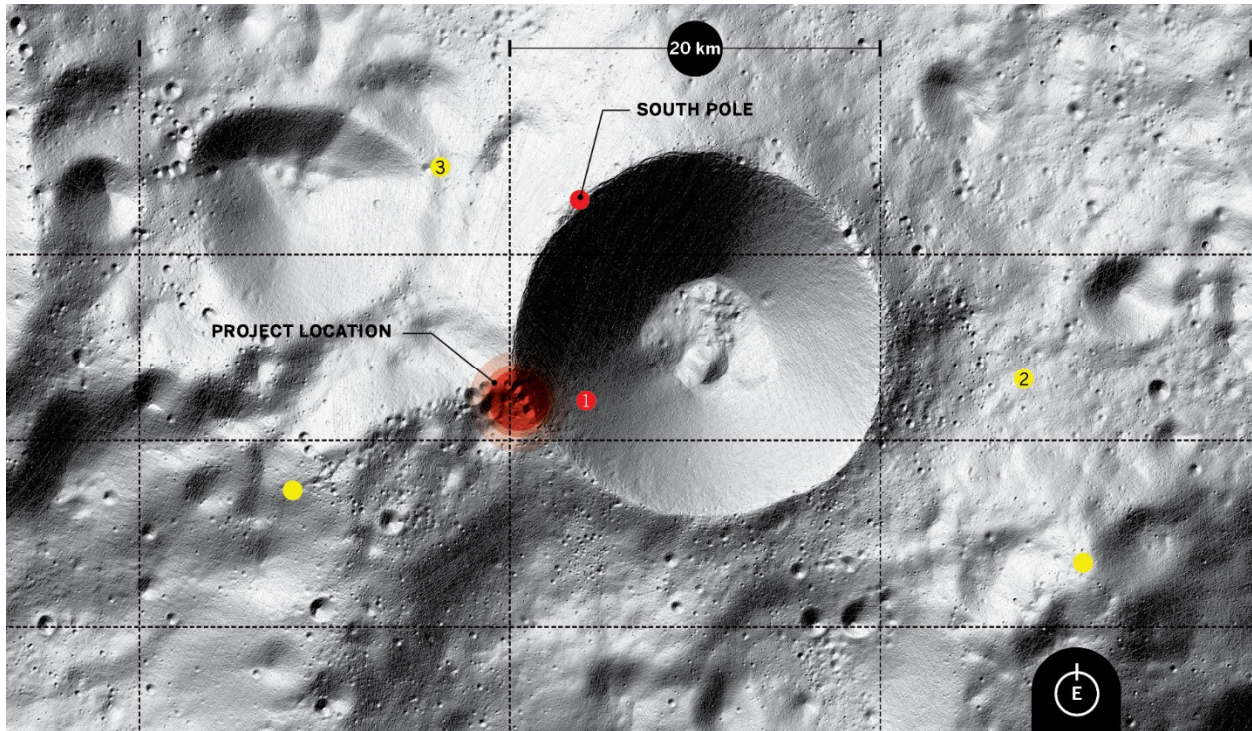


Figure 1. Lunar south polar region. The South Pole is located on the rim of Shackleton Crater. The proposed site for the Moon Village is marked in red. Yellow dots are other potential sites that were rejected.

NASA’s Lunar mapping and Modeling Platform (LMMP) was used to support site selection and analysis. The interface allows for improved navigation, 3D visualization and a reliable source for topographical information. Conducting a detailed analysis and extracting key data sets for elevation, illumination and proximity to volatiles with this platform provided a series of optimal locations that were explored in more detail. After extraction of elevational plots at intervals we then interpolated the cross sections to produce a detailed topographic model to assess the complexity of surrounding terrain. Ultimately, these steps repeated numerous times using computational techniques led us to identifying an optimal zone for the proposed development.

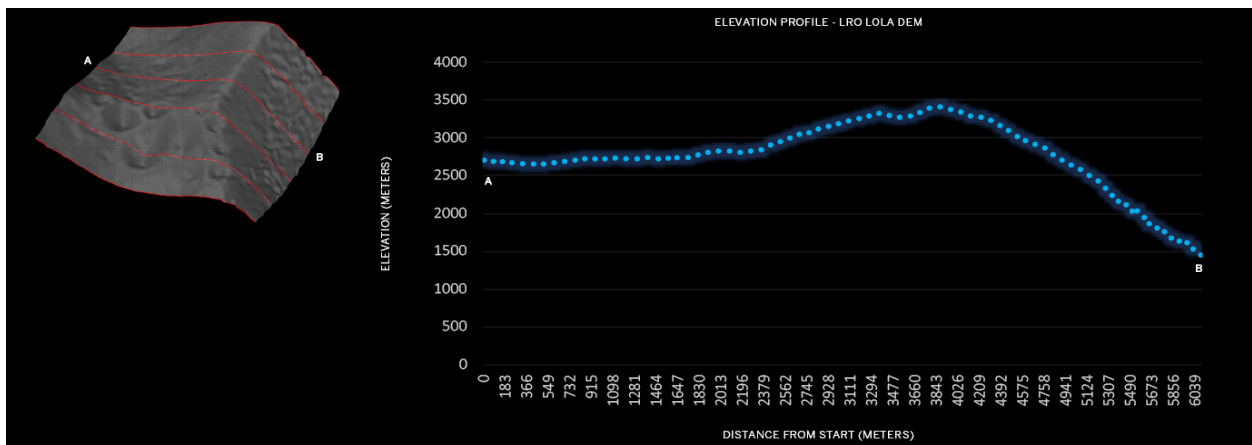


Figure 2. Topographical datasets. Dataset extracted from NASA’s Lunar and Planetary Mapping and Modeling Moontrek platform.

III. Masterplan

A permanently inhabited Moon Village will be humanity's first effort in establishing an off-world society. History shows that the initial act of setting up a new settlement has very long-lasting effect on the resulting society. Setting up the right plan for laying out the physical reality of the settlement will play a role just as important as the social, governance, and legal aspects of the Moon Village.

A. Criteria

The primary engineering requirements for the design of a settlement on an extra planetary surface are safety, efficiency and expandability. Safety requires that there be a number of interconnected and individually pressurizable elements. In case of an accidental loss of pressure, a fire, or other failure, there must be at least two means of egress from every module. Furthermore, the loss of one space must not cut off functioning portions of the settlement from each other. Efficiency is dictated by the large distance from Earth and the associated shortage of labor and energy. The lengths and number of connections of all infrastructure elements, such as pipe, cables, and ducts must be optimized to the bare minimum in order to reduce mass and complexity. Expandability requires that the pattern of development be easily repeatable and expandable without compromising the qualities of the structures that have already been completed.

B. Historical Precedents

There is a rich literature and experience of urban planning and design stretching back centuries that one can draw on for inspiration.

B.1 Grid and Radial Plans

The rectangular grid is the strategy that has been the most widely adopted by humans when creating a new settlement from scratch. The earliest well documented example are the Roman military camps, which were laid out on a rectangular grid and organized around two intersecting "streets", a north-south Via Praetoria and an east-west Via Principalis. All other elements were organized based on the same rules, thus a soldier could always find his way in any camp built anywhere within the empire.

When constructing new settlements in Central and South America the Spanish followed a similar approach. Each new town was organized based on set of rules that were prescribed by the central authorities in Madrid. This is known as the "Law of the Indies." Every colonial city was laid out on a square grid that was offset by 45° from north. The public buildings, like the church and the governor's mansion faced a plaza, which occupied the central plot. The distinguished citizens lived on the plots immediately adjacent to the center and the rest of the population occupied the outlying squares. This vision is so ingrained into the culture that it was widely applied as recently as the 20th century when company towns housing was set up to house mining operations in the Atacama in northern Chile.

In North America, the initial settlements along the Atlantic Ocean grew organically, both in the New England colonies and the southern plantations. However, soon after independence, in 1785 when the new country set its eyes on expanding west, a grid system of surveying and dividing land for sale was established. Known as the Public Land Survey System it divided all the land west of the Appalachian Mountains into square mile plots.

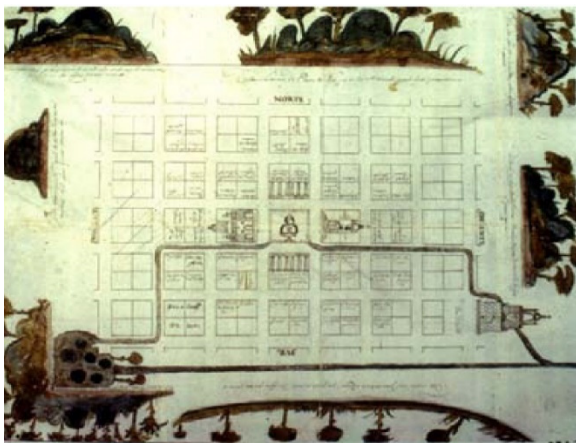


Figure 3. Law of the Indies



Figure 4. Clinton, Illinois

Judging by its enduring popularity, the urban grid has numerous benefits when applied on Earth. However, many of these do not translate well to building on the Moon. Although good for interconnectedness and expandability, the need to connect all modules with pressurized elements means that a grid of modules would create a series of full enclosed courtyards and would limit easy access to the outside of most modules for inspections, repair, or modification. Additionally, the grid is well suited to a flat open terrain, but is hard to adapt to the varied topography that is likely to be encountered at the south pole.

A variation of the rectilinear grid are radial city plans, several of which have also been proposed as ideal designs. The most famous of which is the Garden City design by the English writer Ebenezer Howard⁶. This radial design was Howard's attempt to combine the best aspects of both city life and rural life into one urban plan.

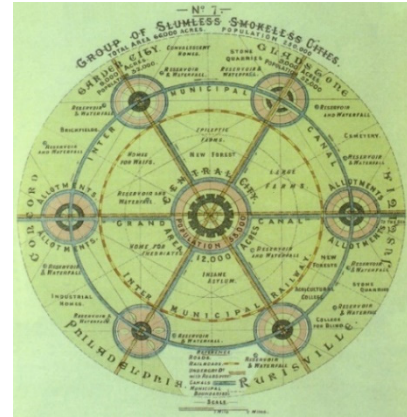


Figure 5. Radial City

B.2 Linear City

The Linear City is a planning idea first enunciated by the Spanish architect and planner Arturo Soria. In Madrid, there is a neighborhood called Ciudad Lineal which is laid out according to this plan along a long street called Calle de Arturo Soria. His plan was 'designed on the basis of an expandable spine of transport ... to ameliorate the crush of population on large urban centers, to integrate the inevitable facts of roads and railways and to allow a continuous growth pattern'⁷. The idea was then further developed and popularized by Le Corbusier.

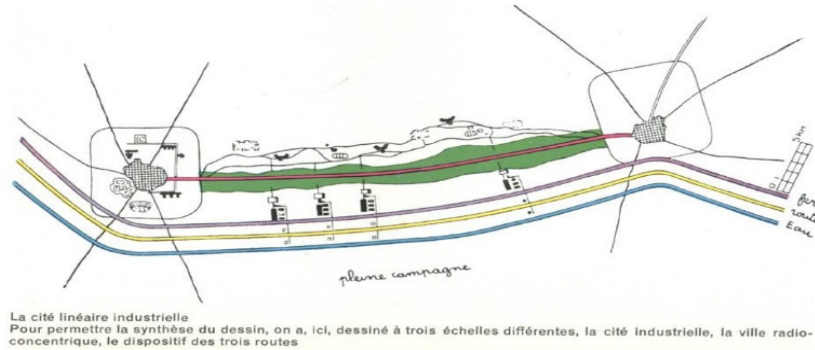


Figure 6. Linear City. Master plan proposal by Le Corbusier.

Arranging the pressurized elements in two parallel bands that are connected at regular intervals best achieves the goals of safety, efficiency and expandability. The external zones of the Moon Village can then also parallel the development. This linear development has the additional benefit of being flexible and easily adaptable to the terrain at the rim of Shackleton Crater.

C. Moon Village Master Plan

We propose to locate the Moon Village along the rim of Shackleton Crater near the South Pole. The layout of the settlement will align with the rim of the crater in four parallel bands. The first band of development, called the Habitation Band, will be on side closes to the crater will hold the pressurized habitats. A second band, called the Infrastructure Band, will be comprised of spaces that will hold all the external equipment that is required to support the Moon Village. A third band, named the Activities Band, will be reserved to staging area for the various stakeholders of the Moon Village. Finally, on the outer most zone, away from the crate wall, will be located the energy generation and transportation activities.

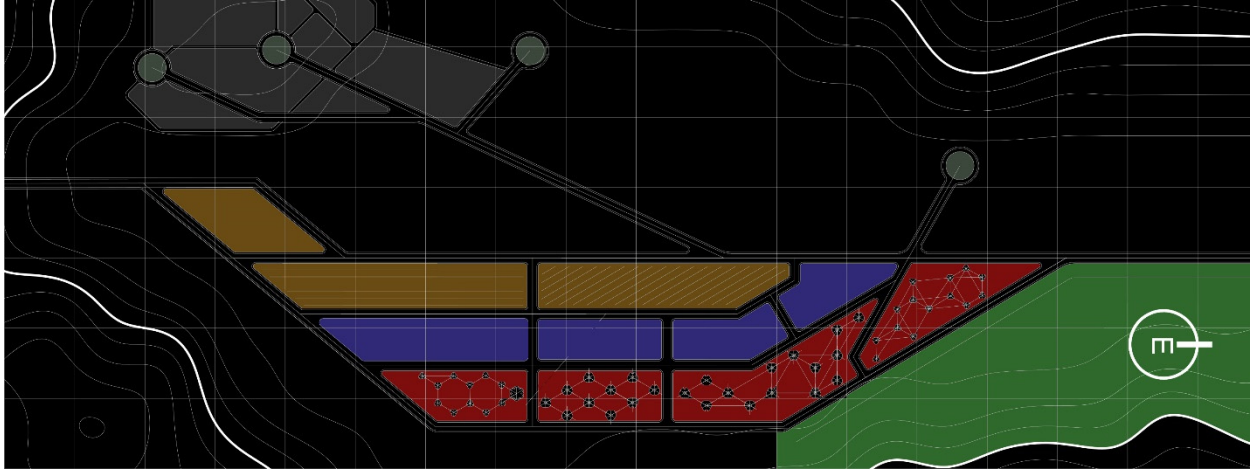


Figure 7. Master plan. Color coded plan of Moon Village. The Lunar South Pole and the Earth are to the right. The bowl of Shackleton Crater drops down towards the bottom. Green is the part of the crater rim that will be preserved to be free of human interference. Red is the band of pressurized habitats. Blue is a band of external infrastructure to support the habitats. Orange are zones that can be used by the various stakeholders for their specific activities. Instead of a North Arrow, the relevant direction here is marked with an Earth Arrow.

C.1 Habitation Band

The habitation zone is located near the crater’s rim to optimize the distribution of an interconnected configuration for living, conducting scientific work, conducting EVA’s, maximizing exposure to near continuous daylight and maintaining an unobstructed line of sight of the Earth. The zone is defined by a series of vertical habitats, tunnels, horizontal modules, equipment facilities and infrastructure, all within proximity to reduce EVA’s and conduct operations in a closed environment when possible. The design of the typical module, allows the branching of each extension to connect to subsequent modules, differentiated by capabilities and specializations. A distribution of utilities such as power, communications, water, oxygen and food would be shared between modules while maintaining a level of autonomy for contingencies. Through the development of habitation zones defined by the architectural interfaces, surface activities, requirements and crew capacity can be determined adequately for sustainable and adaptive growth.

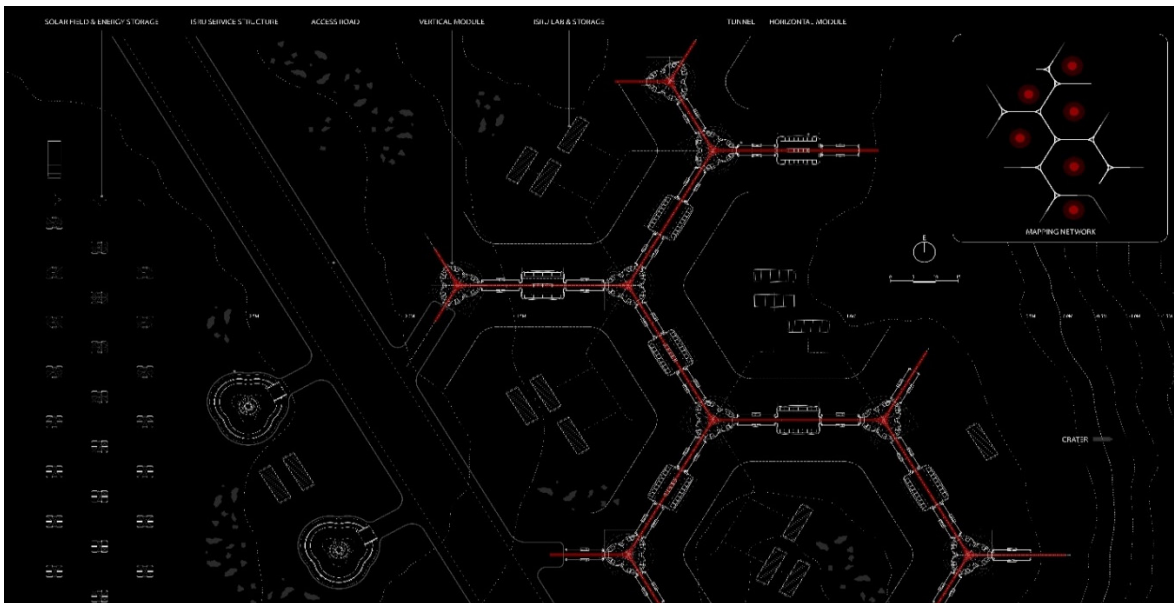


Figure 8. Rendered view of the growth of the Moon Village.

C.2 Infrastructure Band

Lunar activities within the masterplan are organized into disciplines which are critical to expanding science and exploration goals. The first major type of activity zone would be human and robotic exploration zones, designated as proving grounds for human and robotic exploration which include planetary science and use of the environment as a laboratory, and the applied science of resource characterization and extraction. This zone is equipped with storage facilities and ISRU laboratories located near the habitation modules for safety and efficiency requirements. The second zone is characterized by lunar resource development, making use of the environment (materials, vacuum, and energy) to experiment with and industrialize the production of energy from sunlight and metals extracted from regolith and water, oxygen, and hydrogen from ice deposits. These activities will range from complex processing requirements to minimal processing requirements making proximity to energy sources and a safe distance from the habitat zones an important aspect of the planning. The third zone will include the testing of operational techniques and surface system technologies which will be responsible for developing, integrating and implementing infrastructural elements on the surface such as power, ISRU based construction, ISRU based hardware manufacturing, communication, transportation, and large-scale resource extraction.

C.3 Activities Band

Additional space will be reserved for special activities that may be required by various individual partners of the Moon Village. For example, if a space tourism company joins the Moon Village they will require space where their customers can experience the Lunar surface. Similarly, a long range scientific expedition will require area for staging, practicing, and calibrating experiments. This band is a collection of open zones for use of the various stakeholders of the Moon Village.

C.4 Pristine Lunar Park

Besides physical infrastructure that will keep the Lunar settlers alive and will aide them in accomplishing their tasks, in order to thrive, every settlement also requires physical symbols that give the Moon Village a sense of identity and a sense of poetry. When the Apollo astronauts went to the Moon we celebrated the achievement of getting there, however the most enduring image that captured humanity's imagination is not one of the lunar surface. The image that has had the deepest effect on our culture is Earthrise. The view of the living and colorful Earth juxtaposed to the sterile and grey Moon is the one that touches us the most. On the south pole, the Earth will be visible in the same location in the sky just above the horizon. In order to preserve and revere this view, we propose to leave a portion of the rim in the direction of the Earth from the Moon Village to be an undisturbed preserve that will remain free of human impact. Thus, from every habitat, there will be a view of the Earth hanging above the sweeping arch of the crater rim in the far distance and a piece of undisturbed lunar surface in the near distance. The park is shown in green on Figure 7 and the view of the Moon Village with the Earth in background in Figure 9.



Figure 9. Rendering. *Rendered view of the growth of the Moon Village.*



Figure 10. Aerial view. *Rendered view of the growth of the Moon Village.*

IV. Habitat Design

A. Background

Extra-planetary surface habitats are constrained in terms of module design, dimensions and orientations to comply with the selected launch vehicle, orbital assembly and transfer, landing strategy and surface transportation and deployment. Transportation payload envelope and mass limitations are major drivers of critical design requirements. The only extra-planetary surface habitat that has been built and deployed is the Lunar Module during the Apollo missions. The Lunar Module provided space for two astronauts and had a habitable volume of 6.6 m^3 , with Saturn IB and Saturn V as launch vehicles⁸. A planetary architecture needs interfaces with transport and landing vehicles, as well as an EVA access determined by the elevation of module interior entrance levels. The size, design and configuration of the modules determine a variety of utilization and operational effects, such as interior habitable volume and its spatial and functional optimization.

B. Parameters

Establishing a parametric workflow in the design and engineering of the habitat concepts is a critical aspect of how we approach internalizing the various contingencies associated with highly integrated solutions. Determining the dimensional parameters, volume, mass and architectures is driven by baseline assumptions for currently existing and near-term capabilities. As part of this, assumptions for the current designs are based on scenarios, mission infrastructure and life support subsystems provided by the team at ESA and reference systems published by NASA.

The mission parameters of the concept are characterized by a series of missions in which the architecture is incrementally improved through additional capabilities and mission durations. The main habitat will be a Class 2 prefabricated structure as defined by Cohen^{9,10}. An evolutionary model to supporting the addition of increased activity and industry can only be strategically organized by adaptive methods which are informed by integrating the physical mission parameters into the design approach. The parametric relationship between the crew, systems and interfaces provides a useful framework for providing a successful infrastructure that can support any reasonable crew size and duration within the safety and performance considerations requirements.

We have primarily focused on requirements which include structures, environmental protection, environmental control and life support systems, crew systems, power, thermal and extravehicular activities. These systems are essential to facilitating the crew's activities which will initially emphasize exploration science and field work, the deployment of long-term scientific experiments, equipment and robotic systems, technology demonstrations of ISRU

techniques, and the development of surface infrastructure such as power, communication, and navigation systems to support increased activities.

The transportation system limits the mass and scale of a habitation system for performance and cost reasons which is a primary driver for the selection of reusable systems currently available and under development. Two of the selected transport systems include the Falcon Heavy, Space X's reusable heavy lift rocket and the Blue Origin New Glenn launch vehicle. The payloads would be encapsulated by the Falcon Heavy fairing. The fairing is 13.1 meters high and 5.2 meters wide, made of an aluminum honeycomb core with carbon-fiber face sheets fabricated in two-shells. This vehicle has a payload capacity to LEO of 63,800 kg. The New Glenn's proposed 7-meter fairing will have twice the usable volume of any launch vehicle in operation. The currently listed fairing specifications show a height of 22 meters and a diameter of 7 meters. It is planned to deliver a payload of 45,000kg to LEO and is projected to begin launching payloads beginning in 2021.

C. Vertical Habitat

The habitation systems are being designed as deployable multi-purpose modules for habitation, scientific, storage, industrial, and touristic use. The diversity in functions underlines a fundamental need to remain flexible and develop an adaptable architecture. The habitats will comprise of a pressurized volume with an integrated number of systems including docking capability, environmental control and life support systems (ECLSS), logistics management, radiation mitigation, fire safety, crew health equipment, scientific workstations and robotic control station. It will sustain a crew of four. With an interoperable interface, the modules will have a docking system that can link to a rover or to pressurized connectors linking to other habitats.

Several important NASA reports, such as the Synthesis Group Report, identified inflatable structures as an enabling technology that would allow lighter weight structures at a lower cost. NASA has been experimenting pneumatic or inflatable structures, which resist tensile forces due to internal pressure with flexible membranes, since the 1960s for space exploration. The reasons are connected to their main features to reduce mass during the launch and to be folded and compacted in smaller volumes. Other key features are reduced loads while landing on the Moon or Mars and shorter manufacturing time.¹¹

All space inflatable modules require a frame of rigid elements that hold the internal structure together during the large dynamic loads of launch, transfer, and landing¹². These rigid elements then serve as the attachment points of the inflatable membrane. Most past designs starting with the original TransHab, place the rigid elements in a central core^{13,14}. This configuration efficiently packs the structure and the mechanical systems in a central location, however it leaves an awkward doughnut shaped space for the humans to inhabit and does not enable the design of windows along the perimeter rigid structure. Here we propose an alternative configuration of the composite rigid frame and deployable membrane. The rigid elements are pushed out to the perimeter with the goal of leaving a unified central space that is more flexible for human use and better experientially and psychologically. Moreover, the presence of transparent elements in the rigid frame will reduce stressors in living inside a confined environment for a long-term¹⁵. In fact, stressors for human spaceflight associated with habitability, confinement, isolation can lead to a degraded performance, feelings of claustrophobia and lack of motivation¹⁶. The ducts and chases for the ECLSS and electrical systems are paired with the structural elements to create pillars of combined structure and mechanical systems (see Figure 11).

The architectural and structural relationships between rigid elements and composite enclosure also allows for multiple configurations to be tailored for specialized functions. The plans below show the internal layout of a habitat that will be part of the early phase of the Moon Village, thus it has all of the spaces necessary to house a crew of four. As the settlement grows and more infrastructure is added, it is foreseen that the individual modules can become specialized. For example, the early modules can be converted to habitation only element and the science functions can be re-housed in a dedicated laboratory spaces¹⁷.

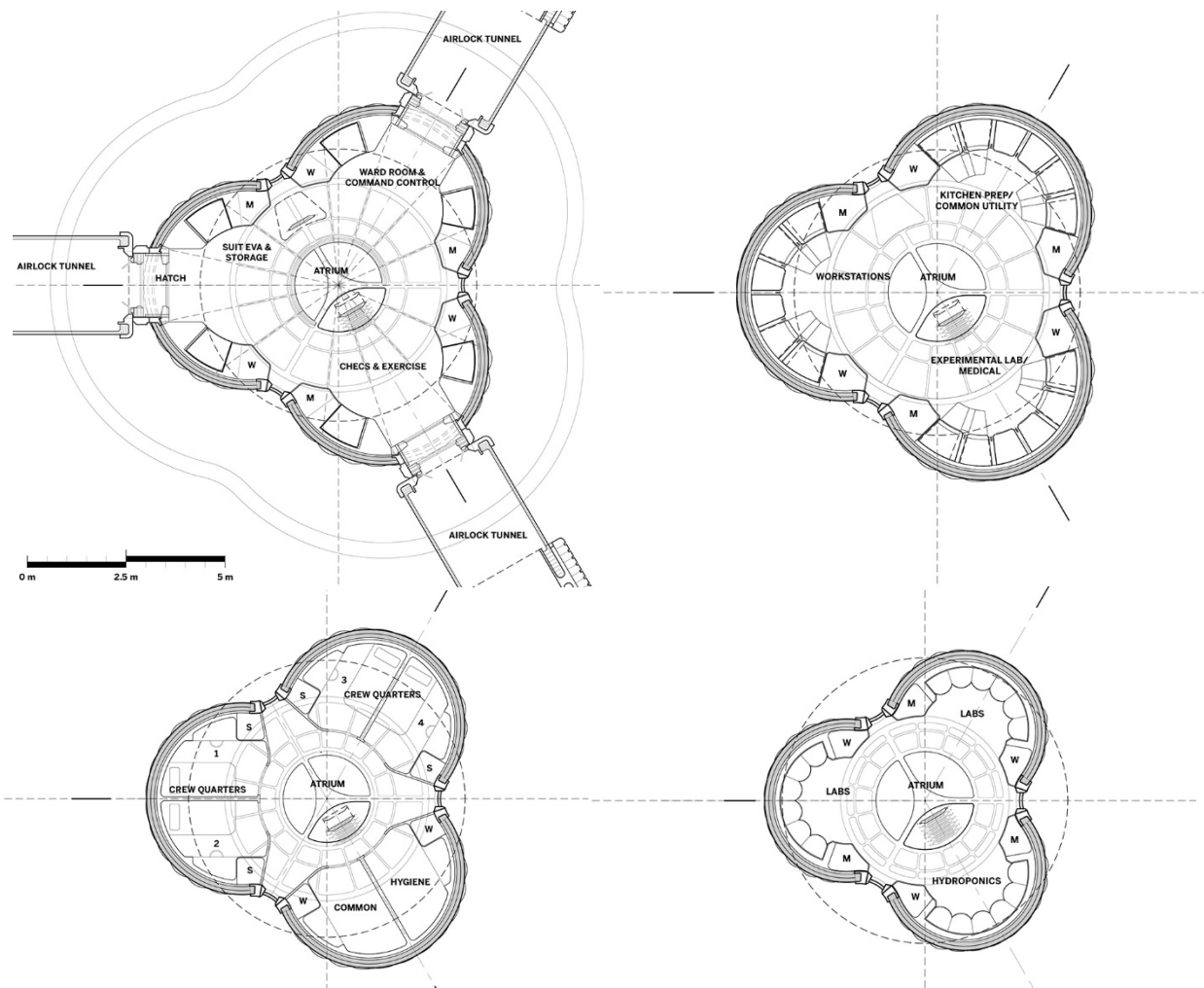


Figure 11. Vertical habitat plans.

C. Human Factors & Habitat Systems

Ensuring human performance and incorporating considerations to optimize various human capabilities is fundamental to providing an architectural solution which considers human integration at both the system level and individual. Human operation on the lunar environment will be a difficult challenge for any individual no matter how well trained and designing for activities that involve humans will need to meet human factors, habitability and environmental health standards provided by space agencies. A holistic approach to designing for human considerations has been optimized by looking closely at a series of concept of operations captured in varying schedules which are determined for each phase of the Moon Village development. The concept of operations for lunar activities informs the design of the habitat by allowing spaces and functions to remain flexible while centering on the health and safety of all crew members. For example NASA's STD-3001, human centered design process states "Effective human-centered design starts with a clear definition of human activities, which flows down from the concept of operations and anticipated scenarios, to more specific analyses of tasks and to even more specific questions of allocation of roles and responsibilities between the human and systems (where the term "systems" refers to machines or automated systems)" which is a philosophy which we try to enhance through our parametric design methodologies¹⁸.

Characterizing the physical requirements which emphasize this philosophy in design means identifying the interfaces between humans and systems which control and utilize the necessary resources for the activities defined by each phase. A key factor is intelligent interfaces which can be accessed independently and are centralized, providing full control and visibility. The architectural design places an emphasis on this by distributing the interfaces and systems at the perimeter and giving all crew members direct-line of sight at any given moment for any occupied level (see Figure 12). The solution also places a major emphasis on increased volume necessary for the crew to perform complex

mission tasks and simultaneous activities for collaboration. Volume is also necessary for longer duration missions, which place increased stress on behavioral health and degrees of freedom. Another key concern are the illumination levels to support the variety of intricate crew tasks. The level of detail associated with crew operations for scientific and engineering tasks require a well calibrated lighting conditions with the ability to provide immediate visibility of essential equipment and control systems. We investigated a series of design strategies that integrate lighting for emergency, circadian entrainment, health, level of control and circulation. Key lighting features are embedded within the architectural surfaces to supply essential and augmented lighting conditions. Additionally, we also integrated a wide range of requirements including configuration of equipment, translation paths, hatches, restraints and mobility aids, windows and collaborative environmental considerations.



Figure 12. Habitat interior view. *Working space and labs.*



Figure 13. Pre-flight view. *The vertical habitat packaged before launch.*

V. Future Work

The team has planned out the work on this project in stages to mirror the design phases of a typical terrestrial architecture project. The stage of the project that is described in this paper is the end of Concept Design. The more detailed design following the completion of the Schematic Design and Design Development phases will be presented in future papers.

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