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Master Planning and Space Architecture for a Moon Village

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Abstract

Skidmore, Owings & Merrill (SOM), in partnership with the European Space Agency (ESA) and faculty of Aerospace and Architecture at the Massachusetts Institute of Technology (MIT), is working on space architecture and master planning strategies for the first full-time human settlement on the Moon. One aspect of ESA's space exploration efforts in Low Earth Orbit, the Moon and Mars is to aim at "developing new concepts for international exploration activities, encompassing novel cooperation opportunities open to all nations and industrial actors." To support this goal, the partnership envisions future missions to the lunar surface that will be driven by cooperation and sustainable planning strategies. The "Moon Village" idea, first presented by ESA Director General Johann-Dietrich Wörner, is a vision for an open architecture based on global cooperation among multiple nations and multiple partners combining their various expertise for the common objective of enabling long-term exploration of the lunar surface.

Fundamental to achieving this goal will be the establishment of an infrastructure on the Moon, relying on a myriad of architectures and surface system capabilities. As part of this larger effort, an alignment with NASA's 2018 Strategic Plan to "extend human presence deeper into space and to the Moon for sustainable long-term exploration and utilization" provides an essential paradigm for holistic thinking about humanity's future in space. Advancement of new and emerging capabilities supported by commercial expertise, transferring proven technologies toward addressing challenges in space will result in the construction of an early outpost for safe, flexible and efficient human exploration. Achieving this initial goal would produce operational experience for the planning and extensive development of an eventual sustainable and permanent lunar ecosystem that will support a variety of human activities for scientific exploration, industrial development and commercial initiatives. The "Moon Village" aims to demonstrate the potential of an international private-public partnership to advance human space exploration through cross-disciplinary cooperation.

This paper presents a holistic approach to planning lunar development, centered on the need for singular surface habitation units, designed as adaptive multi-functional modules that will enable and support versatile surface operations. Multi-functional structural concepts, 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 strategies. Located on the edge of Shackleton crater near the lunar south pole, the development maximizes In-Situ Resource Utilization by proximity to presumed ice deposits and solar energy potential, using high elevation locations with long periods of continuous solar irradiation. Phasing strategies are explored for evaluating the evolutionary steps of the settlement to anticipate future ISRU-based experimental and construction activities. Only by expanding on the capabilities and the cooperation of both commercial and government entities can we truly address large and micro scale-architectural systems for human settlements beyond Earth.

Keywords: Space Architecture, Habitation, ISRU, Master Planning, Moon, Structures

Introduction

In 2015, the Director General of the European Space Agency (ESA), Johann-Dietrich Wörner, introduced the concept of the "Moon Village" [1,2]. Inspired by the unparalleled level of cooperation in creating the International Space Station (ISS), the Moon Village extends this paradigm to deep space activities. The initiative envisions a model of growth 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 commercial and government energies toward returning humans to the Moon and establishing a permanent settlement.

In this spirit, Skidmore, Owings & Merrill (SOM) has partnered with the ESA and faculty of the Massachusetts Institute of Technology (MIT) Department of Aeronautics and Astronautics and Media Lab to design a permanent human settlement located at the lunar south polar region. This project is a platform allowing us to build on the knowledge and technologies developed for space applications—challenging both space and terrestrial architectures to consider the relationships between human activities and the resources which support them, and developing architectural solutions for the Moon that will in turn advance thinking about terrestrial concerns. Solving how a human settlement might evolve in the extreme conditions of space enables more intelligent methodologies and promises to directly impact how we approach challenges on Earth. 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 living spaces, must be accounted for in the architectural design of an integrated settlement (see Figure 1).

The partnership is grounded on the free exchange of expertise and ideas to generate novel concepts which are supported by the creative, scientific and engineering capabilities of each partner. ESA is providing expertise from its various research and engineering facilities including ESTEC, the European Astronaut Centre, and ESA HQ. Retired NASA Astronaut Jeffrey Hoffman, on the MIT Aero/Astro faculty, brings human spaceflight experience to the team. Together with SOM's extensive 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 holistic paradigm for a future lunar settlement.

Site Selection and Masterplan

After half a dozen robotic missions in the past decade, we are now fairly certain that both poles of the Moon hold large amounts of water and other volatiles in their permanently shaded craters [3,4]. While the nature and distribution of these resources is not yet determined, the frozen volatiles hold tremendous industrial and scientific opportunity as a local source of fuel, commodities, and development. The evidence points to the fact that the current conditions at the poles have existed for a very long time and thus is a treasure trove of stored samples from the early solar system until the present day. This combination of resources and scientific interest has made the poles a logical target for early human exploration.

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

The primary requirements for the design of a settlement on an extra-planetary surface are safety, efficiency, and capacity for growth. Safety requires that there be several interconnected and individually pressurized 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 any one space must not cut off functioning portions of the settlement from each other. Efficiency is dictated by the shortage of labor, materials, and energy associated with the great distance from Earth. Expandability requires that the pattern of development be easily repeatable and expandable without compromising the qualities of the structures that have already been completed.

In order to establish the organizational principles of the masterplan, the team has drawn inspiration from the rich literature on urban planning and design. The precedents that were reviewed included grid plans such as Roman military camps, Spanish cities in Latin America laid out according to the "Law of the Indies," and the American Public Land Survey System, as well as radial plans such as the Garden City design by the English writer Ebenezer Howard [5].

The model best suited for the irregular terrain at the lunar south pole while meeting the above criteria is the Linear

Figure 1. View of Earth rise from the rim of Shackleton Crater.

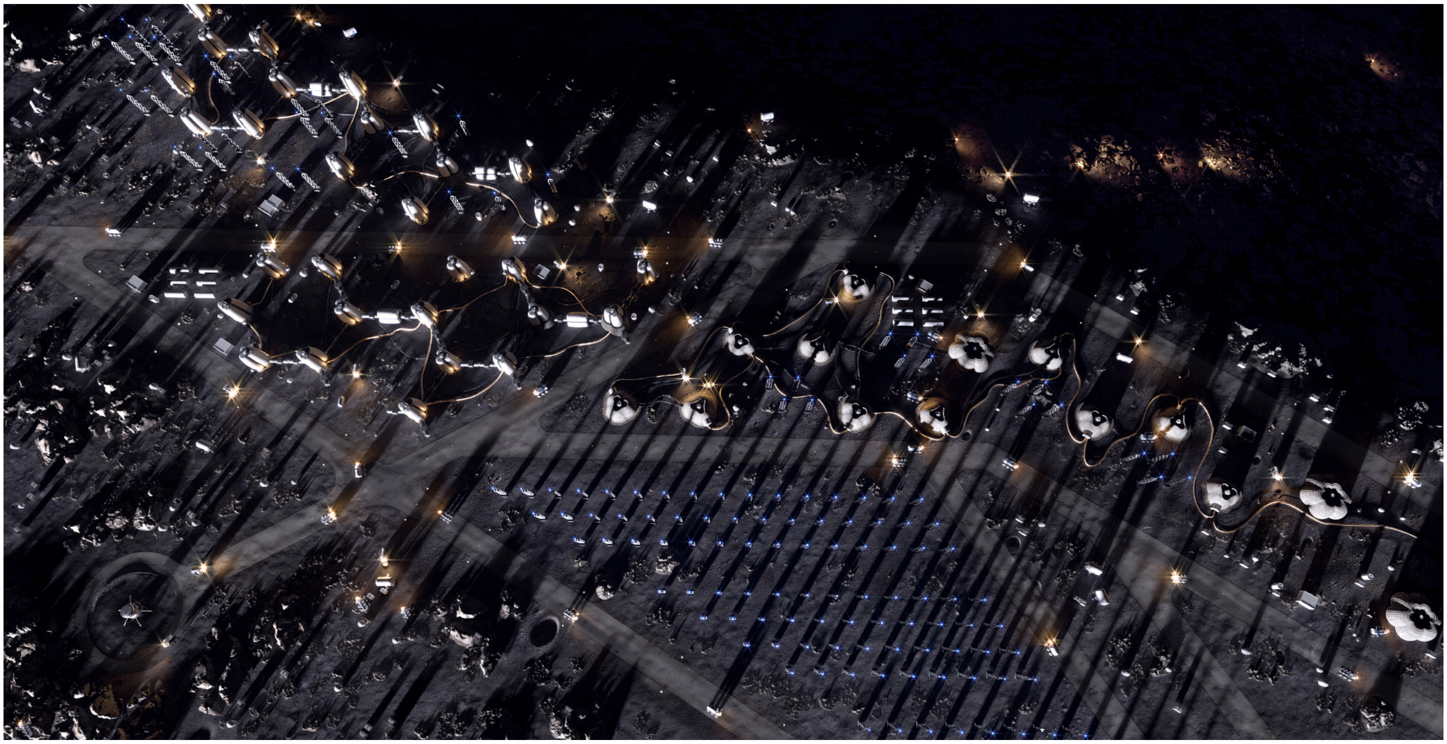

Figure 2. Master Plan view of Moon Village development.

City, a planning idea first enunciated by the Spanish planner Arturo Soria and popularized by the Swiss architect Le Corbusier [6]. 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 [7].

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 of development (see Figure 2). The Habitation Band will be comprised of the pressurized habitats and will be located on the side closest to the crater. A second band, called the Infrastructure Band, will be comprised of spaces that will hold all the external support equipment. A third band, named the Activities Band, will be reserved as a staging area for the various stakeholders of the Moon Village. The energy generation and transportation activities will be located in a zone away from the crater wall [7].

Besides the physical infrastructure to keep lunar inhabitants alive, every settlement also requires physical symbols that give the Moon Village an identity and a sense of poetry. On the south pole, the Earth will be visible just above the horizon. To celebrate this view, we propose to leave a portion of the rim in the direction of the Earth from the Moon Village as an undisturbed preserve that will remain free of human impact [7]. Thus, from the habitats, there will always 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.

Habitat Design

Extra-terrestrial surface habitats are constrained in terms of module design, dimensions and orientations to comply with the selected launch vehicle, orbital assembly (if required) and transfer, landing strategy and surface transportation and deployment. Transportation payload envelope and mass limitations are major drivers of critical design requirements. While it is necessary to define a mission scenario and functional goals for a habitat, the operational features such as level of technological integration and safety will determine performance and hardware requirements.

So far, the only extra-terrestrial surface habitat that has been built and deployed is the Lunar Module (LM) during the Apollo project. The LM provided space for two astronauts for several days with a habitable volume of 6.6 m^3, using the Saturn V as launch vehicle [8]. A planetary architecture needs interfaces with transport and landing vehicles, as well as EVA access determined by the elevation of module interior entrance levels as well as surface mobility unit requirements. 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.

Parameters

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 we envision will be a Class 2 prefabricated structure as defined by Cohen [9,10]. An evolutionary model to support the addition of increased activity and industry can only be strategically organized by adaptive methods which are informed by integrating the physical mission parameters and future surface development strategies into the design approach. The parametric relationship between the crew, systems, and interfaces provides a useful framework for a successful infrastructure that can support any reasonable crew size and duration within the safety and performance considerations requirements.

The SOM-designed vertical habitat known as One Moon was developed with an emphasis on technology development goals including structures, environmental protection, crew systems, deployment, and human interfaces. In addition to these goals, we incorporated considerations for requirements such as environmental control and life support systems, power, thermal and extravehicular activities. Together, these systems are meant to function as an integrated habitable unit designed to support and facilitate the crew's activities. We include in the anticipated design considerations lunar activities that are critical to the advancement of establishing a permanent base and settlement. Activities on the Moon will include both human and robotic exploration science which is meant to gather information about geologic conditions and resource availability. Lunar resource development will provide knowledge and experience on how to use resources in the lunar environment to produce oxygen, hydrogen, metals and various products from ice water deposits, regolith, and solar energy. Experiments leading up to this will require intensive field work which would benefit from habitation modules and strategies that increase safety and performance, since frequent extravehicular activity missions would be required.

Testing operational and surface technologies will be primarily driven through crew-centered and teleoperated methods. Crew-centered control of activities will be conducted by astronauts using augmented teleoperation. The architecture for these future activities will be determined by the duration, location, and centralization of mission operations. It will take a lot of equipment to enable experimentation leading to large scale development and the necessity of infrastructural elements such as high data rate communication equipment, large solar panel arrays, navigation relays, microwave power beam systems. Most of this equipment is cargo that can be delivered ahead of long-term human missions. Additionally, pressurized crew vehicles, teleoperated robotic rovers and surface manipulation systems would need to be delivered to facilitate assembly and construction of equipment. The solution to transporting this much mass lies in reusable transportation that can eventually be refuelled, perhaps eventually by taking advantage of the resources available on the Moon.

Preconstructed habitats are a necessary part of building a base methodically and sustainably. Our designs and approach focus on the pre-emplacement of habitats that eventually lead to the construction of larger occupiable structures but first allow crew to access the most critical sites. These habitats need to be designed within transportation limits and should be fully functional when they are delivered to the mission site.

The transportation system limits the mass and scale of a habitation system for performance and cost reasons which are primary drivers for the selection of reusable systems currently available and under development (as shown in Table 1). For more than 40 years after the Apollo program, the price of launch to orbit has been estimated to be about $10,000 per kilogram ($10 million per metric ton). Comparing this price to what SpaceX has been able to achieve with reusable rockets at about $2,000 per kilogram, we see a clear advantage in reusability. We investigated the dynamic volume, mass and dimensional limits of a variety of current and planned reusable transportation systems, including SpaceX's Falcon Heavy, Blue Origin's New Glenn launch vehicle, and the SpaceX Starship currently under development. We then studied each fairing's dynamic volume and dimensional limits. The Falcon Heavy fairing is 13.1 meters tall and 5.2 meters in diameter, made of an aluminium honeycomb core with carbon-fibre face sheets fabricated in two shells and assembled during encapsulation. This vehicle has a payload capacity to LEO of 63,800 kg (140,660 lb) and a dynamic volume of about 145 m^3. The New Glenn offers a fairing that is 21.9 meters tall and 7 meters in diameter, which results in a usable volume of 450 m^3, twice that of any launch vehicle currently in operation. It is designed to deliver a payload of 45,000 kg (99,000 lb) to LEO and is projected to begin launching payloads beginning in 2021. In September 2019, SpaceX's Elon Musk revealed the first prototype of Starship MK1. The spacecraft has a diameter of 9 meters and height of 50 meters will have the capacity to carry more than 100 metric tons (220,000 lb) to Earth orbit.

Reusability in space transportation will enable large payloads such as One Moon to be delivered affordably to the lunar surface with cargo and crew (see Figure 3). These reusable systems are all capable of carrying large payloads to LEO from where fuelled delivery vehicles will carry the first support and habitable systems to the Moon.

Table 1. Flight Systems

Launch Vehicle	Fairing Length	Fairing Cargo Volume	Mass to LEO	Mass to Moon
	m	m^3	tons	tons
Falcon Heavy	13.1	145	63.8	8.6
New Glenn	21.9	450	45	7.6
SLS	19.1	145	90	12
Starship Cargo Approx.	30 +	1,500 +	100 +	100 +

Vertical Habitat

The pressurized habitats are being designed as deployable multi-purpose modules. The first habitats will have to house multiple functions in one module. Subsequent iterations can be specialised for crew accommodations, scientific laboratories, food production, working, and touristic use. The diversity in functions underlines a fundamental need to remain flexible and develop an adaptable architecture.

The habitats will be comprised of a pressurized volume with numerous integrated systems including docking capability, environmental control and life support system (ECLSS), logistics management, radiation mitigation, fire safety, crew health equipment, scientific workstations and

Figure 3. Pre-flight view. The vertical habitat packaged before launch.

Figure 4. Habitat interior view. Working space and labs.

robotic control station. It will sustain a crew of four to six. 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 [11], identified inflatable structures as an enabling technology that would allow lighter weight structures at a lower cost. NASA has been experimenting with pneumatic or inflatable structures, which resist tensile forces due to internal pressure with flexible membranes, since the 1960s. Their main benefit is to reduce mass and to be folded and compacted in smaller volumes during launch and transport to the target location. Other key features are reduced loads while landing on the Moon or Mars and shorter manufacturing time [12].

The inflatable modules require a frame of rigid elements that hold the internal structure together during the large dynamic loads of launch, transfer, and landing [13]. These rigid elements then serve as the attachment points of the inflatable membrane. Most past designs starting with NASA's TransHab, place the rigid elements in a central core [14,15]. 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 easily permit windows to be placed along the perimeter structure. Here we propose an alternative configuration of a 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 psycho-social stressors of living inside a confined environment for a long term [16]. Stressors for human spaceflight associated with habitability, confinement, and isolation can lead to degraded performance, feelings of claustrophobia, and lack of motivation [17]. 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.

Providing increased volume to accommodate a crew of 4 for long-term missions of up to 500 days plus contingency days presents us with the challenge of designing an integrated habitat that can fit within the payload volumetric and mass constraints of current and near-term transportation technologies. To achieve this, we devised a parametric methodology using computational design technologies which allowed us to test varying payload limits including those of the Falcon Heavy, New Glenn, and Starship. Following NASA's STD 3001 Space Flight Human-System Standard, we identified safety, technical, and performance constraints at an early stage. This technical guide provided an understanding of human capabilities, limitations, and functions while also incorporating architectural standards to maximize performance and the human experience.

The structural designs for the habitat include a hybrid system composed of two key elements: the rigid composite frame and inflatable structural shell. The rigid structural frame consists of three columns (1200mm x 400mm) which are connected at the base and top. The composite floor system to support gravity loads spans between the perimeter columns and cantilevers out between them. In contrast to other inflatable designs, which centralize the structure and mechanical systems, this system liberates the central area, providing large double-height volumes between levels for increased mobility, programming, visibility, and flexible transportation of equipment. The perimeter columns also include windows at each level for visibility and are refined geometrically for structural performance during pressurization of the inflatable shell. The structural columns articulate those loads as concave geometry. Due to the increased complexity of operations and programs, the advantage of a perimeter structural system is to completely free the interior space, offering an adaptable spatial configuration (see Figure 4). Located around the vertical structural elements are mechanical shafts supplying water, oxygen, power and communication lines throughout the habitat. The mechanical system is supported by the security of a high-performance structure while also part of a continuous loop of shafts bringing these systems to every level and space. The inflatable shell is designed as a multi-layer system which includes a Nomex protection shield, a Vectran structural shell, Combitherm, Nextel with insulation foam interlayers, exterior protection shielding and micro-meteoroid and orbital debris shielding protection. This entire assembly is attached directly to the columns, with the structural shell woven directly into the columns to provide increased continuity in structure. The inflatable pressure vessel Vectran restraint layer allows the habitat to incorporate a complex geometry that interfaces with rigid structures such as airlock tunnels. Similar technology has already been tested by NASA with strength exceeding 9,000 lbs for every 1-inch-wide strap.

Additionally, our habitat incorporates radiation protection elements designed to provide passive radiation shielding from environmental radiation for the crew. We are

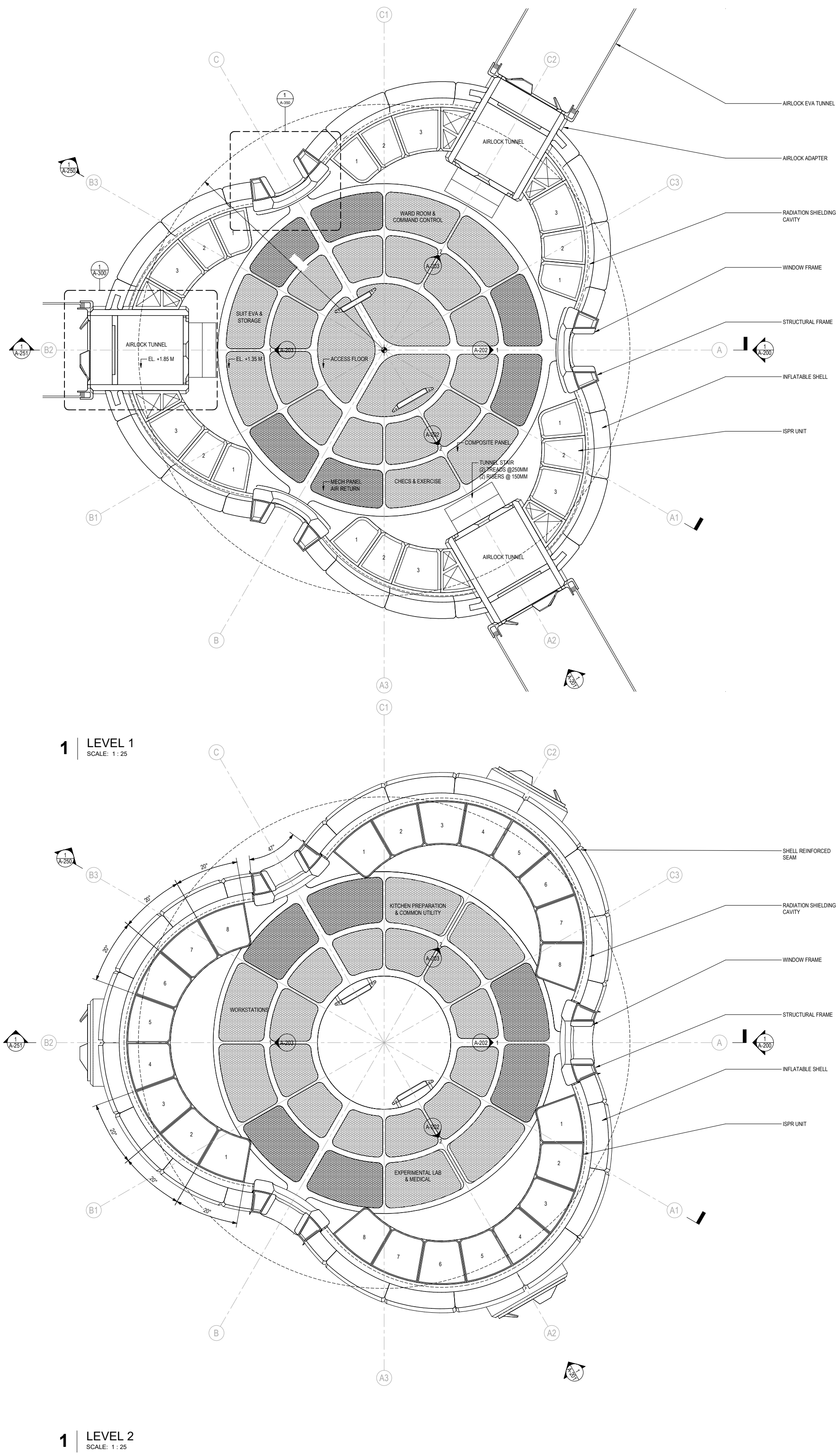

Figure 5. Plans. 1st and 2nd levels.

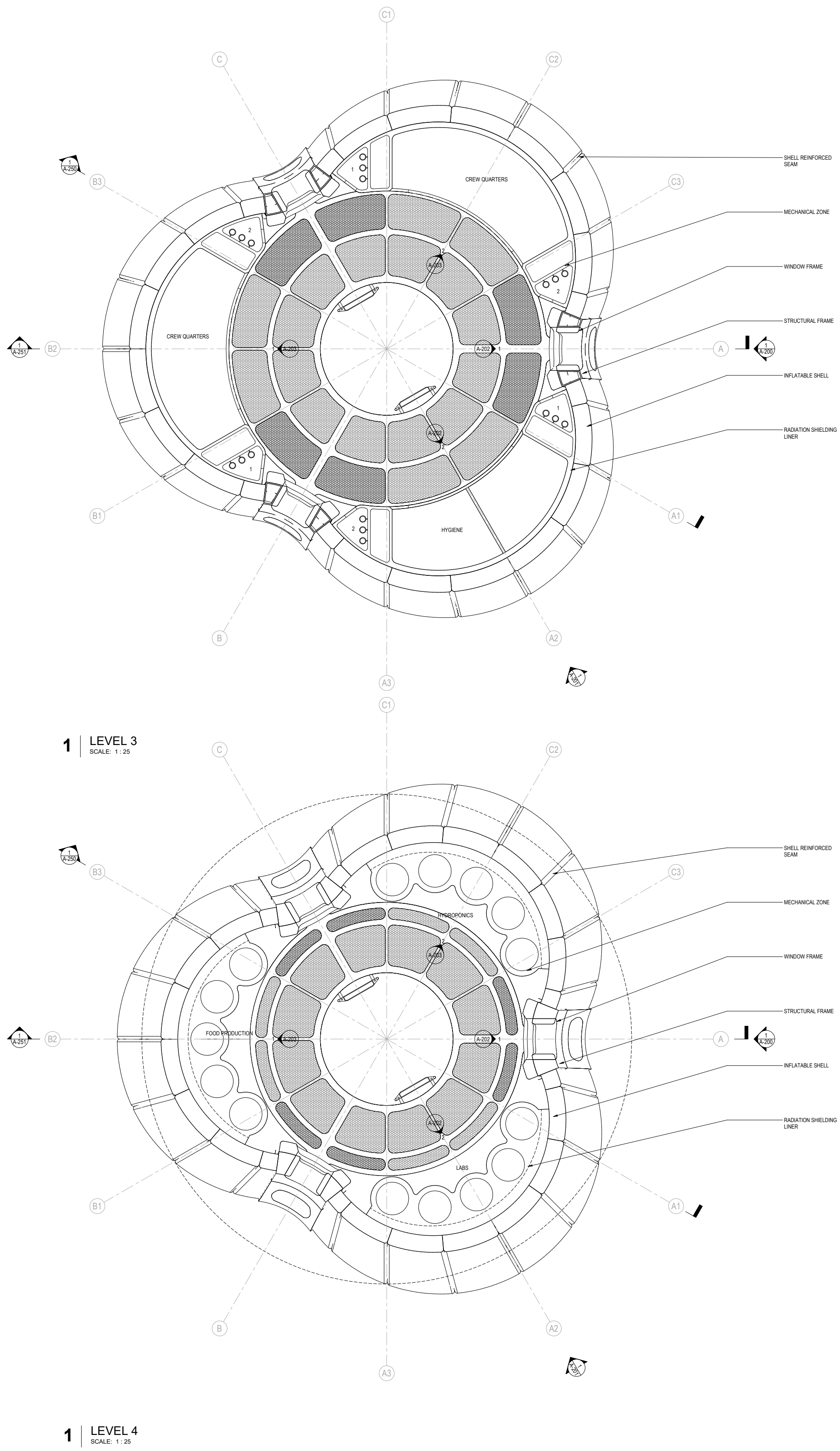

Figure 6. Plans. 2nd and 3rd levels.

leveraging the life support system as suggested by ESA to provide radiation protection in the form of water- and hydrogen-rich materials. The protection would be located and attached to the inner layers of the inflatable shell and include a liner with non-potable water. This system would need to provide enough radiation protection to achieve the allowable limits for one year of exposure on the lunar surface. The increased wall thickness to accommodate the water protection becomes an integral part of the life support system and is maintained by the mechanical shafts located along the primary structural columns.

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 is 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 elements and the science functions can be re-housed in a dedicated laboratory space [17].

The design team has focused closely at the habitation, radiation protection and thermal systems which are affected to a large extent by the design of a high-performance enclosure system. The habitation interface is responsible for accommodating the crew and their working, living and sleeping activities. This includes storage, the layout of programmed areas, food supplies, clothing management systems, fire suppressant, hygiene systems, housekeeping, workstations and other human related functions. Principles driving these sub-systems are derived from the human factors standards to adequately incorporate known constraints and limitations.

One Moon includes four levels with varying areas and volumes at each level, a result of the enclosures geometry and articulated structure. The ground level houses all EVA support and teleoperation stations for the crew to prepare and monitor surface activities (see Figure 5). Additionally, this level interfaces with connection adapters built into the shell. We also include a wardroom & command control function. The second level includes workstations, kitchen preparation, experimental laboratories and the medical station. All functions on the second level are contained within customized payload rack systems that include a variety of features such as compartments, working surfaces, translation aids, lighting and storage areas. The third level is designed for crew quarters and hygiene (see Figure 6). The crew accommodations come in two types: stacked units and divided units. This provides multiple opportunities for living conditions that are centralized and offer increased radiation shielding by jacketing the crew quarters with water. The fourth level includes hydroponic laboratories, experimental food production and other experimental labs. These additional programmatic elements provide the crew with an ability to supplement food needs and study biological systems.

It is important to emphasize radiation protection in the design, as it includes any system designed to protect the crew of environmental radiation and monitor that these systems are working properly. Radiation protection is primarily located at the enclosure including predictive measuring technologies for identifying solar particle events. The radiation protection shell technology in the design is a key architectural driver which offers advantages for increased volume and reduced mass. The ongoing work in this area will result in advanced methods of providing this feature by taking advantage of ISRU resources and regolith-based structures.

Life Support

Selecting the most optimal life support systems is imperative to support future human activities. Considering as a starting point a crew of four for long-term missions up to 500 days, any sustainable approach will be based on an appropriate closed-loop strategy for life support, to increase the usage level of resources, whether produced in-situ or not.

At an early stage of a Moon settlement with regular rotations of a crew of only four, one may not consider yet accomodating the on-site production of a significant part of the crew daily diet (typically 20% or more in mass). However, air revitalization, water-loop closure and potentially production of a food complement would be fully relevant. In that case, the ultimate waste/loss in oxygen and water could be compensated by the processing of in-situ available water resources.

Water, among the various metabolic consumables needed by humans, is by far the heaviest part of the daily bill: about 3 kg/day/crewmember as a minimum, and one may expect higher demand linked to hygiene and household-related uses [19]. Oxygen and food follow, representing each about 1kg/day/crewmember. Waste water is mainly composed of habitat condensates, water used for hygienic and household purposes—all together the so-called “grey waters” and urine.

These various Life Support functions and associated technologies are deeply investigated by space agencies and their contractors and partners. At ESA, the visionary approach lies in the controlled ecological concept of MELiSSA (Micro-Ecological Life Support System Alternative) (see Figure 7).

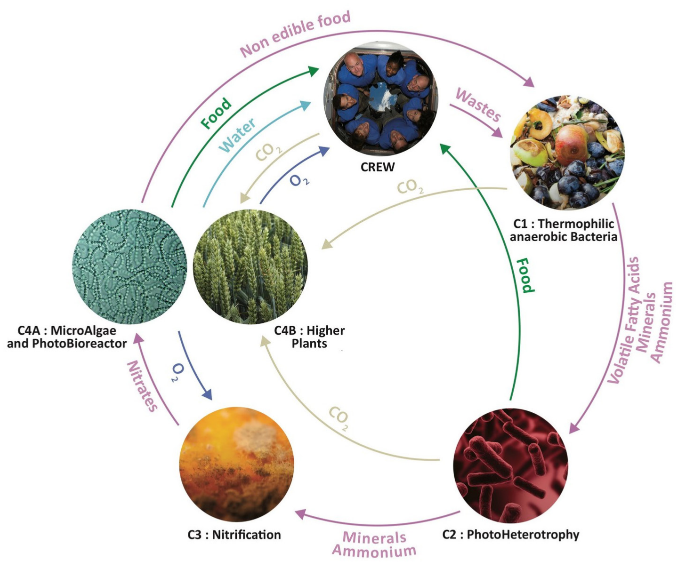

Figure 7. A schematic representation of the MELiSSA loop (courtesy of the MELiSSA Foundation)

From this fully closed loop approach, specific Life Support strategies and Life Support Systems architecture can be tailored to a given human exploration scenario, e.g. a Moon settlement, as described above (see Figure 7).

In the present context, when air revitalisation and water-loop closure are the main drivers, it makes sense to envisage a smart combination of water treatment technologies (membrane-based filtration, nitrification) integrated with a photosynthetic reactor. And if the photosynthetic reactor is colonised by a cyano-bacteria like Limnospira Indica (previously known as Arthospira Platensis, commercially available as Spirulina), a food complement, with a high protein content, can be produced and incorporated in the crew diet: a first step towards closure of carbon and nitrogen loops, on top of oxygen and hydrogen ones. The modularity of the proposed technologies will be an additional flexibility to accommodate them in the multi-functional structural and infrastructure concepts proposed here.

Human Factors & Support Systems

Human performance factors are of key importance in our design which places an emphasis on volume, lighting, floor area, privacy, intelligent interfaces and increased degrees of freedom throughout the habitat spaces (see Figure 9). One Moon has a net habitable volume of up to 390 cubic meters and a habitable area of up to 104 square meters (see Figure 10). Each program makes use of deployed volumes by placing all integral rack systems at the perimeter up against the inflated structural shell. This projection of the program is what allows the central spaces to be free of obstruction. The centralized zone is important for a variety of factors, including better control of ambient lighting conditions, air movement and efficient recycling system locations, higher degrees of communication and collaboration, promoting physical movement, and high visibility of working surfaces. Our approach to designing habitats goes beyond technical requirements, infusing methodology with architectural principles and technologies across disciplines to arrive at a solution distinct from those emerging in the established field of habitat design.

We aim to produce a highly integrated system that minimizes mass and maximizes structural and systems performance, with the potential for adaptation as future surface operations evolve. We are now in the final stages of schematic design with the goal to begin testing and building certain elements for validation in 2020 in partnership with ESA and other potential contributions. 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 individually. 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 concepts 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 not compromising 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)". This is a philosophy which we try to enhance though our parametric design methodologies [20].

Characterizing the physical requirements which embody 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. 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 behavioural 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 requires 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 integrated a wide range of requirements including configuration of equipment, translation paths, hatches, restraints, and mobility aids, windows, and collaborative environmental considerations.

Resource Development

The polar regions of the Moon have been identified as optimal locations for harnessing the power of the Sun for longer durations than at any other location. Studies by the Goldstone Solar System Radar (GSSR) group at the Jet Propulsion Laboratory using digital elevation models of the lunar south pole indicate high levels of illumination near Shackleton Crater. The analysis looked at various sites showing that the best sites are on the rim of Shackleton Crater and specifically along the western ridge where three sites have a multiyear average solar illumination between 90 and 97% and visibility of the entire Earth about 51% of each month. These sites on the western ridge also have 100% solar power generation capacity for 85 to 91% of the year. [21]. Using this study and ephemeris data we were able to identify potential sites for large scale development requiring the highest potential for energy, communications and resource development. Harnessing this near-continuous sunlight means that an architectural array of solar panels much be designed with a vertical configuration and placed at altitudes where the surrounding topography does not cast shadows on the solar arrays. The potential energy capture could provide power to habitats, mobility, robotic equipment, and ISRU operations.

There are also permanently shaded regions at the poles, deep inside the existing craters where water-ice exists from comet depositions. Surveys of the polar regions provide enough evidence to support the idea that enough water in the form of ice exists to support future human activities [22]. Lunar rocks are made up of minerals and glasses. Exposed rocks on the lunar surface are covered with impact craters whose diameters range from more than 1000 km to less than 1 μm. The impacting objects range from asteroids tens of kilometres in diameter to particles of cosmic dust a few hundred angstroms across, a range higher than 12 orders of magnitude. The effects on bedrock have resulted in excavation of craters, followed by shattering, pulverization, melting, mixing, and dispersal of the original coherent bedrock to various locations in and around the cratered regions. The process of lunar regolith formation can be divided roughly into two phases. The first phase is after some bedrock is exposed and regolith is thin (less than a few centimetres), when impacts can still penetrate the regolith and excavate bedrock. The second phase is reached when thickness of the regolith has increased to the point that impacts only disturb and mix the regolith already present, increasing thickness over time.

An assessment and surveying of local building materials begins first with characterization and then a functional approach. There will need to be a classification of materials that can naturally support design features such as tensile reinforcement, high- strength building foundations, and radiation shielding. After this classification is established, equipment would need to be designed and engineered for handling, beneficiation and extraction of necessary elements (such as aluminium or titanium). By identifying types of products and cataloguing their uses and performance metrics, a wide range of architectural possibilities can be achieved. Concurrently with industrial extraction processes and architectural design, it will be possible to to enable optimization and life cycle analysis for extracting natural resources and processing them for oxygen and water extraction [23], construction and manufacturing needs [24]. These construction needs would manifest in the form of disciplines that are directly linked to functional elements.

Table 2. ISRU Disciplines for Construction

Discipline	Element	Function
Granular Mechanics	Berm	Thermal Protection
Regolith Handling	Landing Pads	Radiation Protection
Civil Engineering & Construction	Roads	Structural Reinforcement
Regolith Transport	Shelters	Lander Plume Shielding, Dust Mitigation
Autonomous Manufacturing	Reinforcement Structures	Micro-Meteoroid Protection
Resource Processing & Production	Modular Structures	Habitation
Robotic Tele-Operation	Shell Structures	Infrastructure

The goal would be to enable a technical assessment and ranking of mineral processing options and requirements, which could then be compared to anticipated performance characteristics for constructed materials. Extraction of lunar surface material can be viewed as a component of an integrated solution that can address multiple goals and deliver architectural solutions to some of the most challenging environmental constraints while also developing methods for future planetary construction paradigms.

Computational design provides a unique platform for the development, integration, and implementation of lunar surface habitats. A detailed survey of the local terrain would be conducted to produce a highly detailed model for design and verification. A detailed digital analogue of the local area would provide the design and engineering methodology with a tool for extensive civil planning (excavation, levelling, collecting, constructing). During the integration process, the physical parameters and constraints associated with environmental conditions would be directly associated with a design to manufacturing method, where designed elements are optimized per function (berms, support pads, roads, structural reinforcement, shelters, etc.) to reduce cost, increase performance and optimize construction time. This would be an iterative procedure making use of parametric and digital automation at varying scales for primary, secondary and tertiary structural and functional elements. Finally, the implementation of designed elements would be contained in a repository organized into products and parts for each discipline (architecture, engineering, civil and operations) for modification and coordination efforts. A data management system for construction would allow logistical management, improvements and workarounds to take effect at various stages in the process. Computational tools are of key interest and mature methods which have been proven in the architecture, engineering and construction industry in highly complex building scenarios and would be essential in solving engineering challenges where teleoperations would play a major role.

Regolith-based additive manufacturing in a reduced gravity environment allows us to push the limits of structural performance using new material processes. In this case additive manufacturing techniques can be applied together with digital design methods to produce unconventional structural solutions. These solutions are then calibrated for efficiency using analytical methods such as finite element analysis, topology optimization and energy deposition simulation. By leveraging these analytical methods and a single digital design model, the engineering and safety factors can be addressed using analysis to target adequate material densities for structural loads and radiation shielding. Some of the analytical methods would include finite element analysis and topology optimization. These methods simulate the effects of real-world forces, loads, temperatures, velocities, displacements, pressures and structural properties. Bringing a high level of external information into the initial design stages would lead to minimized redundancies and the discovery of potential solutions not readily available using conventional design approaches. Using customized analytical tools globally and locally for designed elements would yield strategies for making the manufacturing and fabrication process more efficient. Understanding the limitations of regolith materials using computationally intensive processes allows us to push the limits of manufacturing in a constrained environment. Although the analytical techniques proposed here may be unfamiliar to aeronautical engineers, they are similar to the methodologies and tools currently in use for state-of-the-art architectural design as practiced at SOM.

We proposed multiple shell type structures that prioritize safety, functionality and performance. Shell structures are meant to be used for multiple purposes such as servicing large equipment and working in a protected environment that shields from high exposure to radiation. The shells are designed with a minimum of 500mm wall that is constructed from processed regolith and sintered using additive manufacturing with direct energy deposition techniques. The largest shell structures would span approximately 30 meters, allowing vehicular and storage equipment to be securely stored. Preliminary studies of these shell structures resulted in occupiable volumes of up to 1,815 m³. To economize material and energy, the shells vary in width from 1000mm to 500mm, with larger thicknesses at the base. Smaller shells would need to be designed for shielded, enclosed and pressurized conditions. Preliminary studies of these smaller shells span approximately 20 meters and include heights of up to 9.8 meters. Results have produced occupiable volumes of about 1,500 m³. In-situ construction can be utilized to produce a wide range of functional architectures that advance surface construction capabilities and produce solutions to multiple uses for a large-scale development (see Figure 11). Each shell structure is designed using finite element analysis and optimization methods. The possibilities for constructing highly functional shell structures using techniques which will be advanced on the Moon are already being tested in terrestrial applications and will pave the way for even larger surface construction techniques on extraplanetary surfaces.

Figure 9. Habitat interior view. Crew quarters.

70th International Astronautical Congress (IAC), Washington, DC 21-25 October 2019.

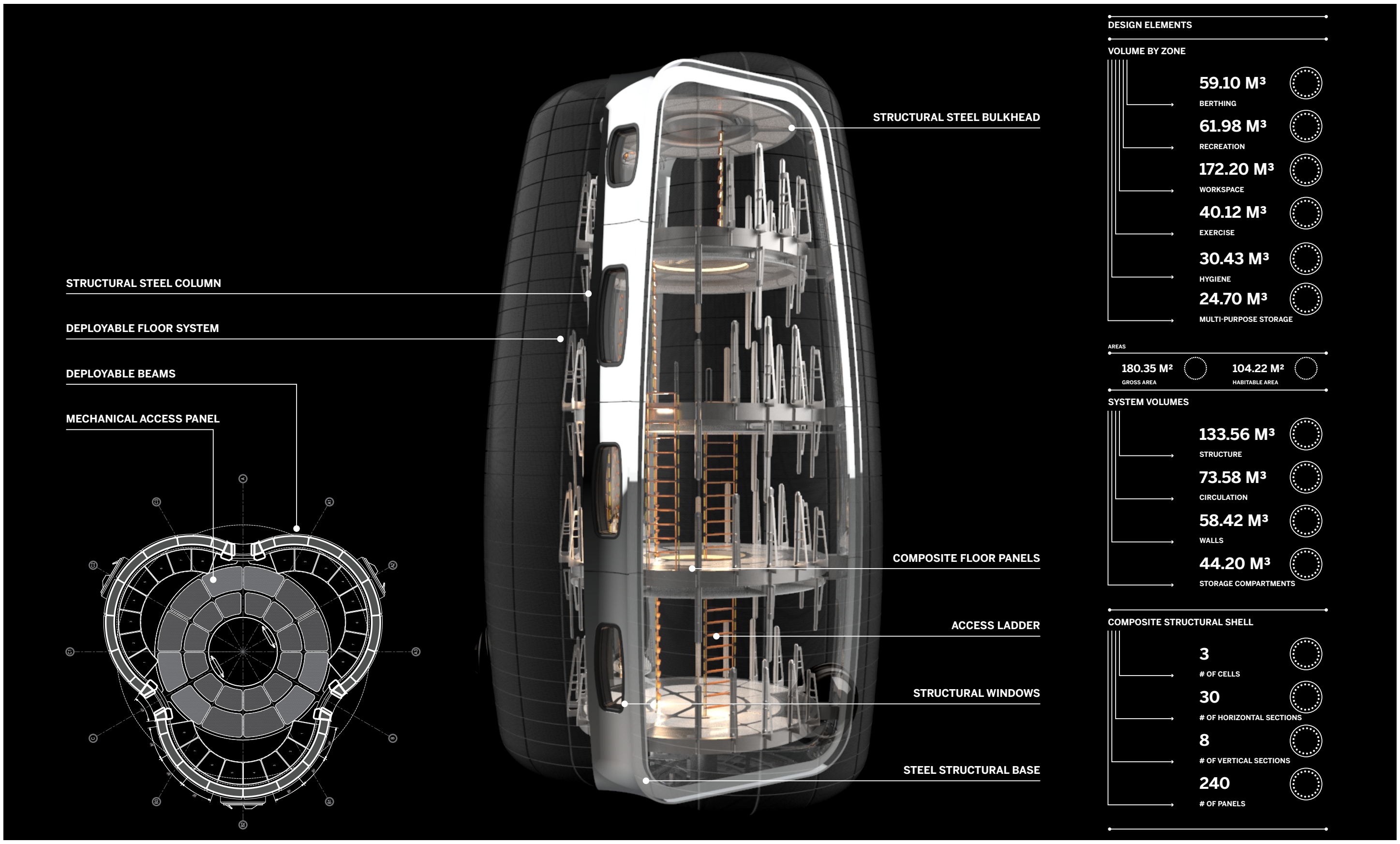

Figure 10. Habitat system calculations. Axonometric.

Figure 11. Moon Village development & ISRU construction. Aerial View.

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