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Mars X-House: Design Principles for an Autonomously 3D-Printed ISRU Surface Habitat

Melodie Yashar[1], Christina Ciardullo[2], Michael Morris[3], Rebeccah Pailes-Friedman[4]
SEArch+ (Space Exploration Architecture) LLC, New York, NY 10023

Dr. Robert Moses[5]
NASA Langley Research Center, Hampton, VA 23666

and

Daniel Case[6]
University of Colorado, Boulder CO 80309

MARS X-HOUSE V.1 and MARS X-HOUSE V.2 demonstrate architectural principles applied through an evidence-based design process supporting two concepts of operations for autonomous construction of a pioneering and durable habitat supporting future human missions to Mars. The two habitat designs have evolved in parallel to research advancing the viability of cementitious 3D-Printing in off-world construction, and present a scheme to develop an ISRU-based concrete material for future Mars infrastructure as well as habitat development. SEArch+ and Apis Cor are participants within NASA's Phase III Centennial Challenge for a 3D-Printed Habitat on Mars, winning first place in Construction Levels 1 and 2, fourth place in Virtual Design Level 1 (60% Design), and first place in Virtual Design Level 2 (100% Design). MARS X-HOUSE celebrates innovations in radiation shielding techniques while allowing natural light to penetrate the structure, supporting the astronauts' physiological and psychological well-being in a long-duration mission. Our human-centered approach prioritizes safety, redundancy, and the wellbeing of the crew above the Martian surface. Rather than burying habitats underground or entombed within regolith, the designs of MARS X - HOUSE seek to exceed current radiation standards through a combination of thermoplastic, fibrous, and cementitious materials while safely connecting the crew to natural light and views to the Martian landscape. In conversation with ISRU, planetary, and radiation experts, new studies (Cucinotta et al.) indicate that the density of Mars atmosphere along the horizon can allow light transmission up to 30° above the horizon. This critical finding essentially enables a relaxation of constraints and supports architectural concepts featuring windows and apertures allowing vistas to the Martian surface. Additionally, interior partitions, load-bearing walls, and interstitial material layers are parametrically optimized to provide greater radiation protection to programmatic areas inhabited most frequently by the astronauts. Research indicating whether concrete structures may indeed contain an atmosphere in off-world conditions remains inconclusive. The evidence-based design process of MARS X-HOUSE 1 and 2 advances research supporting the structural and material development of additively-manufactured airtight structures, essential for the development of future surface habitats on the Moon and Mars.

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[1] Co-Founder, Mars X-House Team / Project Leader, SEArch+ Space Exploration Architecture
[2] Co-Founder, Architect, SEArch+ Space Exploration Architecture
[3] Co-Founder, Architect, SEArch+ Space Exploration Architecture
[4] Co-Founder, Industrial Designer, SEArch+ Space Exploration Architecture
[5] NASA Langley Research Center
[6] Ph.D. Candidate, Aerospace Engineering Sciences, University of Colorado – Boulder

Nomenclature

3DP = 3D-printing
AAC = automated additive construction
ACME = Additive Construction with Mobile Emplacement
BIM = building information modeling
ECLSS = environmental control and life support systems
EDL = entry, descent, landing
GCR = galactic cosmic rays
HDPE = high-density polyethylene
ISRU = in-situ resource utilization
MEP = mechanical, electrical, plumbing
NASA = National Aeronautics and Space Administration
TRL = technology readiness level
USACE = United States Army Corps of Engineers

I. Introduction

FUTURE missions transporting humans to the surface of Mars are dependent on the creation of safe, durable and protective housing. The first permanent settlements on Mars will be semi-autonomously constructed prior to a crew's arrival. Such settlements will require the use of local and indigenous materials as well as pre-integrated habitat systems and technologies brought from Earth to support robotic assembly and construction. Perhaps the most important principle within the scope and parameters of semi-autonomous construction for future surface habitats is situ resource utilization (ISRU), as materials and resources brought from earth must be highly restricted to mission-critical equipment. Due to the extreme cost of transport, relying on a habitation system brought entirely from Earth is not a sustainable strategy for autonomous surface habitat construction.[1] As cargo support flights will likely only occur every two years, minimizing payload elements to high-technology equipment that cannot be produced locally is absolutely crucial to the economics of a sustainable Mars mission. Payload mass-optimization is thus a major rationale for ISRU manufacturing of materials, technology, and resources supporting surface habitat construction. A future surface habitat will be crucial to perform high-value scientific and engineering research and to grow a single pioneering outpost into a larger permanent settlement.

The next logical step for ISRU habitat construction is the integration of existing in-space manufacturing processes with advanced additive manufacturing and autonomous robotic assembly technologies. However, research supporting large-scale additive manufacturing within micro- and reduced-gravity environments using cementitious 3D-printing is still in its infancy. The term automated additive construction (AAC) has been coined to refer to automated processes for large-scale civil engineering structures that differ from small-scale and high-precision manufactured parts representative of a majority of additive manufacturing prototyping and build processes to date.[2] To advance the viability and technology readiness of additively manufactured ISRU surface habitats, research must be undertaken not only in materials science and technology development for extrusion mechanisms supporting automated construction, but likewise in the development of construction schemas and sequences supporting an architecture most appropriate for compression structures in an off-world environment as well as the overall success of a surface mission to Mars.

Mars X-House is a joint design and construction prototyping project undertaken collaboratively by SEArch+ and 3D-printing technology company Apis Cor, to envision architectural solutions employing large-scale additive manufacturing techniques in the context of a Mars mission. The following is a discussion of the architectural, environmental, and constructability principles which guided the evidence-based design process, which may apply to future concepts for the AAC of ISRU surface habitats.

A. NASA Centennial Challenge Phase 3: Motivations and Context

The design of Mars X-House was undertaken in the context of a multi-year competition sponsored by NASA and Bradley University, with Caterpillar, Bechtel, and Brick & Mortar Ventures. SEArch+ with Clouds AO won 1st place in NASA's Phase 1 Centennial Challenge for a 3D-Printed Habitat in 2015.

The Phase 3 3D-Printed Habitat Competition is a NASA Centennial Challenge organized with the intention to not only endorse future visions of Martian surface habitats, but asks participating teams to autonomously construct a structural prototype or preliminary terrestrial analog of the habitat structure at 1/3 scale using state-of-the-art additive manufacturing technologies. The competition asks for a habitat proposal supporting a crew of four for one earth-year, and culminates with a live demonstration of 3D-Printing the structure as well as robotic placement and integration of a scaled-down rover port, view port or vision window, and suit port. The Phase 3 3D-Printed Habitat Competition is subdivided into multiple Virtual Design as well as Construction submission levels, with an ultimate intent of advancing the applicability of building information modeling (BIM) to large-scale additive manufacturing projects. In the context of Mars, advanced BIM techniques would enable the robotic deployment system of the habitat to read and scan the terrain, and introduce the information in the model to the robotic platforms on-site, and subsequently cue the deployment or actuation of the printing process.[3] BIM enables us to simulate the full construction sequence of the habitat, and eventually, data-capturing technologies will be able to check the process in real-time to ensure that errors and failures are avoided.[3]

A goal of *Mars X-House* has been to investigate and synthesize the constraints of the competition rules and parameters with the design of an autonomously-constructed structure for human habitation, including the constraints of the head-to-head competition, the constraints of current technologies and material developments. The designs presented herein contain some restraints based on the parameters of the competition brief and deliverables that would perhaps not otherwise be placed in the Mars mission context.

B. Same Principles, Two Architectures: Mars X-House Version 1 and Version 2

The Design Development of *Mars X-House* resulted in two viable structures which responded fundamentally to shared design drivers in regards to radiation protection, human factors needs, and mission constraints. The paper will go on to describe the fundamental mission, human, architectural, environmental, and constructability drivers that guided two unique architectural resultants.

There are three classes of extraterrestrial space architecture: Class I is best characterized by the ISS, which is a pre-integrated hard-shell module tested and integrated on Earth. Class II habitats are prefabricated and surface-assembled modules such as inflatable structures. Class III space habitats utilize ISRU to derive structures that integrate with Class I and II modules.[4] Mars X-House presents two iterations of surface habitat designs representing approaches to Class III space architecture.

The most mission-critical structures to support human crews are to provide appropriate protective habitats—shielding the crew from galactic cosmic rays (GCRs) and solar energetic particles. SEArch+'s human-centered approach prioritizes safety, redundancy, and the wellbeing of the crew above the Martian surface. Rather than burying habitats underground or entombed within regolith, the designs of Mars X-House seek to exceed radiation standards while safely connecting the crew to natural light and views to the Martian landscape. Mars X-House presents two alternative comprehensive habitat designs that explore concepts of operations for autonomous construction, ECLSS and MEP systems integration and a method of living that not only supports human life but would enable pioneering astronauts to thrive on Mars.

Mars X-House 1 responded to the use of bulk surface material regolith as primarily a compressive material. Compression-intensive structures have not typically been used in space due to the fact that pressure differentials are expanding forces that are more efficiently managed using tensile structures. Building on years of research into inflatable structures, the 3D-printed regolith portion of the habitat was mainly conceived as radiation shield. Two redundant inflatables brought from Earth constituted the habitable area while the design and construction of the structure overall responded to expressive possibilities for the regolith shield, which was generated as a formal resultant from environmental and internal planning constraints.

Mars X-House 2 is based on the same environmental and architectural principle as Mars X-House 1 but assumes and supports the competition challenge brief that the 3D-printed structure may also provide the necessary pressure boundary. By developing a form which maximizes the compression forces of regolith to respond to outward pressure, in addition to integration of ISRU basalt fiber reinforcement to take additional tension forces, ISRU high density polyethylene (HDPE) as a non-porous lining and protection, Mars X-House 2 developed into a multi-level habitat which imagined the potentials of creating habitats without the need for additional Earth-constructed enclosures.

Both Mars X-House 1 and 2 followed the same architectural principles and through the rigorous and evidence based design development process led to different and specific results out of the same human-centered approach for health and safety with material and methods for autonomous fabrication at the core.

Figure 1. Left: Mars X-House 1. Right: Mars X-House 2

II. Constructability and (ISRU) Material Drivers

A. Background of 3D-Printing for Space

3D-printing has reached new heights in the aerospace industry. Perhaps one of the most visible applications of 3D-printing occurs on the International Space Station by astronauts to 3D-print with plastics a variety of items for educational to proof-of-concept projects. 3D-printing serves as a fast and inexpensive way to manufacture parts on-site and on-demand, reducing the need for costly spares on the International Space Station and future spacecraft. Long-term missions would benefit greatly from having onboard manufacturing capabilities. Data and experience gathered in this demonstration improve future three-dimensional manufacturing technology and equipment for the space program, allowing a greater degree of autonomy and flexibility for astronauts.

With a renewal of human missions to Mars and now a strong push to return to the Moon, NASA continues to examine opportunities to increase mission success and long-term program sustainability by using in situ resources instead of bringing everything from Earth. Those studies indicate the need to implement on the Moon and Mars several construction and manufacturing activities as early in the mission timeline as possible. Not only does building with in-situ resources on Mars reduce the overall launch mass for Martian missions, but research into the innovative use and production of building materials made from the Martian environment brings Martian surface habitation one step closer to Earth independence.

On the Moon, printing with regolith and basalt is desirable for horizontal structures such as landing pads and driving aisles and vertical structures such as berms, shielding, and unpressurized structures, and pressurized habitats.[5] The vast quantities of water and carbon dioxide on Mars as well as regolith and basalt offer opportunity to 3D-print spare parts out of plastics as well. High-density polyethylene (HDPE) is a material that will be produced using local ethylene resources on Mars. Methane fuel produced by the Sabatier reaction is expected to be a necessary component of future Martian missions derived from subsurface water and atmospheric carbon dioxide. Methane may then be polymerized to form complex hydrocarbons via the Fischer Tropsch process, including plastics. While this is an energy intensive process, it is expected that Martian missions will need to be energy rich to ensure crew and mission safety. A portion of polymer production may also be generated by grinding, melting and re-cycling packaging and other expendable materials from the spent spacecraft. Additional plastics can be made using similar processes. If these items cannot be created from resources on Mars, then the number of launches from Earth to Mars will need to increase considerably which makes the human missions to Mars unsustainable.[6]

Successful penetration of 3D-printing into domestic and aerospace applications provides an incentive for others to explore its use in other industries. The National Academies and the Transportation Research Board (TRB) are sponsoring the First International Conference on 3D-Printing and Transportation during November 2019 in Washington, DC. The objective of this conference is to share knowledge and information on how 3D-printing in construction and manufacturing is impacting the transportation industry, including impacts on freight, air, marine, rail, space explorations, energy efficiency & sustainability, safety & security, education & workforce development, and policies & regulations.

B. Adapting 3D-Printing Technologies from Earth Construction to Space Missions

The development of 3D-printing for the building industry is still in the early infancy of scaling up from small, table-top object prototypes into large and inhabitable structures. Our industry partner, Apis Cor, is an established leader in the arena of additive construction and best known for achieving significant results in radically reducing material costs, construction time, and for producing unique architectural forms. While construction of 3D-printed buildings on Earth becomes closer to a present day reality, there are modifications to the technology, material, and construction procedures required for a Mars or Moon mission scenario.

1. Field Robotics

Robotics for construction on Earth are made to be mobile. Apis Cor has developed a rotational gantry arm that can be transported between locations and fits on standard mobile platform. Yet the constraints for transport and weight for a Moon or Mars mission mean the equipment used to raise, lower, rotate, and reposition the print head will need to be smaller and lightweight. Many have suggested the use of multiple smaller climbing robots, and there are a few in development for Earth construction.

Figure 2. **Left: Apis Cor 3D-Printing Earth construction with gantry crane. Right: Modified Apis Cor radial gantry.**

Following NASA's Design Reference Architecture for Human Missions,[7] and in conversation with EDL and ISRU experts, we employed the Hercules Single-Stage Lander[8] to precisely deliver payload of machinery, equipment, and supplies, including the necessary printing arms, excavation robots, and undeployed airlocks and inflatables (further payloads will be necessary for additional equipment such as the rover vehicle). For Mars X-House, the design for a mobile 3D-printer as well as mobile platform have been developed based on both Apis Cor's current construction technologies as well as the size constraints of the Hercules lander. The printer deploys on-site through an innovative telescoping mechanism at the base. It also features a six-axis robotic arm connected by a boom-arm system which deposits material at the print head. A mobile telescoping platform has also been developed for supporting two mobile printers during the printing process and minimizes the risk and costs involved in developing an overly tall gantry system for the printing technology. The mobile printer has been designed to fit in the 6-meter circular payload bay and the 20 ton limit of a Hercules lander.

2. The Pressure Environment

The most significant difference between Earth and space construction may be the pressure environment. Although Earth buildings in extreme climates are generally fairly sealed to prevent thermal leakage, most Earth architecture does not consider a pressure differential as a significant structural driver. As such, 3D-printed materials must be made to take tensile forces.

A major challenge for structural applications of 3D-printed concrete is the lack of tensile strength and ductility due to a lack of reinforcement. One approach might be to design a structure with limited applicability to compression loads, thus obviating the need for tensile strength. However, even compressive structures require a certain robustness and impact resistance.[9] One concept developed by TU/Delft demonstrates in-process applied cable reinforcement to embed various types of cables. Another solution is to print fiber reinforced concrete.

Currently within Apis Cor's concrete 3D-printing system, steel reinforcement members are manually inserted by an on-site crew at distinct intervals within the printing process. In a Mars context and for an ISRU surface habitat, the reinforcement method must however integrate with the 3D-printing system either within a separate end-effector depositing reinforcement material in real-time from the same industrial print head, or from a separate 3D-printing robot altogether.

3. Development of Necessary ISRU Materials

Materials for use off Earth will be different than Earth construction as well and will be required to print, cure, and operate in the extreme of Martian temperatures and vacuum conditions. In-situ printing materials will need to be sourced, either mined from the soil or extracted from the atmosphere, and adapted for use in the printing process.

a) Regolith

As the most obvious and abundant material on planetary surfaces, printing with regolith is a high priority. Printing with regolith, the Additive Construction with Mobile Emplacement (ACME) project is developing technology to build structures on planetary surfaces using in-situ resources. The project focuses on the construction of both 2D (landing pads, roads, and structure foundations) and 3D (habitats, garages, radiation shelters, and other structures) infrastructure needs for planetary surface missions. The ACME project seeks to raise the technology readiness level (TRL) of two components needed for planetary surface habitation and exploration: 3D additive construction (e.g., contour crafting), and excavation and handling technologies (to effectively and continuously produce in-situ feedstock). Additionally, the ACME project supports the research and development of new materials for planetary surface construction, with the goal of reducing the amount of material to be launched from Earth. ACME is a joint venture between NASA's Space Technology Mission Directorate Game Changing Development Program and the United States Army Corps of Engineers (USACE). The USACE is interested in the additive construction technology as a means to build Army structures to enable field operations. The ACME project will help USACE minimize the number of people it takes to build a structure, minimize the amount of time it takes to build a structure, allow digital design and 3D printing of structures to resemble local buildings, and reduce the amount of material brought into the field and waste produced by the construction process. These goals are similar to those of NASA in the establishment of planetary surface mission infrastructure.

At the same time, regolith is understood to contain perchlorates that are toxic to humans. Every design effort has been made in to protect the human inhabitants from direct or indirect regolith exposure. In Mars X-House 1, the innermost layer to come in contact with the crew was a pre-integrated inflatable. In Mars X-House 2, regolith was lined with HDPE.

b) Basalt

Basalt plays an important role in 3D printing on the Moon and Mars where it is abundant and easily accessible within the regolith. By heating basalt, basalt fibers can be made through a simple extrusion process. Basalt fibers are twice the strength of steel and only about one-third the weight. On Earth, rebar and other extruded components made of basalt fiber are replacing many steel items typically used in construction.[10] Pacific International Space Center for Exploration Systems (PISCES) has been working with Hawaiian basalt as a feedstock for ISRU (in-situ resource utilization) to create novel materials for sustainable products on Earth and in space. Hawaii's basalt meets the specific chemical profile needed to manufacture CBF, a material similar to fiberglass and carbon-fiber. CBF products possess favorable characteristics including resistance to corrosion and heat, and high tensile strength. Globally, CBF manufacturing is valued at around $100 million and expected to double in the coming decade.

c) Plastics

Plastics will be an additionally critical material to support construction in space. It would provide a non-porous boundary layer for air-tight structures, a layer of shielding from potentially toxic regolith, and also provide for many additional components of the architecture such as window, walls, doors, and floors.

Plastics such as HDPE will be produced using local ethylene resources on Mars. Methane fuel produced by the Sabatier reaction is expected to be a necessary component of future Martian missions derived from subsurface water and atmospheric carbon dioxide. Methane may then be polymerized to form complex hydrocarbons via the Fischer Tropsch process, including plastics.[2] While this is an energy intensive process, it is expected that Martian missions will need to be energy rich with nuclear power to ensure crew and mission safety.[11] A portion of polymer production may be generated by grinding, melting and re-using / re-cycling materials from the spent spacecraft. Additional plastics can be made using similar processes. Polycarbonate windows can also be made with in-situ materials. Polycarbonate has high visual transmissivity offering the potential for true vision windows necessary to connect the crew to their new landscape.

III. Mars Environmental Drivers & Resultant Architectural / Formal Principles

Environmental drivers dominate the formal, material, and organizational choices for habitat design in extreme conditions, and yet architecture evolves from a human-centered design approach in which these environmental drivers, rather than offering limitations of habitat design, offer possibilities for invention and innovation when considered holistically with human needs.

We take as a baseline principle the idea that human beings sent to the Martian environment will want to experience their new landscape visually especially with natural light and views to the Martian landscape. The resulting architecture represents a systemic approach which incorporates each environmental driver and creates an architecture with humans at the center. Each environmental driver offers a number of possible architectural solutions, many incorporating and re-interpreting lessons learned from passive architectural design.

A. Radiation Environment

1. Radiation Considerations for Mars Missions

The radiation environment on the Martian surface is predominantly composed of a diverse mixture of particle species at a wide variety of charges and energies.[12] Like the radiation environment in interplanetary space, many of those particles originally come from galactic cosmic rays (GCRs) or solar particle events (SPEs), although there are a few important differences that make the Martian surface environment unique. First, the Martian surface reduces the solid angle for space radiation exposure by approximately half relative to interplanetary space; the planet itself provides a large amount of material shielding beneath the astronauts' feet. Second, the Martian atmosphere is expected to provide 16-22 g/cm^2 of material shielding (mostly carbon dioxide) in the vertical direction; although it may not sound like much, it can be enough to attenuate and fragment some of the primary particles, thereby changing the composition of the particle spectrum relative to interplanetary space.[13] Furthermore, the amount of material shielding provided by the atmosphere depends on the angle of inclination; it is 16-22 g/cm^2 at the zenith angle, but it can be >100 g/cm^2 in the direction of the horizon.[13] Third, the Martian surface has 'albedo' particles, including neutrons, which are produced when the primary particles fragment in the shallow Martian subsurface.[14][15] And fourth, the dose rates on the Martian surface may undergo minor diurnal and seasonal fluctuations because the mass of the atmosphere is affected by a strong thermal tide.[16]

2. Material Choice / Passive Shielding

One of the predominant ways to protect astronauts from space radiation exposure is to use passive shielding. Passive shielding uses a physical material, placed between a source and a target, in order to attenuate radiation before it can reach the target. On the Martian surface, the habitat structure provides passive shielding, acting as a layer of protection between the space radiation and the astronauts. The principles for providing passive shielding are well documented; the energy loss by the incident particles in the medium is driven by electronic stopping,[17] while the fragmentation processes are the result of inelastic nuclear interactions.[18] [19] [20] The mass electronic stopping power[‡‡] (S/ρ) is directly proportional to the electron-to-mass (z/A) ratio of the medium:

$$\frac{S}{\rho} \propto \frac{z}{A} \tag{1}$$

[‡‡] I.e., the stopping power per unit mass of material.

Hydrogen is the most electron dense element per unit mass, thereby providing a basis for using hydrogen-rich materials as passive shielding. The likelihood of an inelastic nuclear interaction (σ) is dependent upon the sizes of the projectile and target atoms (A_P and A_T , respectively), such that:

$$\sigma \propto \left({A_P}^{1/3} + {A_T}^{1/3} - \delta\right)^2 \tag{2}$$

Hydrogen has the smallest atomic mass of any element, once again making hydrogen-rich materials advantageous to use as passive shielding, except this time because they are less likely to induce fragmentation in the incident or target nucleus.

The efficacy of passive shielding is driven by three things: material selection, thickness, and order. The importance of material selection essentially falls out of the above equations; some materials will be more effective than others at attenuating space radiation. In particular, habitats constructed from aluminum-2219[§§] or pure Martian regolith[***] will provide similar shielding per unit mass, but polyethylene[†††] will be significantly more efficient per unit mass. With respect to material thickness, thicker materials tend to provide more opportunity for attenuation as incident particles attempt to pass through. However, for metals and metal-like materials, fragmentation processes can actually increase the dose equivalent behind shielding at moderate thicknesses (>20 g/cm^2).[21] The same behavior is not observed in hydrogen-rich materials, presumably because more electronic stopping and less fragmentation is taking place. Finally, when there are multiple shielding materials, the order of those materials also makes a difference in the shielding efficacy of the layered composite. This principle can be notably relevant in satellite design, where graded-Z shielding can be used to provide aluminum-equivalent protection at a reduced mass.[22] In the context of habitat design, using a hydrogen-rich material as an interior lining for both regolith shielding and a metallic pressure vessel enables a habitat designer to reap the benefits of all three: the regolith provides in situ shielding, the metal provides structural integrity and holds pressure, and the hydrogen-rich lining helps attenuate both primary and secondary particles.

Mars X-House 1 relies on regolith alone to provide passive radiation shielding. The exterior layer is 3D-Printed regolith, taking advantage of the natural, in-situ shielding materials available on the Martian surface. Within the regolith layer is an aluminum alloy pressure vessel, ensuring that the burden of holding pressure does not fall on 3D-printed material. Additionally, a layering approach was used. In areas where astronauts spent less time, only half of the thickness was required, but by creating multiple layers of walls equivalent to 1m of thickness the habitat's most inner areas were more thoroughly shielded.

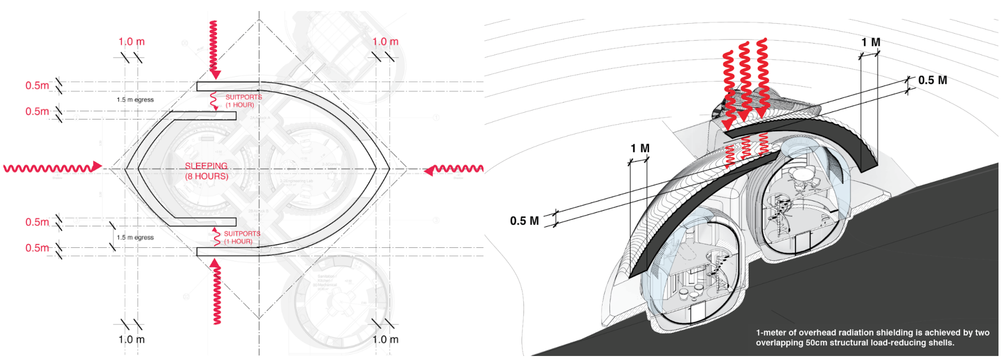

Figure 3. Layered Wall concept Mars X-House 1

Mars X-House 2 makes use of regolith as both radiation shielding as well as a structural pressure retention layer. As the function of the 3D printed layer needed to respond to this new constraint, a layered wall section that included

§§ Aluminum-2219 properties: z/A ≈ 0.480 electrons/nucleon; ρ ≈ 2.84 g/cm^3.

*** Martian regolith properties: z/A ≈ 0.499 electrons/nucleon; ρ ≈ 1.7 g/cm^3. Note that these quantities are dependent on the landing site.

††† Polyethylene properties: z/A ≈ 0.571 electrons/nucleon; ρ ≈ 0.96 g/cm^3.

a thinner layer of regolith shielding with a thicker layer of high-density polyethylene (HDPE) was utilized. The innermost layer scavenges the primary and secondary particles before they can reach the astronauts.

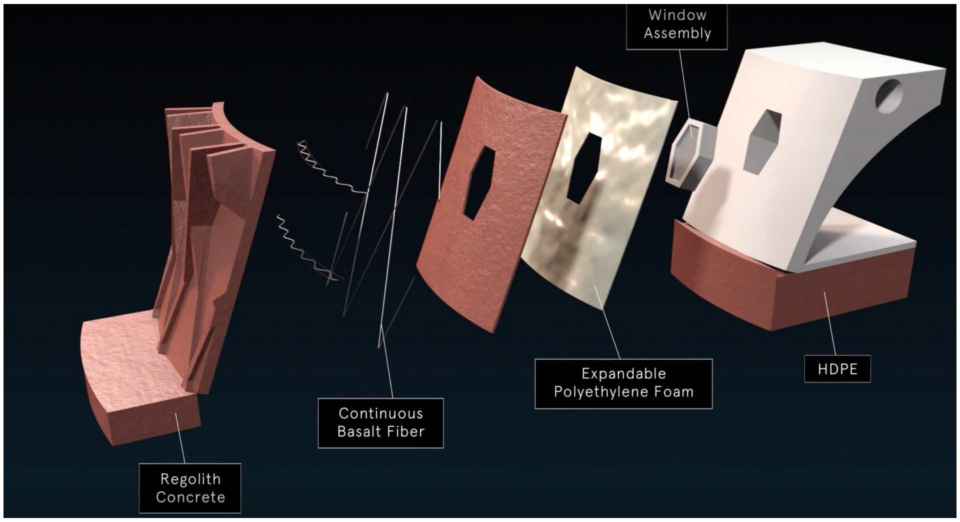

Figure 4. Layered Wall Composition Mars X-House 2.

3. 30° Relaxation

For inclination angles <30°, artificial passive shielding is less necessary because the atmosphere provides >40 g/cm^2 of material shielding at inclinations so close to the horizon.[23] This enables natural light to be incorporated into the design without compromising the shielding capabilities of the habitat. This essential relaxation of the radiation requirements allows a multitude of potential opportunities to introduce both natural light and vision windows: two things regarded as essential for human psychological well-being and connection to their new environment. Each design developed from this essential principle, that natural light and views be brought into the habitat while offering essential protection from higher incident rays.

Solutions to the radiation environment stem from examples of light control in earth-based analogues in which horizontal light is favored and brought into the structure for diurnal lighting and vision windows, while radiation from higher incident angles is shielded.

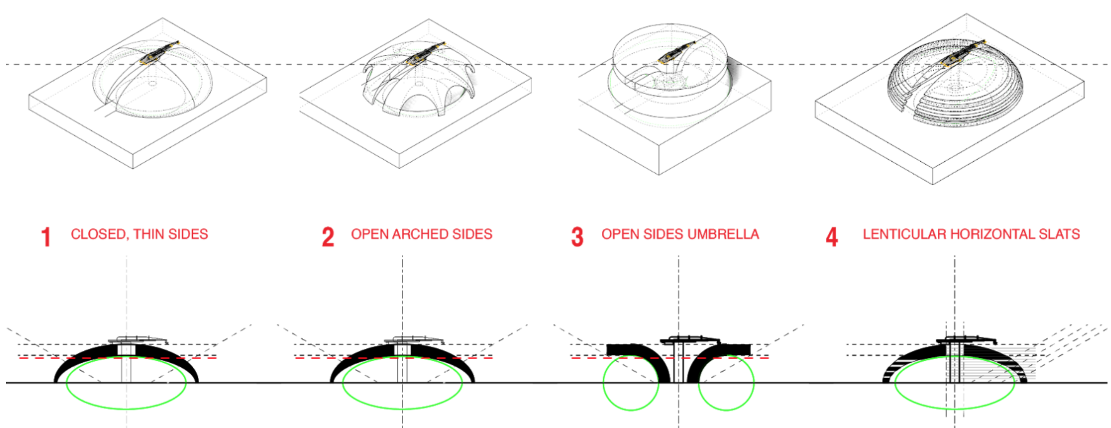

Figure 5. Exploration of design responses to allowing 30 degrees and below of horizontal lighting. *Here shown as part of architectural process drawings which included printer constraints.*

a) Light Scoops

In high northern latitudes, where sunlight is lower to the horizon, horizontal light is brought deeper into a building through the use of "light scoops." Similar techniques are used to bring indirect light into spaces such as art galleries where direct sunlight is undesirable but indirect light is directed in, reflected, and bounced into deep interior spaces.

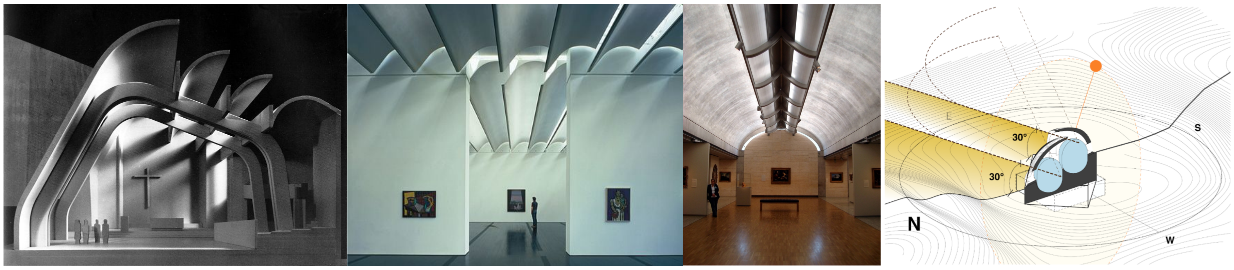

Figure 6. Examples Light Scoops and Indirect Lighting. *Alvar Aalto (Church of the Three Crosses), Renzo Piano (Menil Art Gallery), Louis Kahn (Kimbell Art Museum). Right: Mars X-House 1 showing light scoops allowing indirect natural lighting.*

Mars X-House 1 makes use of a stepped program to introduce a light scoop which brought horizontal lighting deeper into the habitat. Translucent inflatable walls collected, bounced, and reflected the indirect light into the interior, creating a light-filled interior within a regolith shield.

b) Overhangs

One typical technique of shielding high angle radiation is a simple overhang or colonnade. In hot climates, high angle solar radiation is blocked to keep the building cool. While the X-House does not shield solar radiation in the same way, it is analogous to shielding high angle particles.

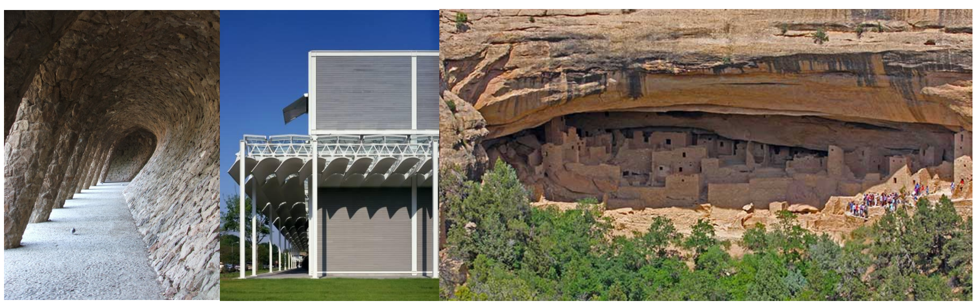

Figure 7. Examples Architectural Shading with Overhangs. *Gaudii (Park Guell), Renzo Piano (Menil Art Gallery), Anasazi Architecture*

c) Window Depth

These lighting solutions can be applied at a number of scales. ***Mars X-House 2*** resolves the overhang at the scale of the window. The depth of the wall essentially provides an overhang at a smaller scale, rather than the scale of the entire building.

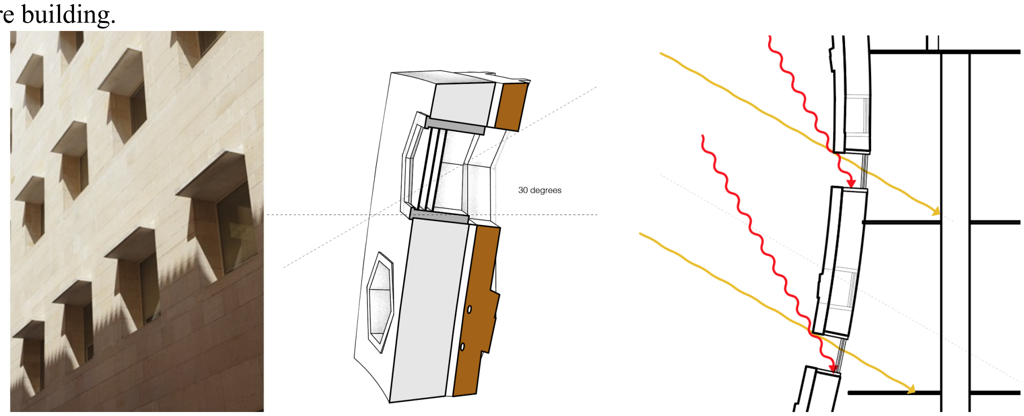

Figure 8. Example: Deep Windows. Rafael Moneo (Murcia Town Hall), Mars X-House V.2 Window depth

B. Pressure Environment

At about 0.6% of Earth surface pressure, the greatest force exerted on the habitat is the force of one atmosphere of interior pressure pushing outwards. This has significant impact on the form and shape of any pressurized habitat. While the critical pressure boundary layer is traditionally conceived as a pre-integrated tension structure, the promise of ISRU materials implies construction with regolith which would be a cementitious material. Mars X-House investigated both the combination of ISRU 3D printed regolith with separate deployable tension structures, as well as what it would take to use 3D-printed materials to provide the pressure boundary.

Traditionally, pressure vessels are outward bulging forms made with materials that favor tension materials such as steel, aluminum, or fabric structures. ***Mars X-House 1*** takes its reference from inflatable habitat designs conceived and designed as lightweight and compact deployable structures. *Mars X-House 1* uses two redundant inflatables, deployed from aluminum transition nodes pre-packaged in the lander.

Formally, inflatables are vertically oriented pill shape structures. This pressure form shows little increase in tension stresses on the pressure body, while creating more opportunity for habitable floor space. *Materially,* these inflatables are based on translucent polymers specified for SEArch+/NASA Langley's Mars Ice Home. These materials adapt the material layers from standard inflatables to those that would allow light to pass through, in some cases offering natural light, in others allowing true vision windows.

The promise of ISRU materials, however is that materials like regolith are used to make a habitat. ***Mars X-House 2*** explores both the maximization of formal potentials of using a compression material to hold internal pressure, as well as the in-situ manufacturing of tension materials.

When working with a material that is better in compression like regolith/concrete, the outward thrust of pressure is best resisted with an arch. An inward facing arch is a more efficient compression-based form, holding back the forces of air pressure like a dam holds back the force of water. The arch is one of the most efficient shapes on earth, distributing vertical distributed loads into horizontal thrust that can be transferred to the ground or to abutments.

The structure has been designed and evaluated assuming normal (Earth-based) atmospheric pressure within the habitat, therefore the structure will experience an internal pressure close to 100.7 kPa. Dead weight of the concrete structure is significantly reduced in Martian gravity (37.8% of Earth) and cannot be relied upon to resist resulting tensile forces from internal pressure.

To combat pressure distribution, the hyperboloid structure acts as a rotated catenary arch that distributes the tensile stress between the structure's foundation and the roof. The large concrete dome constructed in the roof will act as large member able to withstand horizontal tensile forces from the pressurized hyperboloid shell, as well as having the added mass to withstand uplift forces from the internal pressure despite the reduction in gravity. To resist the pressure forces pressing upwards a

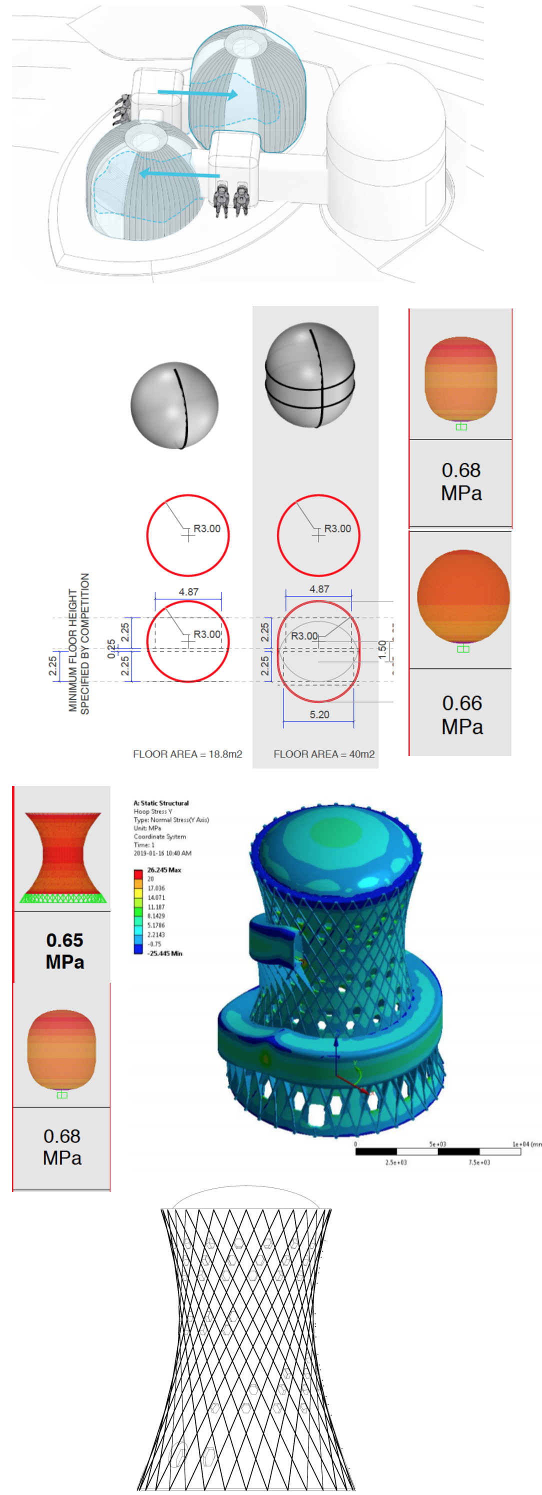

Figure 9. From Top: Deployable Inflatables, Mars X-House 1. Pressurization analysis of pill / capsule shaped deployable form. Pressurization of Hyperboloid form / Load case 1, Mars X-House 2. Representation of Hyperboloid structure and reinforcement.

water bladder servicing the habitat's wet programs is placed at the top of the structure. This weight resists upward forces and keeps the "pressure can" from exploding.

Despite the efficiency of the hyperboloid design, the structure experiences tensile stresses that are beyond the modulus of rupture of the concrete mixture. Diagonal and circumferential hoop (horizontal) basalt reinforcement further act to resist tensile forces, acting as a perimeter truss structure around the hyperboloid. Circumferential hoop reinforcement has been placed in close proximity above and below window penetrations, which are located at regular intervals in elevation. Basalt is an indigenous material that will already be used as aggregate in the concrete. The unique shape of the hyperboloid allows for continuous reinforcement from the bottom to the structure's dome.

IV. Architectural Drivers for Human Factors & Planning Principles

Design thinking was guided by architectural programming and planning principles that expressed themselves in various forms. The same architectural values resulted in the planning logic behind each version of the project.

A. Programming for Radiation Protection, Access to Natural Light & Views

Because radiation is a primary environmental driver as well as human access to natural light, care was taken to evaluate the architectural program by occupancy. Similar to planning and building code on Earth where occupancy function and number dictate a certain architectural criteria, Mars X-House designers looked towards the various anticipated functions on a possible Mars mission to create a nested program based on requirements for maximum protection or access to light or views.

Areas in which the crew spent longer amounts of time were placed in areas of maximized shielding, or behind multiple layers of walls, whereas areas where the crew spent less time could be shielded with a thinner wall section. These layers were cross-referenced with a need for light or view in a particular function space and the program was distributed accordingly.

Room Name	Activity	Hours/Week /Crew	%Day	% of Cumulative Wall Thickness	Protection Level	Window/Light?
Ops	Routine ops	4	2.38%			
	Conference Tag-Ups	7	4.17%			
	Public relations	1.5	0.89%			
	Training	4	2.38%			
	Work Prep	6	3.57%			
			13.39%	31%	2	**Window**
Ward Room	Exercise	10	5.95%			
	Food Prep	2	1.19%			
		12.25	7.29%			
	R&R (rest & recuperation)	20	11.90%			
			26.34%	62%	2	**Window**
Lab 1	Lab 1: Science	25	14.88%			
	Medical	4	2.38%			
	Inventory Lab 1	1	0.60%			
			17.86%	42%	2	**Light**
Lab 2	Lab 2: Engineering	25	14.88%			
	Inventory Lab 2	1	0.60%			
			15.48%	36%	2	**Light**
Bedroom	Pre/post sleep	10.5	6.25%			
	Sleep	59.5	35.42%			
	Personal Communication	1.5	0.89%			
			42.56%	100%	1	**Light**
Shower	Hygiene - Shower	7	4.17%	10%	3	
Toilet	Hygiene - Toilet	7	4.17%	10%	3	
Rover Port	Entry/Exit	4.5	2.68%	6%	3	**Window**
SuitPort 1	Entry/Exit	4.5	2.68%	6%	3	**Window**
SuitPort 2	Entry/Exit	4.5	2.68%	6%	3	**Window**
ECLSS						

n/a	Inspection	2	1.19%	3%		

Table 1. Mars Mission Activities by Time[24] separated into program area and level of protection.

B. Redundancy

With a harsh exterior environment, it is critical that pressurized habitable space have backup habitable areas in case of emergency.

1. ***Mars X-House 1*** achieved redundancy through two identical inflatable enclosures, each connected to two identical nodes acting as emergency egress with space suits. The inflatables and node structures themselves were of identical size to introduce manufacturing efficiencies anticipating future scalability of the design.

2. ***Mars X-House 2*** used principles of redundant mechanical spaces. Three separate service zones keep lab areas and living areas safe and cellularized in case of emergency. Airlocks separate each lab environmentally from the rest of the habitat and the other habitation areas.

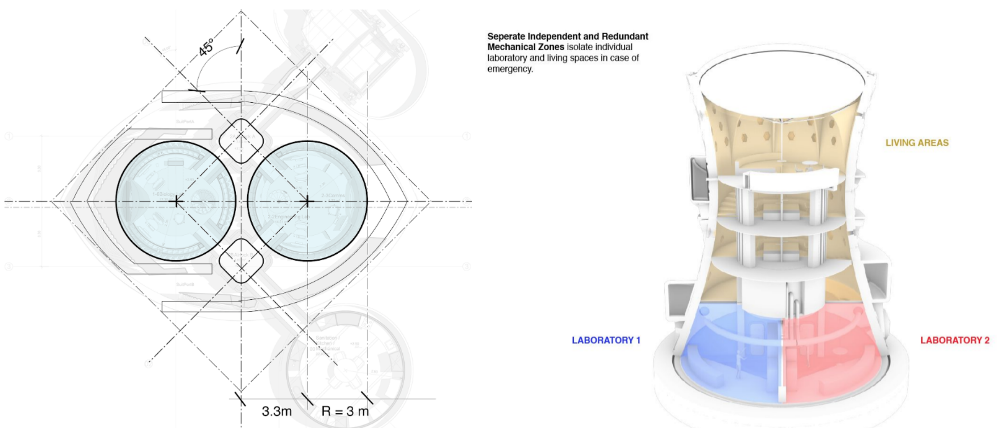

Figure 10. Left: Mars X-House 1 showing redundant spaces in plan. Right: Mars X-House 2 showing three separate mechanical zones.

C. Emergency Egress

Similar to issues of redundancy, quick egress in case of emergency either to an area of refuge or to a separate exit, to a whether suit port or rover. Just as in Earth buildings of highly dangerous function, building code requires access to two unobstructed paths of egress.

1. **In** ***Mars X-House 1*** each inflatable area is connected to two nodes with suit ports, the redundant inflatable, or connection to either the rover or lander core.

2. **In** ***Mars X-House 2,*** emergency egress is provided by an exterior stair that winds its way down the outside of the building, allowing access from floors 1, 2, and 5. The stair system functions as an area of refuge that is environmentally separate from the main structure, enabling the crew to plan and strategize options prior to performing extra-vehicular activity and/or completely vacating the building. Types of emergencies the crew may encounter could include a fire, chemical spill, or a microbe becoming a pathogen in oxygen

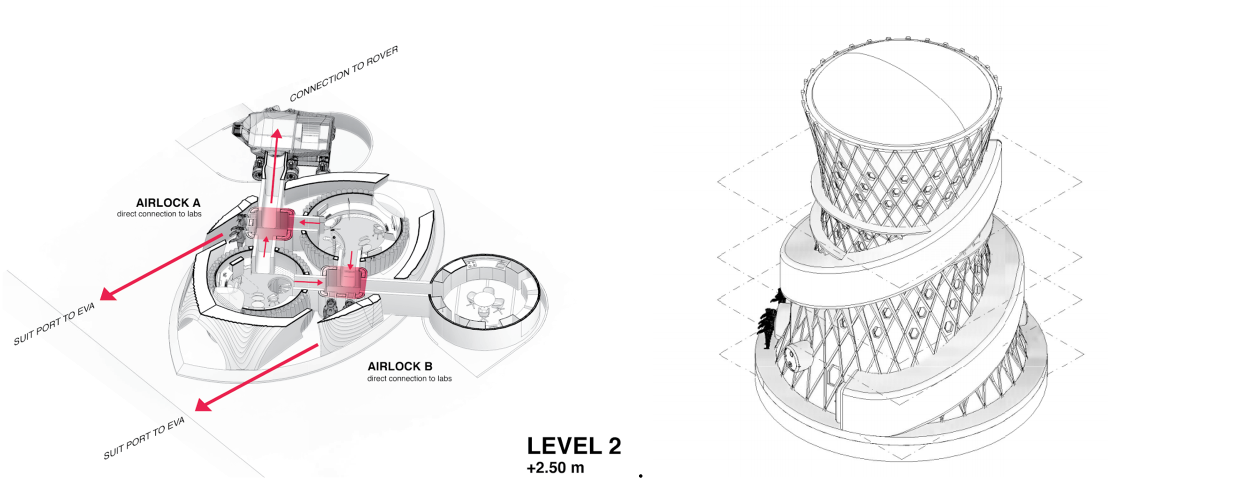

Figure 11. Left: Mars X-House 1 showing two exits through twin airlocks. Right: Mars X-House 2 exterior egress stair.

D. Laboratory Planning

In a future Mars mission, astronauts will be actively engaged in analyzing sample rocks and soils on the planetary surface for life detection, metrology, characterization, etc. The analysis of foreign extraplanetary material is highly dangerous and every step must be taken to ensure the crew is protected from potentially lethal pathogens.

In the limited program area given by the competition, laboratory spaces were divided into two separate and redundant spaces, separated from the private and public living areas. Laboratory 1 was devoted to biological and life sciences. Laboratory 2 is intended as an engineering, repair, maintenance, and medical treatment center for the habitat.

1. ***Mars X-House 1*** placed each laboratory space in separate redundant inflatables, yet connected at the same level, and connected through suit ports through which astronauts go on EVA and Rover expeditions.

2. ***Mars X-House 2*** took Laboratory Planning further, separating the lab spaces environmentally from public and private living spaces by airlocks. Each lab features separate and independent ventilation systems.

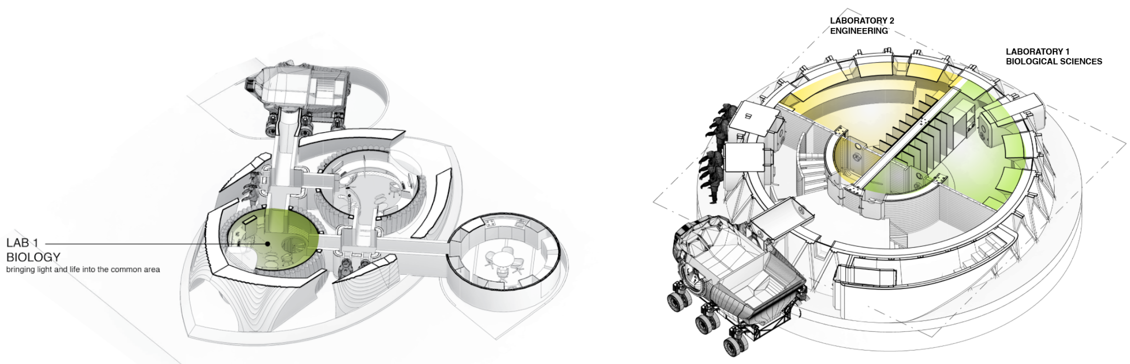

Figure 12. Left: Mars X-House 1 showing two labs on the same floor in separate inflatables. Right: Mars X-House 2 separate lab spaces.

Laboratory 1 contains a material pass-through to safety and automatically cache and transfer foreign objects into a life sciences experimental station. Within the lab, additional experimental modules will include: diagnostics, life detection, chemistry, characterization, as well as a glovebox module.

Laboratory 2 is intended as an engineering, repair, maintenance, and medical treatment center for the habitat. The lab features experimental modules for: medical diagnostics, pharmaceuticals, and medical fabrication. The lab also features a large, open working area for 3D-printing parts, tools, repairing hardware, and maintaining other elements of habitat engineering.

Each of the experimental modules are pre-integrated, packaged and brought from earth to be installed within a rack system which is deployed on-site prior to the astronaut's arrival. The ground floor also features an area for communications and operations, in close proximity to the habitat's main power lines (within sub-floor). Additional stowage for processing of mission critical items including food is located beneath the habitat's main staircase, as well as within the sub-floor allowing elevated access to the rover.

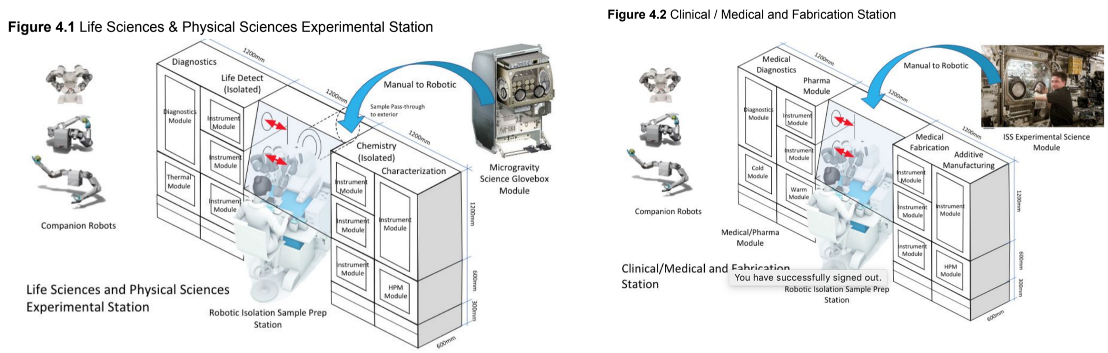

Figure 13. Example standard and modular racks systems for laboratory spaces.

E. ECLSS and Pre-Integrated Mechanical Systems

Each design incorporated a pre-integrated mechanical unit serving as the core containing the ECLSS as well as primary wet functions such a hygiene area.

1. In ***Mars X-House 1***, the Hercules Lander itself contained the ECLSS systems as well as the wet functions and connected to the inflated habitable areas through the connector node.

2. ***Mars X-House 2*** featured a pre-integrated ECLSS unit placed in the center of the habitat creating a central core around which the habitat was printed.

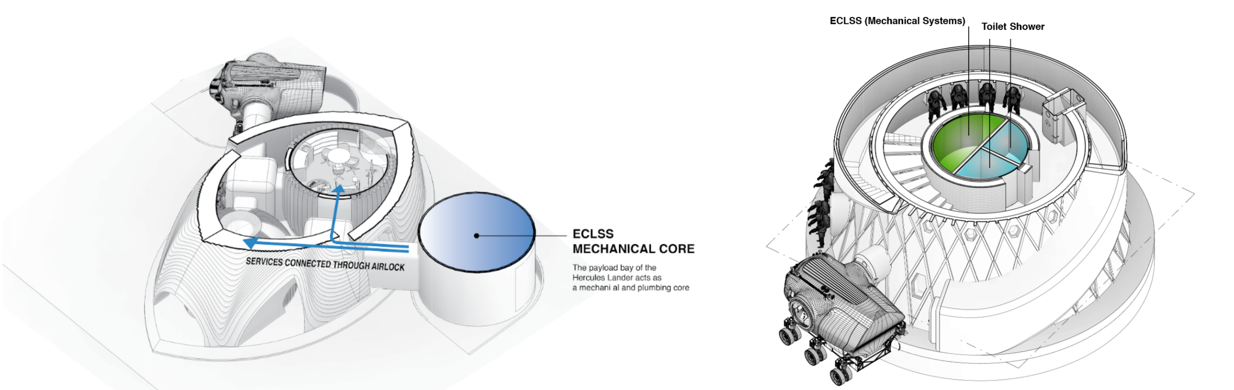

Figure 14. Left: Mars X-House 1 showing connected ECLSS in Hercules Lander. Right: Mars X-House 2 with ECLSS core.

F. Biophilia and Bio-Regenerative Systems

Mars X-House features several opportunities for the use of bioregenerative mechanical systems for air and water treatment and use these as dual-use human relaxation spaces. Additionally and critically to the program organization, the design team employed a sense of "looking outside" by placing green systems either towards the exterior or where they could be seen through windows, so that the crew would have a sense that they were looking out to a green area.

1. In ***Mars X-House*** *1*, greenhouses were built into pockets into the exterior translucent walls of the habitat creating the feeling of looking out and connecting to MEP systems embedded and services through the inflatable walls.

2. In ***Mars X-House 2*** the MEP walls surrounding the bedrooms host a vertically oriented hydroponic greenhouse with harvest area along the central staircase. The plantings and growing media in this garden offers greywater re-use and recycling opportunities for the habitat. These walls can be 3D printed to host growing media. This vertical garden turns what would otherwise be circulation space into a livable and enjoyable recreation area. Natural light from the window areas supplement grow lighting. Openings from the bedroom look onto the garden area, creating a feeling of looking outside for the astronauts.

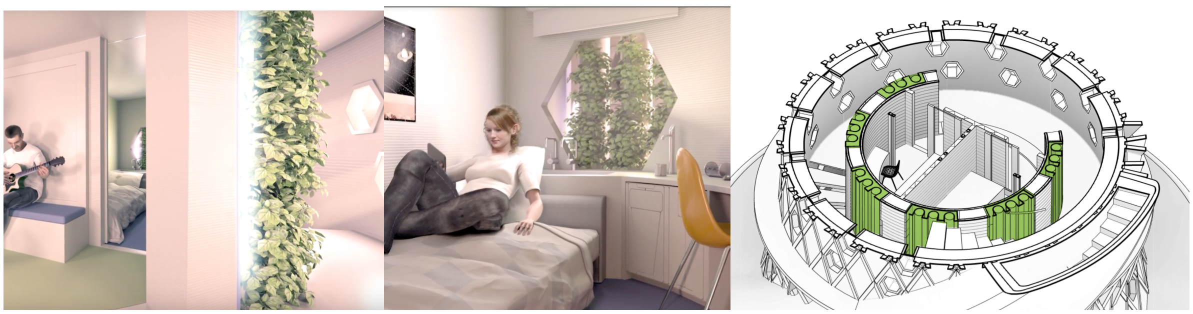

Figure 15. Vertically oriented hydroponic greenhouse embedded within MEP walls along central staircase.

G. Verticality & Separation of Functions

On long-duration human missions in confined spaces, designers considered that having a variety of spaces on multiple levels would reduce monotony and promote a sense of separation between public and private areas as well as a separation between work and living areas. In vertically oriented or stepped spaces, more privacy can be achieved between levels.

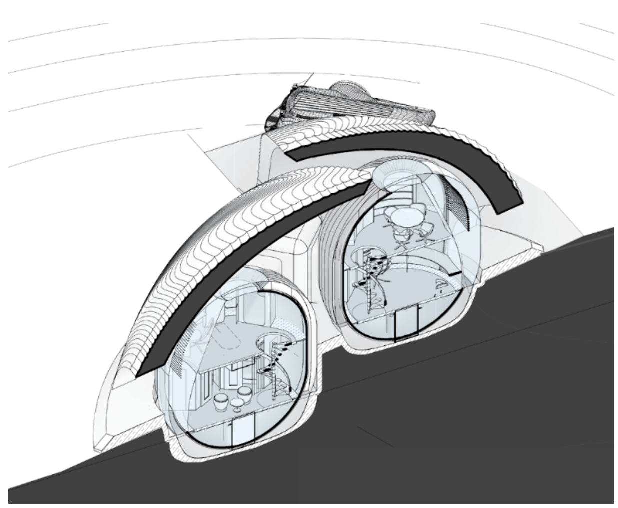

Figure 16. Section through Mars X-House 1 inflatables.

1. In ***Mars X-House 1,*** laboratory and EVA spaces are located on one level and split between the two inflatable areas, connected to each other via suitport nodes. Sleeping and crew group areas are located in the upper and lower extremes of the habitat. The main crew bunks are in the lowermost area protected by multiple layers of shielding. The ward room is located at the uppermost area with light streaming in from the light scoop above.

2. In ***Mars X-House 2,*** laboratory spaces are located at the ground level of the habitat along with connections to EVA and Rovers. Three floors in the center stacked hygiene and two floors of bedrooms, leaving the uppermost level for a collective ward room including kitchen area and observation.

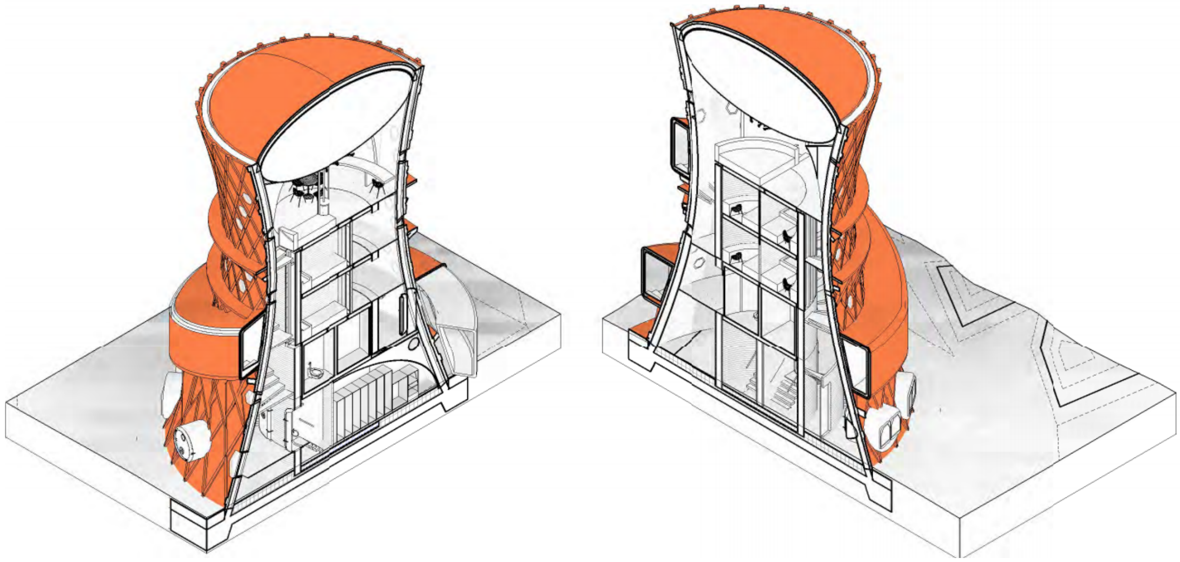

Figure 17. Section through Mars X-House 2 vertical habitat.

V. Constructability, Construction Sequencing, & Resulting Architectural / Formal Principles

In ***Mars X-House 1***, all systems for ISRU construction as well as pre-integrated subsystems of the habitat are first deployed from the Hercules payload module, and positioned into place at the construction site. Next the site will be prepared by excavators, and material gathering and processing will begin for regolith construction. The foundation is 3D-printed by two mobile construction printers. Subsequently the airlocks and suitports brought from earth are deployed and positioned on the site. The inflatable modules deploy and connect with the airlocks and suitports, followed by 3D-printing of the regolith shells protecting the habitat interior.

In ***Mars X-House 2***, a regolith foundation is printed first, followed by an HDPE floor at level 1. The mechanical core and rack system for the laboratory experimental modules are positioned within the habitat. A single layer of concrete regolith is printed prior to the diagonal basalt reinforcement diagrid or the circumferential hoop reinforcement. The emergency egress tunnel is printed after the primary hyperboloid form and reinforcement have been printed completely to ensure stability and prevent overturning of the structure.

Habitat systems including MEP and ECLSS are built into a pre-integrated mechanical core which acts as a wet core for the habitat. A pre-integrated ECLSS system serves the habitat through the secondary inner vertical walls, leaving the exterior walls free to let in light and views. The mechanical core is a pre-integrated unit containing the ECLSS hardware volumes as well as hygiene program of the habitat (toilet and shower). The ECLSS volumes are located in closer proximity to the living areas to take advantage of positive pressurization within the living areas and negative pressurization (-50 pa) within the laboratories, creating a circulation system that filters the air of pathogens and particulates. The mechanical core deploys by telescoping upwards to the second and third levels of the habitat. At the appropriate time, horizontal spokes deploy from the sizes of the core, functioning as support structures for printing horizontal floorplates. The precision-manufactured inflatable membrane for the water bladder deploys from a reverse-umbrella mechanism deploying from the highest plate of the mechanical core. The water bladder is deployed into place and a 3D-printed HDPE support structure is then printed around the bladder itself to support the weight once filled.

As mentioned, the mechanical core features radial spokes which deploy outwards to provide a scaffolding for printing floorplates and landings in the upper floors of the habitat. 3D-Printing horizontal spans and cantilevers are a present technology challenge for all 3D-Printing processes and materials. To date, a viable and foolproof 3D-Printing technology solution for printing horizontal structures without supporting scaffolding is yet to exist or be demonstrated.

The spokes address this current constraint in technology and introduce an intermediary solution for the development of multi-story extraplanetary structures. Additionally, the inner layer of HDPE provides structural support for printing of the regolith-concrete dome. Furthermore, in our construction prototyping with Apis Cor, we have demonstrated a capacity to print unsupported horizontal forms by tilting the regolith-concrete printhead by 30 degrees, and allowing the print-head's trajectory to print a three-dimensional cross-section in successive layers, rather than depositing material as 'flat' or horizontal layers alone.

The design for a mobile 3D-Printer has been developed based on Apis Cor's current construction technologies. The printer has been sized to fit with sufficient binders and additive materials necessary for the regolith-concrete print. The printer deploys on-site through an innovative telescoping mechanism at the base, in addition to a six-axis robotic arm connected at a boom-arm system which deposits material at the print head.

VI. Conclusions

Mars X-House synthesizes radiation protection, natural light, egress, and the required program given the parameters of Construction Level 3's head-to-head event. It has been scaled to fit within the 4.5m x 4.5m footprint at 1/3 scale for the purposes of printing constraints at the head-to-head competition. Our refined and rapidly-curing material mixture allows for the construction of the regolith-hyperboloid while providing adequate mechanical properties for the protection and safety of the crew.[25] Our refined 3D-printing prototypes developed by Apis Cor are not only applicable to construction on Earth, but correspond and may be transferred to a mission-scenario for future 3D-printed habitats as well as civic infrastructure.[26] The concrete mixture combined with basalt fiber reinforcement enhances the structural integrity and robustness of the habitat, effectively and soundly protecting the crew.

Acknowledgments

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