Martian Ice Habitats: Approaches to Additive Manufacturing with H_2O Beyond Mars Ice House

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The design of Mars Ice House has instigated new spatial and scalable approaches to habitat construction with solid H_2O as a primary building material supporting human health and well-being for long-term habitation on the Martian surface. Mars Ice House was the first place winner of NASA's 2015 Centennial Challenge to 3D print a habitat for Mars employing indigenous material resources. Unlike most traditional design concepts making use of Martian regolith, the project makes use of subsurface ice in the construction of a full 3D-printed habitat made out of solid H_2O. Citing new evidence of the potential hazards of perchlorates in the Martian soil, and working within NASA's "follow the water" approach towards space exploration, H_2O serves as a radiation barrier for the crew while nonetheless allowing light transmittance in the visible spectrum. Mars Ice House was able to demonstrate scaled 3D printing of ice as well as use small-scale robotic technologies capable of building large-scale structures. Next steps for a variety of models of ice habitat construction require continued investigation into the process of water-ice collection and transparent or translucent materials for pressurized enclosures which exploit the manipulation of pressure and temperature to build with ice according to the physics phase change within an interior pressure membrane.

I. Introduction

After establishing a baseline for the essential human needs, including requirements of the habitat to be made from in-situ materials that would provide radiation protection, thermal comfort, volumes for human habitation, and transcendent spaces for celebrating our collective aspiration to pioneer and explore Mars—relatively few material candidates remain. The Mars Ice House project is a concept design approach for additive manufacturing of a human habitat with in-situ water-ice on Mars. The project was designed in response to a call from NASA and America Makes in 2015 to present proposals for NASA's Centennial Challenge. Calling for a design and method for constructing a habitat no more than 1000ft^2 (92 m^2) to last a 500 day surface mission for a crew of 4 astronauts, the goal of the competition was to elicit design ideas for an autonomously or semi-autonomously processes for large scale additive manufacturing. Among the primary concerns for long duration manned Martian exploration is the health of the crew, including reduction of exposure to radiation on the surface as well as the psychological health of spending a 500 day surface mission and two 180 day transits wholly inside an enclosure.[17] In designing a habitat for human Mars mission, the concern is not only based on structural optimization, nor in environmental conditioning, but also in human experience.

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II. Motivations for Construction with H_2O

The Mars Ice House was a holistic response to the idea of a habitat meant for human occupation using mostly in-situ materials (incorporating the mechanical lander at its core). The use of water as the primary construction material was the basis of a project for both human psychological as well as radiation and construction factors. H_2O continually proves to be a promising construction material for the following considerations:

A. The Risks of Regolith

Many architectural concepts for Mars and other planetary bodies assume a kind of "bunker mentality," assuming underground construction, or habitation covered with multiple layers of regolith, the human experience is buried to protect inhabitants from radiation levels at the surface. Radiation levels at the surface has been estimated at 0.64 mSv/day (230 mSv/year) from cosmic radiation (GCR) and 0.025 mSv from solar events (SEP).[20] Annual exposure for humans on the ISS had been set to no more than 200 mSv/year.[19]

It is believed that a regolith covering of 50 cm thick (at a density of 1.5 g/cm^3)[13] could provide the necessary protection, and as the most visible and prevalent material on the surface it seems to be the material of choice.

However, recent studies indicate the possible presence of perchlorates (ClO_4^-) in the Martian soil, a chemical toxic to human humans impairing the proper function of the thyroid by inhibiting the uptake of iodine ions.[5] The use of this material in construction could cause potential hazards if not completely isolated from the interior environment, making it all the more reasonable to search for an alternative material when it comes to human habitation.

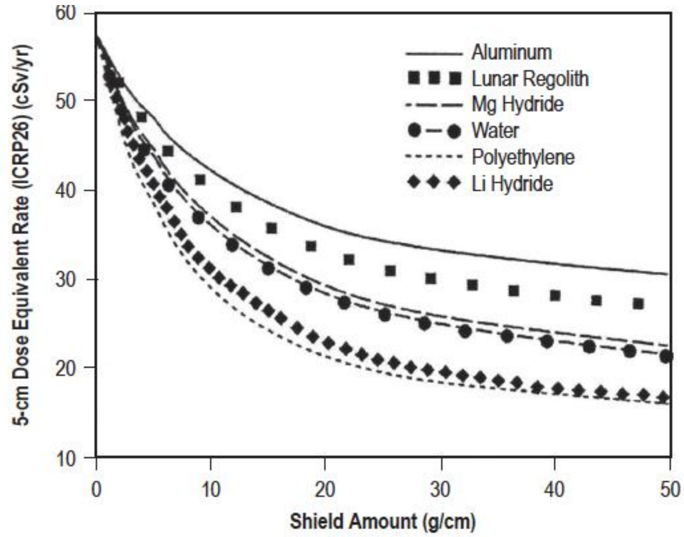

Figure 1. Radiation shield comparison showing necessary thickness of water versus lunar regolith for shielding. (Simonsen, 1991)

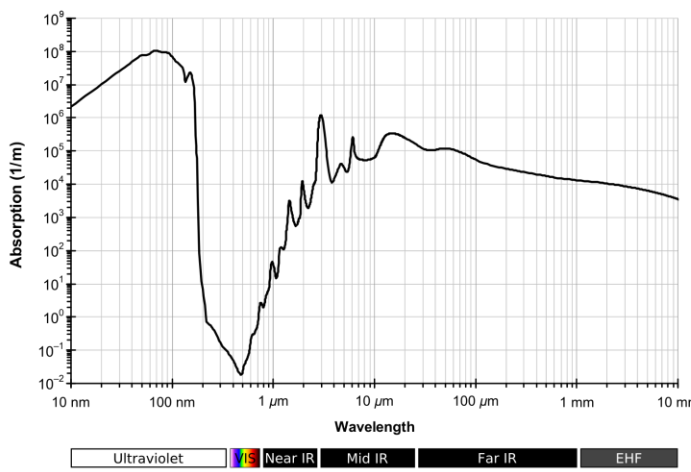

Figure 2. Absorption spectrum of liquid water showing absorption in the UV and transmission in the visible spectrum. (Warren, 2006)

B. Radiation

As a material with high hydrogen content, H_2O has often cited as a material capable of providing shielding in the high radiation environment. Results indicate that hydrogenous materials of low atomic weight are substantially superior to heavy metals for energetic ion shielding.[13]

From Figure 1, one could show that a water thickness of 20cm would provide proper shielding against GCR which is of main concern. This thickness, if distributed across multiple layers of a habitat would be enough to provide a significant storm shelter. The Mars Ice House distributes ice to 10cm thickness of ice on an outer layer and 10cm thickness on an inner layer.

The difference between ice and liquid water for radiation protection requires further study. The Mars Ice House calls for the use of an ice re-surfacer for both the clarity and visibility of the ice as well as to increase density. As one of, if not the primary driver, in the design of exterior sheltering for human missions, the ability for water to theoretically outperform regolith makes it a particularly interesting material consideration.

C. Visible Light

The importance of windows on spacecraft for psychological and practical purposes has been studied even though the integration of windows in spacecraft introduced possible locations of failure. There still appears to be a psychological benefit between being able to see and experience the space outside from the interior.[7]

The effects of natural light as well have been widely studied in building occupancy as being beneficial to human mental health.[4] While many have experimented with what could potentially be artificial replacements for sunlight, and exposure to natural light through fiber optics, artificial substitutes do not hold the same circadian variance or ability to balance a crew's mental and physical health as does experiencing the sun's actual and unmediated daily cycles.

Additionally, sunlight is just one, but one important way of connecting human inhabitants with their new surroundings. The ability to have windows across an entire surface allows the astronaut to be connected to the environment which they came to study.

As seen in Figure 2, just as water absorbs higher energy wavelengths, it transmits light in the visible spectrum. The transmittance levels vary based on the fabrication process, yet even domes made with snow blowing and contain opaque additives have shown some light transmittance. Experimentation with different techniques for the deposition of ice were explored in Mars Ice House which included methods of resurfacing ice to remove air bubbles that may affect light transmission.

Of course allowing visible light through the membrane needed to encase the water also requires the encapsulating material to be translucent. Through study we have investigated several translucent material possibilities that would compliment the transparency levels of ice.

E. Availability / Necessity

Requirements for any manned mission in more remote locations include the presence of in-situ water, something which new discoveries have proven to be perhaps more plentiful in our solar system and the broader universe than once imagined. Recent research on the Moon, Mars, Pluto, Europa, Ceres, etc. have all indicated the presence of H_2O in some form, leading to the belief that it is in fact quite common.[11] NASA has, for targeting it's Martian surface research also adopted a "follow the water" approach as these areas will be of high scientific value.[8] As we continue to propose missions that might extend to these areas, perhaps in a long term future to human exploration, it's availability a common material, and one we already require to survive, makes it an interesting option to explore as a potential building material.

F. Human Psychology and Habitability

Mars Ice House used water as primarily a material in order to experiment with not only the environmental, but human psychological requirements of providing visual stimuli, changing imagery, and landscape contemplation through visual connection to the exterior.[18] Architectural and design features based on their formal, organizational, and material properties directly affect behavioral issues on long term interior isolation including: sleep, exercise, hygiene, food preparation, group interaction, and privacy and personal space, among others.[18] The methods of construction offered opportunities for spatial configuration that would provide a type of outdoor relief while still inside a pressurized habitat. These new possibilities were only explored as a result of human considerations in parallel with environmental ones. It is imperative that in the consideration of manned missions that a more holistic or inclusive set of requirements be evaluated as they pertain to the mission objective. The presence of humans in space potentially has quite more objectives than simply the return of science content, and these objectives must be explored and understood thoroughly before the selection of technical criteria.

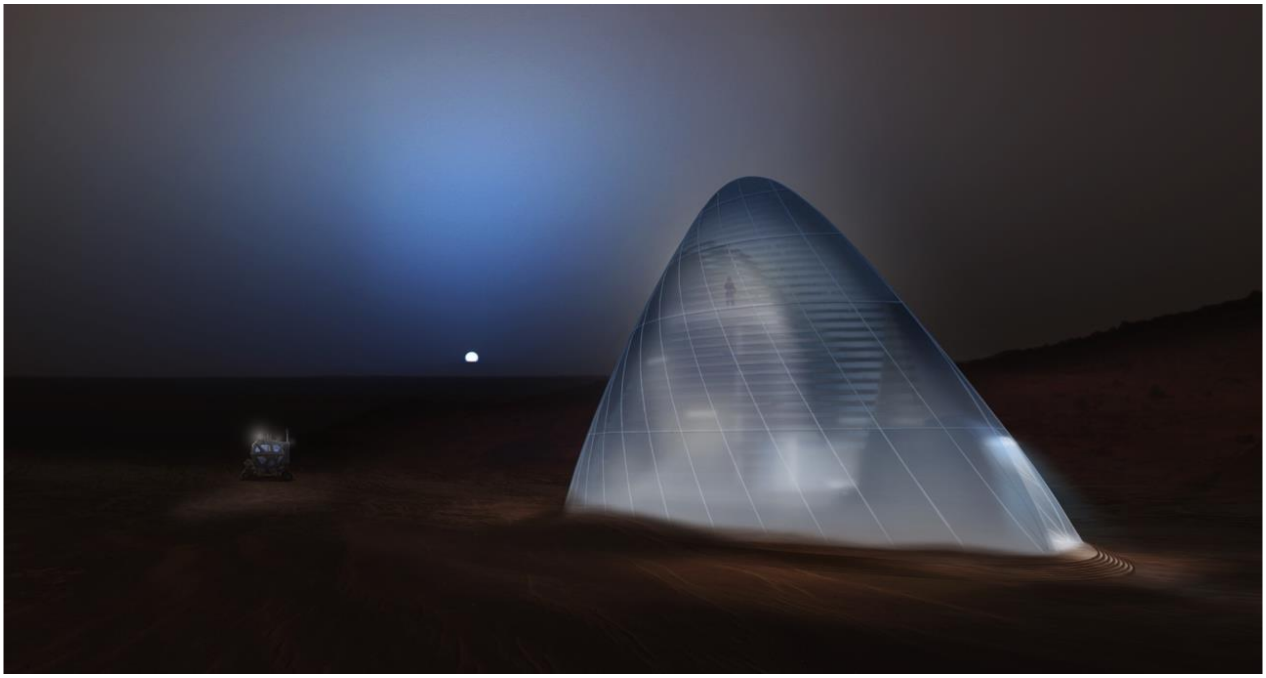

Figure 3. Exterior view of the translucent habitat.

III. Concept of Operations for an Ice Habitat

A concept of operations for the autonomous or semi-autonomous deployment of an ice habitat is speculated to follow a rough sequence as such:

A. Entry Descent and Landing (EDL)

In the Mars Ice House concept, a single lander, sized for the currently available payload of a Space X Falcon Heavy and NASA's Space Launch System (SLS), was assumed to carry with it a deployable pressure membrane. Environmental Control and Life Support Systems (ECLSS), ice collection, harvesting robots, or ISRU equipment, as well as water storage, could be included within the habitat lander or in separate or earlier mission deployments.

B. Ice Harvesting and Foundation

The first phase of in-situ resource utilization (ISRU) is exterior in focus, mining the surrounding landscape for water and creating a foundation in which to ground the lander. Per ISRU subject matter experts, the latest Mars architecture assumes a production rate of 1.25–2.0 kg/hr. This rate is based specifically on the propellant production needs for a Mars Ascent Vehicle. A rate of 0.25 m^3/day (~10 kg/hr.) is recommended to support deployment to full operational capability in a reasonable time frame.

We have suggested that ice could be sublimated and collected in a gaseous form to eliminate any impurities. The necessary purity of the water should be less than that required for human consumption.

C. Deployment and Printing

Prior to the printing or construction of any ice structure, a pressurized interior volume must be created due to surface pressures in which H_2O will remain solid. It is therefore conceived that the lander or mechanical core would inflate a transparent membrane serving as a pressure vessel. Reinforced along biased stress lines, this inflatable transparent exterior must be deployed before any interior construction can take place inside.

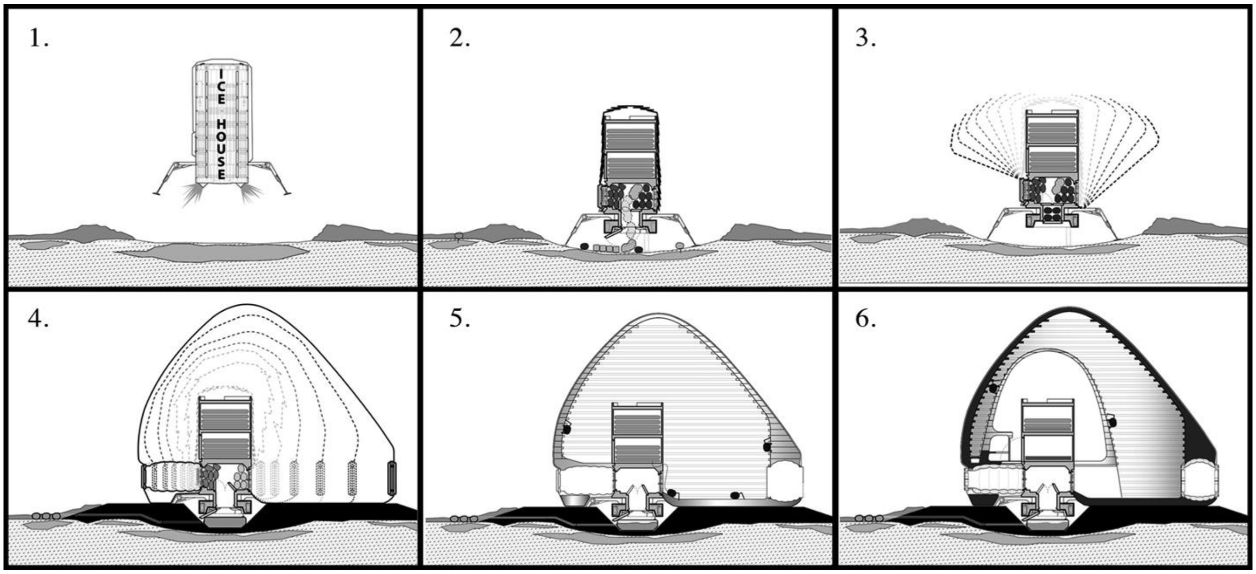

Figure 4. Concept of Operations and Deployment from the Mars Ice House project (1) Vertical Landing (2) Release of robotic water extraction (3-4) Deployment of Pressure Membrane (5-6) Interior Printing with climbing robotics.

IV. Structural & Environmental Considerations

In the consideration of an in-situ material structure, a survey of concepts to date rely on the presence of a pressure membrane sent from Earth to act as a supplement to an in-situ structure. To construct a pressure-vessel out of in-situ materials would require a concrete-like solution to have extreme thickness, or a more metallic or tensile solution, which is complex to produce. Assuming that the pressure would be handled then by a supplemental structure questions the functional role of the in-situ material as several concepts for deployable or expandable structures address other environmental factors within the concept of the skin of the structure itself.[9] However, in calling for in-situ construction there must be some kind of optimal balance between a pressure boundary and the supplemental in-situ materials, and so we assume the primary *environmental or shelter functions* of the in-situ material to be *radiation protection* and *temperature insulation,* assuming wind force and precipitation to be of lesser concern due to the thin atmosphere.

A. Pressure Membrane

Most in-situ 3D printing concepts rely on a supplemental enclosure to serve as a pressure vessel. The Mars Ice House design also calls for the containment of air by a reinforced pressure membrane brought from earth on the exterior of the habitat (rather than interior). Also differing from typical strategies for inflatables with an internal bladder and structural restraint layer, models investigating stress indicate the membrane to be capable of supporting the overall load, leaving the ice to primarily support its own gravitational load. Internal pressure was derived from that aboard the space shuttle at 70 kPA.

The Mars Ice House explored the idea of placing the pressure boundary on the exterior due to the necessity of keeping water ice from sublimating into the atmosphere. This restructuring of the pressure envelope allowed for a number of different spatial configurations with the in-situ printed materials. By creating an overall pressure envelope into which we can build multiple layers of structures, it allowed for the freedom to create more and varied functional spaces on the interior. Using one or more exterior pressure envelopes allows us to create several interior spaces with in-situ material and also to create a sense of outside by being able to pass through multiple enclosures while still within the pressure boundary.

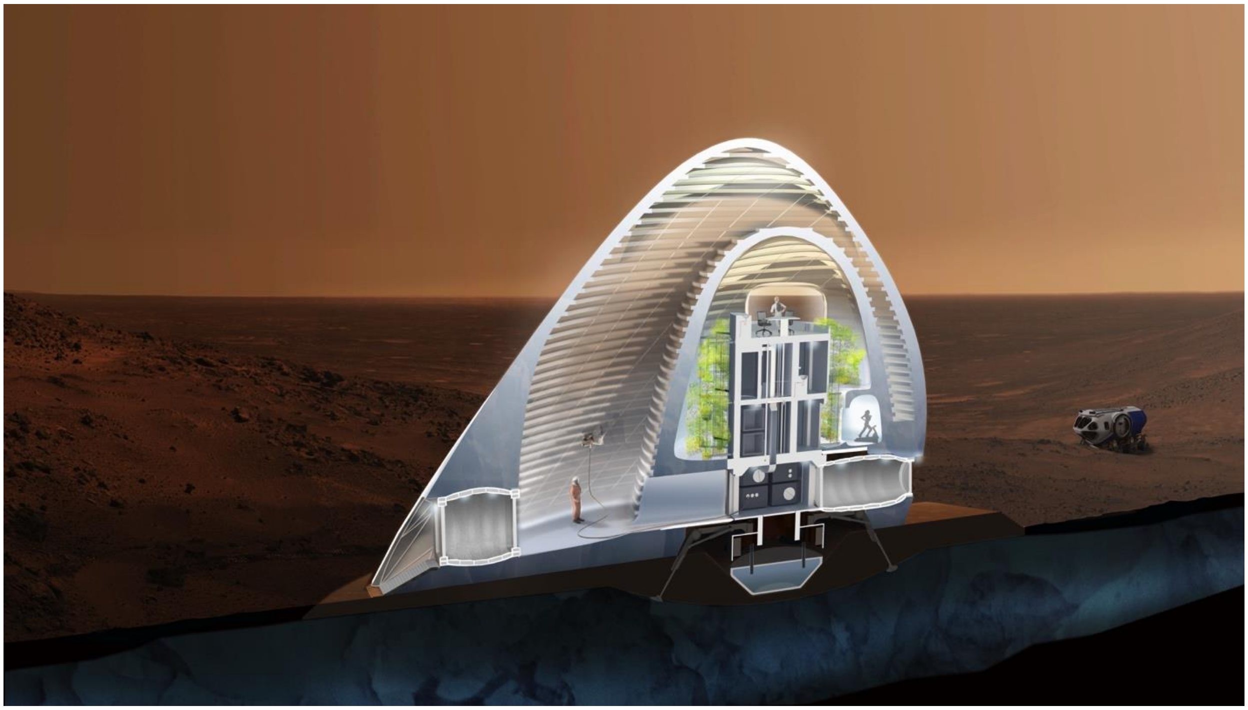

Figure 5. Sectional view through the interior revealing double wall condition, vertical garden, and interstitial "yard."

There are a number of ways to approach the problem of using a hybrid pressure envelope with materials providing these other environmental functions. Many approaches use an interior pressurized area, often inflatable, onto of which is constructed secondary environmental layers using regolith. This approach protects an inner pressure but limits spatial functions on the interior. There is a consistent sense of enclosure and interiority inherent to this method of construction because the occupant is always exposed to the internal pressure volume.

B. Thermal

Of particular importance in the concept design of a structure made with ice is the thermal control of both the interior habitat as well as the maintenance of subfreezing temperatures for the ice itself. Mars Ice House describes a wall section in which the outer layers of ice remain at Mars temperatures or a maximum of 0°C with the interior at room temperature near 20°C. In Mars Ice House, it is anticipated that the interior will be heated largely through mechanical systems, but will also experience heat gain from the sensible and latent heat of the occupants within, as well as some solar gain through the translucent structure.

There will be a need to vent or radiate heat to the exterior without transmittance through the ice wall. A venting system through the lander is possible, as well as the storage of thermal heat in water storage units already supposed for the printing mechanism. To prevent heat from the habitable areas from reaching the ice layer, a translucent hydrophobic aerogel layer[11] with light transmittance of 66% between the inner ice shell and the inhabited programmatic spaces could be used to ensure thermal comfort.

In precedent examples on earth ice and snow have been used as insulators. Given the ability to vent enough heat to the exterior or store it, there could be potential for other ways of distinguishing between drier warmer interior layers and colder but habitable exterior layers. Further research is needed to conduct thorough energy models.

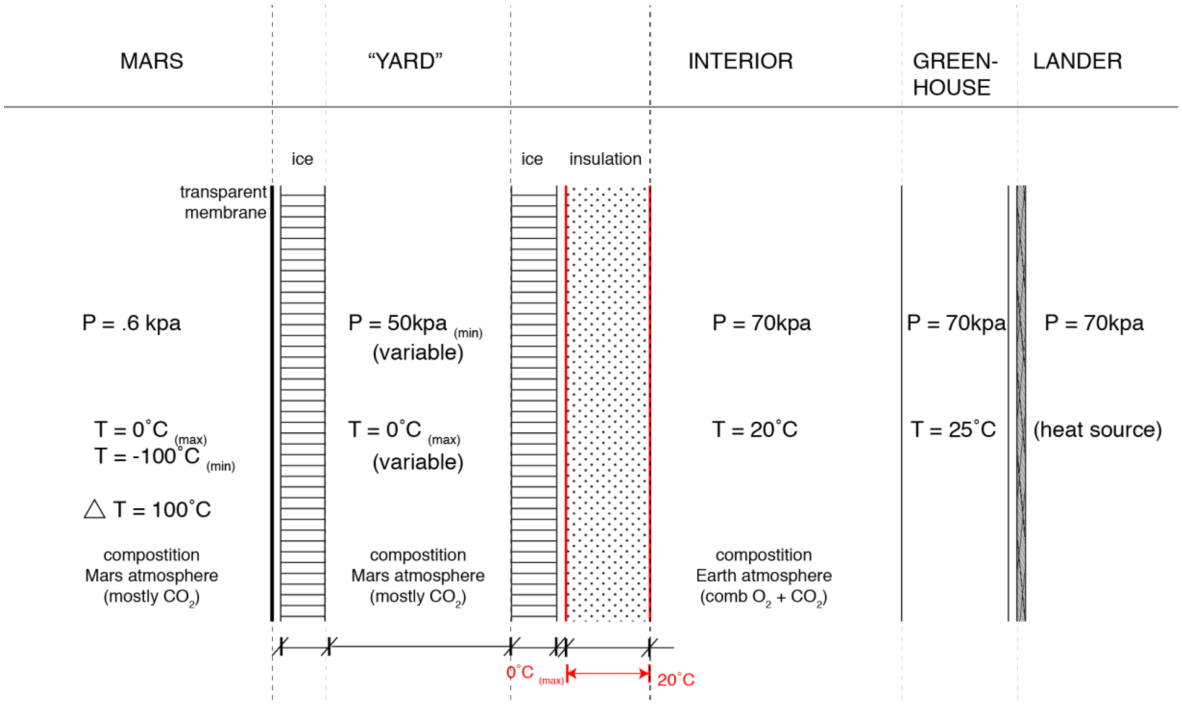

Figure 6. Conceptual Wall Section for MarsIceHouse indicating the layered composition and variable pressure and temperature in each zone.

V. Precedents for Ice Construction

A. Precedents in Earth Construction

Construction with ice on Earth is not without precedent. In addition to long standing cultural practices in arctic climates using thick snow blocks for insulation, modern examples of structures include Pykrete, a composite material developed in 1942 using ice reinforced with wood pulp, much like reinforced concrete, and with a similar strength. Field experiments using ice domes to span 20-30 meters have been carried out in Japan since 1999, and Pykrete structures larger than 30m were constructed in the Netherlands. In the mid 20^{th} century, Swiss architect Heinz Isler famously constructed thin shell structures using ice and fabric, experiments that have been repeated in universities over many years.

Perhaps a common factor in these precedent examples is the temporality of structures that exist in only persistent climates. Consistently cold temperatures on the surface of Mars promise a more permanent solution. Ironically, or perhaps not surprisingly, adaptations of earth precedents were present in the conceptualization for the construction of an ice structure on Mars, including additive silica fibrous reinforcement (potentially drawn from surface minerals or the recycling of lander parachutes) which was the technique used in pykrete (using timber fiber reinforcement), and potential insulation techniques adapted from igloo snow construction.

Figure 7A: Pykrete Construction: Inflatable Scaffold, Spray On. Thermal Control: Snow/air as insulation

Figure 7B: Cal Earth (SuperAdobe) layer by layer deposition construction method.

Figure7C: Pneumocell: cellular membrane construction.

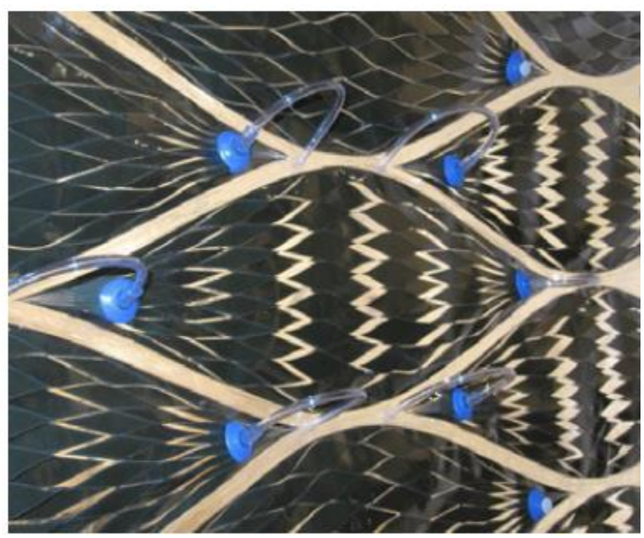

Figure7D: Pneumatic membrane, Uni. of Toronto.

B. Precedents in Space Applications

Though referred to in extensive publications for its radiation shielding abilities,[12,13] the idea of using water as a construction material has only begun to be explored for space missions, perhaps due to the relatively recent discovery of water on many other solar system bodies. One design of note where water was used was in the design for NASA's TransHab module, which called for water walls on the interior core, which doubled as utility services as well as radiation protection.[9] One concept for a water regolith slurry infill between deployable membranes was recently selected as a winner in the 2015 *Innocentive Challenge for Space Pioneering: Achieving Earth Independence.* New ideas certainly will proliferate following more feasibility testing.

C. Ice Harvesting/Collection

On Mars, water is abundant in the higher and lower latitudes.[6] Site selection was determined by a multitude of parameters, including balancing access to a shallow ice table from the surface (within 20cm-1m), with temperatures that remain below freezing throughout the Martian year.

To extract filtered H_2O from the subsurface, depending on the depth of the ice table, which in many cases is believed to be from 20cm to 1m below the surface, [6] solid ice could be exposed, cut, and captured. Heating a contained block of Martian ice with solar radiation while still in low atmospheric conditions could allow for the collection of water vapor into storage compartments as well as naturally filtering the pure liquid water form any remaining minerals or contaminants that may disrupt storage or viability of the printing systems.

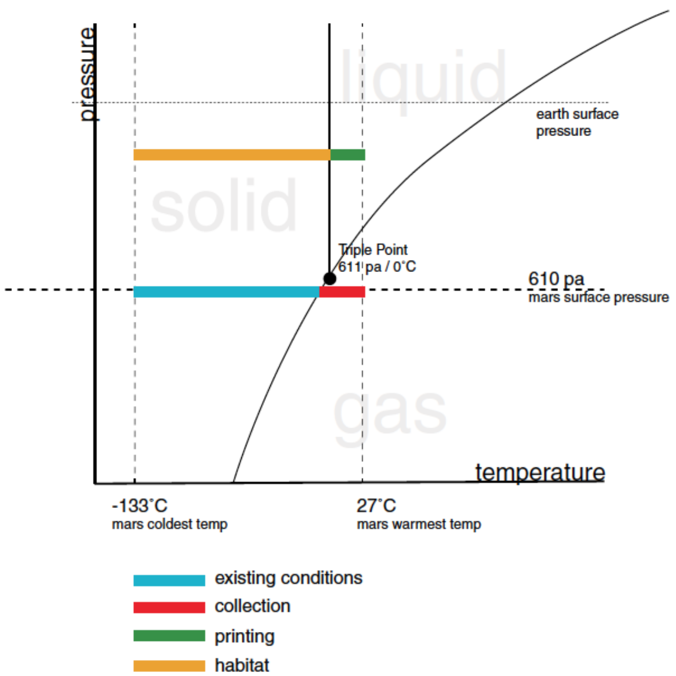

Figure 8. Phase Diagram of Water showing one potential process of construction from collection, deposition, and construction.

VI. Alternate Methods: Water-Ice Construction

Working with water on Mars requires manipulation through phase change. The exposure of solid H_2O to the Martian atmosphere would result in its immediate sublimation as the Mars surface pressure of 610 pa is below the triple point of H_2O. The Mars Ice House project relies more on the physics of phase change than on potentially laborious mining and laying techniques. Instead we sought a way to extract the subsurface solid, to collect it as a gas (thereby purifying it), accumulate or print it as a liquid within the interior of the membrane, and maintain it as a solid.

Several possible construction methods were discussed and are described here.

A. Passive Ice Accumulation onto an interior surface

Releasing H_2O into a low pressure environment, the possibilities of having it accumulate passively onto the interior surface was discussed. This method, while compelling due to its low-energy and low-tech nature, was also noted to be highly imprecise. It would require further study and testing to understand the merits and possibilities of such a method.

B. Spray-On Ice Mix onto an inflatable

Referencing Pykrete construction, in which ice and timber composite is sprayed onto an inflated dome, it was contemplated that an additive mixture of ice and regolith might keep the ice from sublimating and create a unique radiation shielding material. However, the mixture would not be translucent and therefore was not further considered.

C. Layer by Layer Deposition / 3D-Printing

More "traditional" 3D printing methods seemed reliable to deposit layer by layer ice through a nozzle attached to a moving robot is discussed in the following section.

C. Ice Membrane

Alternate approaches to ice habitats consider mining for water-ice, flowing increment amounts of liquid water into a double-layer membrane, and allowing it to freeze layer-by-layer. This approach assumes the following critical components: purification of the subsurface ice, storage within a heated bladder system, constant heating of water lines until reaching the interior of the pressure membrane, and a mechanism for achieving required flow and pressure within the membrane overall. The double-layered membrane is assumed to maintain the minimum practical pressure needed for water to enter the structure and freeze. It is important to consider that any approach or method of ice-habitat construction should be deployable with simple robotic mechanisms.

Deployment is presumed to occur through an inflatable membrane packed within a lander. Deployment may possibly occur through an airlock, so as to minimize possible complications or issues with access points that compromise the interior habitat prior to human arrival. Considered forms of the inflatable should resemble a dome or a vault, as these geometries are anticipated as the most structurally sound and efficient pressure membranes, while nonetheless providing ample interior volume for habitation and spatial programming or partitioning.

A primary access point will be necessary for ice habitats, though two or more are suggested (as in the case of Mars Ice House) and should be factored within the design for the sake of redundancy. Soft hatches and a smaller airlock may be acceptable if the habitat is to be connected or networked with other Martian structures or architectures. Possible benefits of a large airlock include the potential to bringing in expedition vehicles within a shirt-sleeve environment for maintenance work, since they will be the primary means for surface exploration of Mars and will include much of the functionality needed for life support. Nonetheless, the aforementioned dangers of perchlorates within Mars regolith pose cause for concern and further study, demonstrating the need for an approach more cautious of contaminating the habitat.

Based on the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) concept, cellular membranes may be inflated and filled with water to freeze one layer at a time. This method does not presume the translation of subsurface water-ice to gas, liquid, and solid.

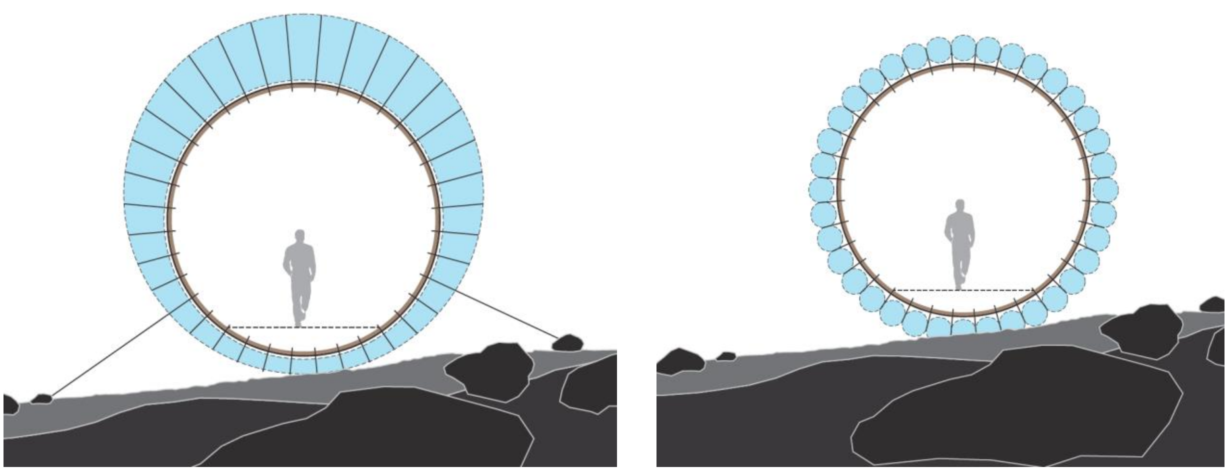

Figure 9A. Section: vertical spiral coiled ice tubes
Figure 9B. Section: shell with matrix of individual ice pockets

The thickness of the ice within or outside of the pressure membrane is crucial in determining the success of the habitat in radiation protection over prolonged periods. Additional study is necessary to investigate what ice-thicknesses would be appropriate for missions of various lengths on the Martian surface. Considerations of what ice-thickness would provide the greatest structural Factor of Safety factor into the structural design of the inflatable. The cellular method of construction using HIAD-type tubular membranes establishes the fully-filled condition of the membrane as a fixed amount. In Mars Ice House, the construction method allows for additionally deposited spraying of super-cooled water-ice within the pressure membrane prior to astronaut arrival, and also exterior to it once the structure is inhabited—securing the potential to repair unforeseen surface damage to the habitat.

Despite the fact that water-ice demonstrates advantageous structural and radiation-shielding properties on its own, water-ice may also serve as a notable binding agent when mixed with regolith in the event that subsurface mining proves to be too cost- or time-inefficient.

Designing for changes in internal pressure is a significant challenge to the cellular-membrane concept, and indeed for Mars Ice House as well. Expansion features in the design or the possibility of including relief valves are still needing to be explored.

VII. 3D-Printing with Ice

For the Mars Ice House Project, traditional deposition mechanisms were investigated for creating ice structures. Additively creating a structure with ice requires both the tools for moving and the tools for depositing material.

Traditional 3D printers consist of three-dimensional axes of movement and appropriately designed deposition tool (print head) for a particular material. The ability to control the three-dimensional axes has kept 3D printing until now quite contained within the defined boundaries of access. Robotic arms have increased the axis of movement, but still the construction of objects remains of a scale within the range of the arm of the robot. Printing large scale structures requires either a much larger range of axis, or the ability for the axis (the robotic arm or print head) to be moved itself to cover a larger area. In addition, the design of the print head itself would vary based on materials.

The design of these tools in tandem has a significant impact on the overall formal and structural possibilities of the habitat.

Figure 10. (Left) "Minibuilders" construct and simultaneously climb a wall at the IAAC was the basis for the **(Right) Mars Ice House concept** image of a robot capable of scaling the wall it has already constructed.

1) Mobility

Mobile printing robots are based on the concept of "minibuilders," a design investigation done at the Institute for Advanced Architecture at Catalonia (IAAC) with whom we collaborated on this project. A number of small robots, would be connected mechanically to water storage. These small robotic movers are capable of both depositing material as well as climbing the walls of that material once deposited through the use of vacuum gripping. By gripping onto the sides of a layered wall surface they can continue to climb and deposit material as they go. These gripping mechanisms are being designed as well to hold onto ceiling or roof constructions, and so eliminating the need for support structures typically necessary in 3D printing.

There are similar concepts in earth construction. Musgum mud huts, where footholds are incorporated into the surface of the hut as a built-in scaffold to allow workers access to complete the upper portions. This directly inspired the spiral self-printed rails that allow the rovers access to continue printing the shell

2) Deposition Mechanism

To achieve structural and thermal properties, we called for a printing head capable of depositing

1) water
2) fiber reinforcement
3) a conceptual tool for the re-surfacing of the ice layer through instant melting and re-freezing to achieve greater clarity or transparency in the ice
4) an aerogel insulation layer

We focused primarily on the deposition of water as the primary objective.

Several methods were considered in the additive construction of ice through phase change. Two were seriously considered. One concept was a method to sublimate water vapor into a pressurized interior on the undersurface of a pressure membrane. Due to the unpredictable nature of this method, a more traditional additive procedure was pursued but further research is required to test the viability of such of concept. This concept, while additive in nature, requiring no precise robotics, was potentially imprecise and untested.

The alternative was a more traditional means of layer-by-layer gravitational deposition of material, again, within a pressurized volume. This membrane, precision manufactured on Earth, is critical protection for the future ice shell, preventing any printed ice from sublimating into the atmosphere.

A heated supply of liquid water would be fed through insulated hoses to the mobile "printer heads." A low-volume, close-range nozzle would ensure that any water that freezes mid trajectory melts and refreeze instantaneously via the energy of its impact (a contact weld).

3) Additives

Precedent earth ice construction like Pykrete have benefited from the addition of fibers like wood pulp for the reinforcement of the ice shell. Thinking of an analogous potentially translucent reinforcement material, a fibrous clear silica additive (flat-packed in the lander) could provide the ice form with greater tensile strength,[1] calculated to bolster the strength of ice to the order of 3 times. While ice has been shown to possess tensile properties (~2-3 MPa)[10] that are, in fact, superior to materials such as brick (2.8 MPa) and granite (4.8 MPa), the fibrous reinforcement ensures the longevity and integrity of the structure.

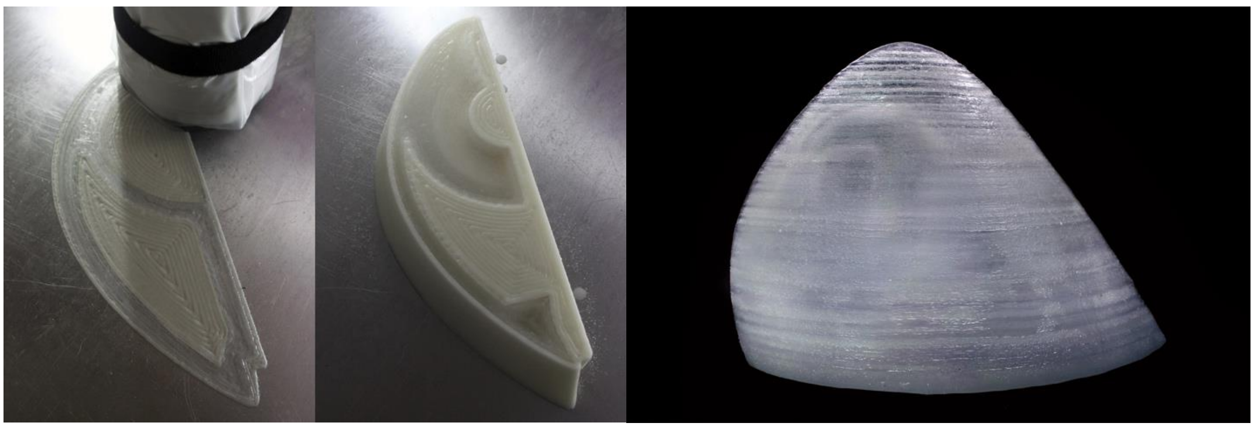

Figure 11A. (Left) Additive deposition of water ice and brine support structure conducted for this project in freezer facilities with an insulated robotic arm at McGill University, Montreal. **(Right) final 3D printed ice structure** after the melting of the brine support material.

Figure 11B. (Left) Additive deposition of water ice, constructed by Petr Novikov for SEArc. **(Right) water ice deposition mechanism** showing movement in multiple axes.

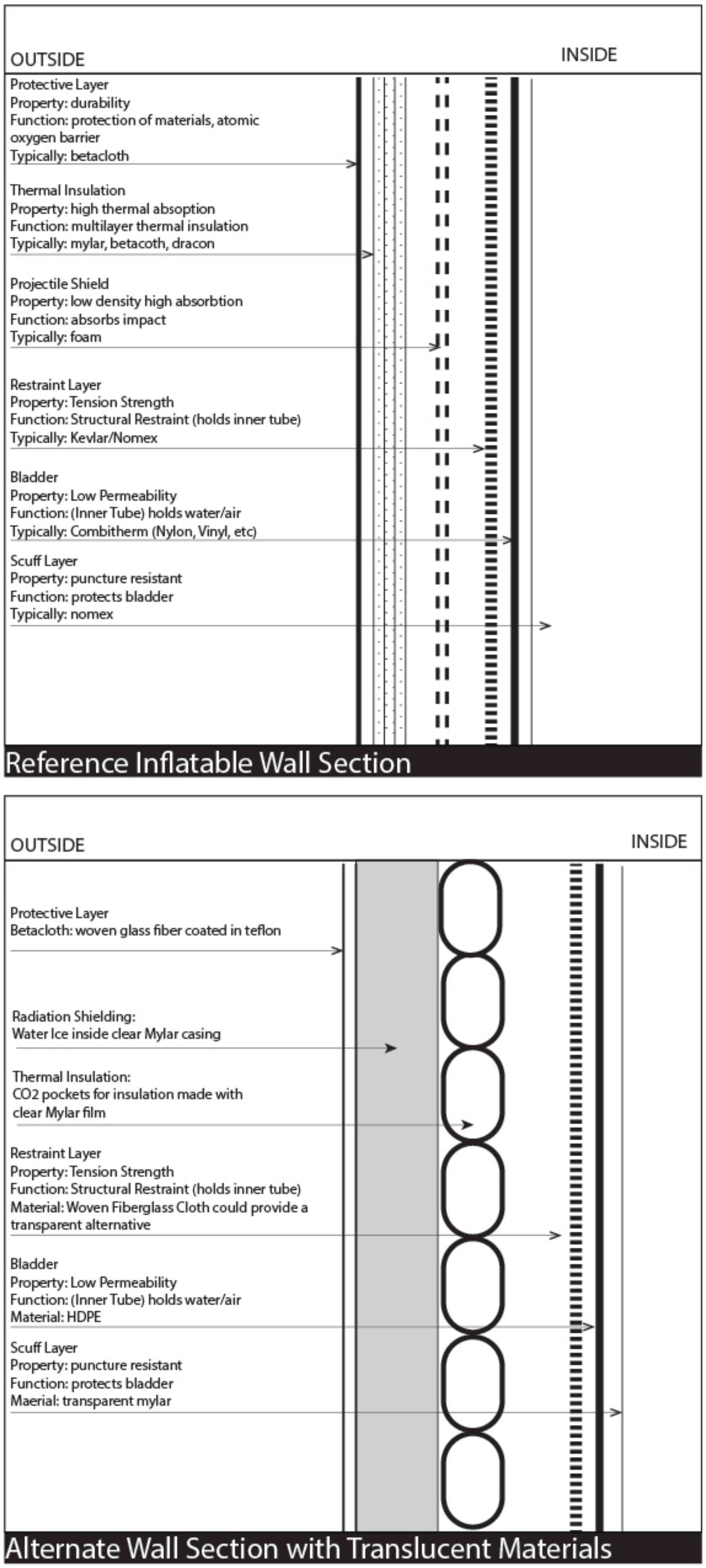

Figure 12. Above: A "typical" inflatable wall section comprised of multiple bladders, restraints, and shielding. Belwo: reconsidering these materials with translucent alternatives.

E. Earth Analogue Testing

Tests in the 3D printing of ice were performed on Earth. The Mars Ice House team in collaboration with McGill University in Montreal printed a prototype within a freezer environment. In this case, a traditional robotic arm was used and frozen brine was substituted as support structure, which melts at a lower temperature than the pure ice. Through the use of mobile robotics, we anticipate that no such support structure would be required in full-scale construction. Further testing was conducted using larger scale robotics outside the freezer environment with some success.

We continue to explore possibilities for testing this equipment in the proper environmental conditions, both with thermal and pressure differences, and at larger scales.

VIII. Transparent or Translucent Pressure Membranes

In all cases, the translucency of ice is only beneficial when combined with the transparency or translucency of the pressure membrane that surrounds it. A number of transparent materials were discussed which are analogous to traditional materials used in inflatable membranes today.

An outer cover traditionally is made of a betacloth material for protection from scuff and atomic oxygen. A clear oxygen resistant cover made from woven glass fiber and Teflon.

Radiation Protection is achieved through ice which may be encased by a clear mylar film.

Insulation might be achieved either through as previously described, a translucent hydrophobic aerogel layer[11] with light transmittance of 66%, or thought was given to insulation using CO_2 directly from the atmosphere in an air pillow layer. Such a gaseous material would be transparent and could be encapsulated also using a clear mylar film.

Structural restraint, usually

A Kevlar or nomex product, could be replaced by a woven fiberglass cloth. With strong tensile strength and low moisture absorption this woven material might easily hold in an atmosphere.

The air bladder, or redundant bladders typically made from a combitherm or nylon, could instead be made with one or several layers of high density polyethelene (HDPE) which is flexible at a large range of temperatures, puncture resistant, and serves well as a gas and vapor barrier.

The final interior scuff layer as protection of the internal bladders both puncture and flame resistant, applied in a thin layer of white will allow light also to pass through the layers of the habitat.

IX. Conclusion

Development continues on earth for traditional methods of depositing materials for additive manufacturing. Certainly we will see from terrestrial pursuits the continued feasibility of large scale construction using 3D printing methods and the development of the appropriate robotic mobility as well as material investigation and deposition tools. The concept of building with H_2O, despite its long history and clear benefits in radiation protection, remains a novelty on Earth and its potential uses for space still untested. The notion of constructing with such a simple material, and even possible low-tech construction techniques using the basic physics of phase change is what makes the project concept both exciting, and also possibly unnerving.

Further research is required in the development of the printing nozzle of the right pressure, temperature, and velocity to create accurate prints with water but the research is underway, also for terrestrial pursuits notably in arctic climates or where temporary structures would be required. Its ability to be used in full-scale construction should track with those of similar materials in additive manufacturing. The alternative method mentioned for sublimation of gas directly onto the interior of a surface as a potentially lower tech solution should also be pursued. For space applications, testing of ice within a pressure membrane at Mars similar temperature and pressure ranges is a necessary next step as well as the undertaking of energy modeling and analysis to determine appropriate levels of insulation and heat rejection needs.

The concept design of the Mars Ice House demonstrated material possibilities but also a design methodology resulting in the consideration of new possibilities and ideas for human space exploration. As the overall winner in NASA/America Makes' Centennial Challenge one can only assume that the originality or vision of the concept was perceived of as a value. In continuing to pursue ideas for human habitats, a design methodology rooted in equating technical, environmental, and structural concerns, within the context of a human based mission provides a suggestion for new approaches to design methods. The Mars Ice House, composing itself of an interdisciplinary team of subject matter experts, lead by architects, continues to challenge traditional design approaches by considering fundamental physics, re-visiting design requirements, and organizing behind an objective consistent with a human centered mission.

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