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Technical Risk Reduction for the Mars Ice Home Habitat Concept

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Abstract

A realistic architecture for a human mission to Mars requires an effective habitat where crews can operate autonomously on long surface stays while remaining well protected from the harsh Martian environment. Galactic Cosmic Rays (GCRs) are a significant issue for human health on long duration Mars surface missions. Any effective habitat for Mars must provide GCR shielding for crews. It is impractical to transport the needed shielding material from Earth. Burial of the habitat is an option but presents many engineering and operational challenges. The Mars Ice Home is a low launch mass deployable Mars habitat concept based on an inflatable structure that utilizes water ice collected by In Situ Resource Utilization (ISRU) water collection systems as radiation shielding. The Mars Ice Home also provides a large, flexible, and cost-effective workspace that can be used for many of the key activities that will be critical for the long term success of a human outpost on Mars. The Mars Ice Home incorporates many human factors features that will provide a comfortable home for future explorers to Mars and other deep space locations where water resources are available.

The original Mars Ice Home study in 2016 developed an initial design that received worldwide publicity. A follow up risk reduction study in 2017 addressed many of the key technical risks such as deployment, filling, and water cell material performance. Several candidate water cell materials were tested at NASA's Langley Research Center and methods of freezing water at low pressures were tested at Brown University. In addition, the 2017 study team refined the Mars Ice Home water cell design and performed GCR shielding assessments of specific designs to better understand the tradeoffs between water collection requirements and shielding requirements.

Keywords: (maximum 6 keywords)

Acronyms/Abbreviations

Galactic Cosmic Rays	GCRs
In Situ Resource Utilization	ISRU
Concept of Operations	ConOps
Center Innovation Funds	CIF
Mars Ice Home	MIH
Mars Ice Home Risk Reduction	MIHRR
Environmental Control & Life Support Systems	ECLSS
Entry Descent and Landing	EDL
Mars Ascent Vehicle	MAV
Evolvable Mars Campaign	EMC
As Low As Reasonably Achievable	ALARA

1. Introduction

Long-term stays on the Martian surface require habitats that reduce both launch mass and cost while providing an effective working environment with a high level of shielding from Galactic Cosmic Rays (GCRs), which are a significant issue for human health on long-duration missions. Any effective habitat on Mars must provide sufficient radiation shielding for crews. Current habitat concepts either do not address requirements for shielding from GCR or propose burial of the habitat by several meters of Martian Regolith. The latter poses significant challenges in the autonomous deployment of an effective habitat. Also, current integrated habitat designs do not address the need for large, pressurized workspaces that would enable crews to perform crucial repair and maintenance activities on equipment that must operate in severe conditions for long periods of time.

The Mars Ice Home (MIH) is a deployable Mars habitat concept that uses In Situ Resource Utilization (ISRU) derived water ice to fill an inflatable structure, serving not only as a structural component but as a crucial GCR radiation shielding mechanism. Ice Home also provides a large, flexible, and cost-effective workspace that can be used for crew operations and activities critical to the long-term success of a human outpost on Mars.

A Concept of Operations (ConOps) for Mars Ice Home was first developed in 2016 as part of a NASA Internal Research and Development feasibility study using Center Innovation Funds (CIF) to develop a key systems engineering product for the concept.

Ice Home was further explored in a Risk Reduction effort focused on a feasibility study to reduce the technical risk associated with water ice cells. The Risk Reduction effort included physical testing and design updates to further investigate material selection, water cell structural configurations, filling methods, and initial radiation assessments.

This paper describes the systems context and habitat design proposal for MIH, and further examines design development and physical testing of water ice cells, including its material properties.

The goals of the MIH design, development and risk reduction efforts were to provide a habitat design concept that:

(1) Improves mission *effectiveness* by
   a. Reducing GCR dose by more the 50% over habitats based on an aluminium structure.
   b. Improving human factors through large, pressurized work areas with natural, diurnal lighting.
   c. Providing a scalable design that supports a wide variety of mission scenarios.

(2) Improves mission *affordability* (reduced life cycle costs) by
   a. Reducing launch mass per cubic meter of pressurized working space.
   b. Providing a flexible architecture with dual-use functionality.
   c. Utilizing components that can be pre-deployed with basic robotic systems.
   d. Minimizing technology development risks.

Each iteration of the MIH architecture was evaluated against these goals to objectively determine the most effective concept.

2. System Description

The Ice Home System includes the soft-goods Ice Home Inflatable Structure as well as Deployment and Access Subsystems. MIH is the habitat component of a human Mars outpost designed to provide flexible work and living space with a high level of radiation shielding for Mars mission crew members.

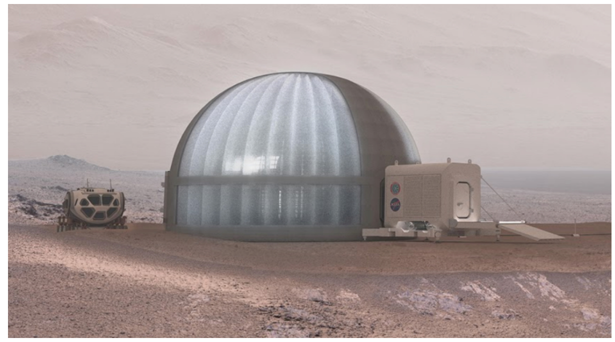

Figure 1. Artist Rendering, Mars Ice Home Inflatable Structure.

2.1 Operational Context

In addition to a 550-day operational phase, the length of the deployment phase for Ice Home relies on the ability of the ISRU systems to collect water and fill the Ice Home structure. Thus, the deployment phase may last two years or more, making the minimum operational life ~4 years on the Martian surface. The nominal operational life would be extended if an “Exploration Zone” architecture is selected; in this case assets remain functional for 3 crew rotations as described in the Evolvable Mars Campaign (EMC). In this case, the operational lifetime of MIH rises to an estimated 15 years. While longer duration estimates heighten potential risks associated with mechanical failure, using longer term estimates expands the potential applicability of the system for future development.

The assumed crew complement during MIH design is also set by the EMC. While the Humans to Mars Architecture recommends a crew of 6, the EMC recommends a crew of 4. The latter value was assumed as a baseline.

2.2 System Context, Basic Assumptions, and Interfaces

MIH will interface with external ISRU, Power, Command and Control, Entry, Descent and Landing, and possibly Environmental Control and Life Support Systems (ECLSS). The assumptions upon which the design of the Ice Home concept is predicated are described in the following sections. These notional interfaces are based on inputs from Mars ISRU experts and the latest Mars Architecture [1] including Entry, Descent and Landing (EDL) systems.

2.2.1. ISRU Water Interface

It is assumed that water will be introduced into the MIH through one, primary attachment point, and that this connection will be made robotically. Hoses will require appropriate insulation and helical heating elements to prevent freezing. The Ice Home concept includes a heated water storage tank, integrated pumps, water manifold(s) with remotely commanded valves, heated tubing, and water management sensors monitoring integrated pressure, temperature, and strain for routing water throughout the various water cells in the system.

The Exploration Zone sites currently under consideration do not exhibit features of solid near surface water ice [1]. As a result, it is expected that water will be obtained from hydrated minerals or a regolith/ice mixture that must be mined and processed. In this scenario, water will be provided periodically via carrier vehicle rather than continuously provided by a water extraction system in close proximity. The needed water extraction rates are estimated to be 1.25-2.0 kg/hr and are based on the needs of propellant production for a Mars Ascent Vehicle [1,2].

2.2.2 Power Interface

It is assumed that power will be available from a pre-deployed power system prior to Ice Home deployment. Ice Home will have a standard power interface robotically connected prior to deployment for sensors, data communication, water pumps, valve controllers, blowers, heating, air pumps and airlock mechanisms.

2.2.3. ECLSS

The MIH architecture is flexible with regard to the ECLSS interface. An Environmental Control and Life Support System (ECLSS) may be installed within the interior volume of MIH following deployment, or conditioned air provided via ducting at the interface with an independent module.

Linear soft-goods seals may be employed between sections of the MIH with differing environmental conditions, such as a dry, cool work area and a warm, humid area for plant growth).

2.2.3. Entry, Descent and Landing

The landed mass of MIH is sensitive to Entry, Descent and Landing (EDL) constraints.

2.2.4 Interface to Other Habitats

A flexible, soft-goods package is assumed as a potential connection between habitat modules.

Because Ice Home must be outfitted after the astronaut crew arrives, it is assumed that MIH will interface with a pre-integrated habitat module. It is likely that the crew will initially live in this smaller, traditional habitat module until outfitting and set-up are complete.

2.3 System Phases

2.3.1. Launch and Transit

Ice Home must be packaged in a stowed configuration that can be accommodated (with any other systems being transported to the outpost) within the mass, volume and dimensional constraints of the EDL aero shell, which in turn must fit within the 8m cargo shroud of a standard SLS launcher. The current packaging ratio is conservative (~ 2:1).

Based on discussion with EDL experts, the constraints of a feasible EDL system restrict the mass of the Ice Home system to 18,000 Kg.

2.3.2 Placement and Site Preparation

Because the Ice Home will be one of the first components landed in a potential Exploration Zone and will therefore not pose a risk to previously-landed hardware, it may be landed directly in the habitation zone and deployed in place. If needed, robotic assets will transport the Ice Home deployment package from the Landing Zone to the Habitation Zone, where it will be placed at its operating location. A likely delivery method to the deployment site would be on a trailered cart. MIH will require a footprint clear of large obstructions, so some preparation may be required to level the surface at the deployment location. The design also allows for deployment from an integrated platform.

2.3.3. Deployment Phase

Once the MIH deployment package has been properly located in the Habitation Zone, the first activity will be to robotically attach a pre-deployed power system to attach a heating system and establish a data link. Initial pressurization will be performed with integrated air pumps that inflate the system with filtered air from the Martian atmosphere. Monitored through integrated sensors, once both the interior and water and insulation cells have been inflated to the desired pressure and temperature, ISRU water fills can begin.

Water from the ISRU system will initially be accumulated and held within water cells within an insulation layer above the hub to keep the water heated and to prevent from freezing. Sensors will monitor the water level in the hubs and control fill rates and volume for all water cells. Sections will be filled and allowed to freeze in a sequential order dependant on mission scenarios. Filling the cells may take three or more years depending on water availability.

2.3.4. Outfitting and Checkout Phase

An integrated habitation module should be located near the Ice Home and connected to it with a soft goods airlock to provide a pressurized path to transfer equipment and supplies. Floor sections would be installed first without fully pressurizing the interior space. Crew can transfer smaller equipment directly to the ice home through the airlock.

2.3.5. Operation and Maintenance Phase

The Ice Home is envisioned as a multipurpose workspace. Given its large volume it may be used for a combination of science activities, vehicle maintenance, logistics storage, food production, recreation, and living areas. Operating temperatures are dependent on its use.

2.4 Architectural Habitat Design

There are many potential operational uses for the large volume provided by the ice home. The current 12 meter diameter, 6m high two level torus provides 198 m2 of floor space allowing for a vertical architecture creating either functions separated by levels or a large double height space for operations where needed.

The limiting factor on the size is based on the amount of water that can be collected in a reasonable time frame and still provide protection from GCRs. The toroidal form of this size is small enough that further restraint material is not be required. A packaged MIH will fit within the payload fairing diameter of the SLS cargo vehicle. It can also support a proposed "garage door' size airlock door of 2.2 meters high and 2.7 meters wide. The large access door will simplify outfitting and allow a large equipment to be brought in for repair and maintenance. The recommended living space of 25 m3 per crew member is easily accommodated for a living area.

The primary advantage of this system is flexibility, but one possible configuration consists of an upper level sleeping area surrounded by an aeroponic garden, and a lower level work area.

3. Design Development: Water

Water on Mars will be a precious resource for early human missions. Water can be used for radiation protection, fuel production for the MAV, plant growth as well as crew drinking, hygiene, and oxygen production. Mars Ice Home will therefore be in competition for this resource and the amount of water required by the habitat must be optimized.

3.1 Thickness of Radiation Shielding

The primary motivation for using water ice in the design of a habitation system is to provide superior radiation shielding. The required quantity of water is therefore based upon the thickness of ice needed to substantially reduce astronaut radiation exposure.

A primary tenet in radiation protection is to make the effective dose As Low As Reasonably Achievable (ALARA). Given the constraints on water collection and landed mass, the Ice Home team has identified a target ice thickness that minimizes both radiation dose and the required mass of water.

Radiation exposure was modeled using the TARIS 4.0 code, according to the following factors:

External Environment:

· Galactic Cosmic Rays (GCR), Badhwar-O'Neill 2014 model, 1977 Solar minimum.
· Mars surface at 0 km elevation.

Response Parameters:

· Whole-body Effective Dose.
· Female Adult voXel 2005 (FAX) body model.
· NASA Q quality factor
· NASA tissue weighting factors for average US population.

The effective dose modelled for crewmembers at the center of a hollow sphere of ice show that 2m of water shielding will exceed the design goal of 50% reduction in radiation exposure when compared to an astronaut in a "traditional" aluminium structure (Table 1). Significantly, it should be noted that an aluminum-shell habitat actually *increases* the effective dose received by an astronaut due to the generation of secondary particles. Thus, comparison to the dose received by an unshielded crewmember is a conservative measure of the increase in radiation protection.

Table 1. Effective GCR Dose Reduction Based on Shield Thickness

Shield	Effective Dose (mGy/Year)	Relative to Unshielded Crew Member
No Shielding	178	Baseline
Thin Aluminium Shell	Sm. increase	Sm. increase
Water sphere 1m thick	107	-40%
Water sphere 2m thick	75	-58%
Water sphere 3m thick	50 High Uncertainty	-72% High Uncertainty
More than 3m	Very High Uncertainty	Very High Uncertainty

Figure 2 illustrates effective dose reduction as a function of the thickness of water (or ice) in a hemispherical shell. The figure clearly shows that the greatest reduction in radiation dose occurs with the first 1-2 m of ice, and that further increasing ice thickness has diminishing returns on dose reduction.

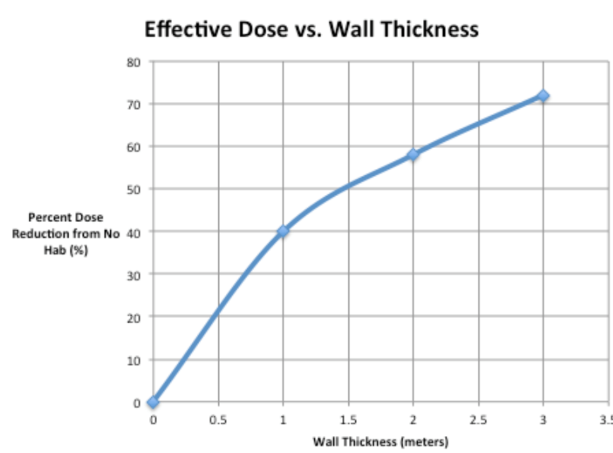

Figure 2. GCR dose versus ice thickness for a hemispherical shell.

3.2 MIH Volume and ISRU Rates

The thickness of ice calculated in the previous section must be extrapolated to obtain the volume of water that is required by a theoretical ISRU system. As a first cut, we assume a 12m-diameter hemispherical interior volume with a flat, 1m-thick ice floor, and 0.5m of insulation between the habitable volume and the MIH water ice cells. This is referred to as "Version 1" of the MIH. Resulting volumes of ice and the corresponding time required to fill the Version 1 volume are shown in Table 2.

Table 2. Water Volume and Fill Time Based on Shield Thickness

Shield Thickness (Inside dia. 13m)	Water Volume	Time to fill at 0.25 m^3/day
1 m	~441 m^3	~1764 days
2 m	~844 m^3	~3376 days

Table 2 includes the time to fill the resulting MIH cells at a rate of 0.25 m^3/day (~10 kg/hr). This rate is optimistic, but is required to support MIH deployment to full operational capability within a reasonable time frame. "Reasonable" is defined relative to the frequency of launch opportunities; even at 10 kg/hr, for low energy launch windows every 26 months (1560 days), an ice home of 12-m diameter would need to be pre-deployed at least two launch opportunities ahead of the crew.

Additionally, increasing water production rates for Ice Home will necessitate increases in the ISRU/power system mass. This increase must be offset by mass savings over conventional habitats. Overall, an Ice Home with a complete hemisphere 1-2 m in diameter presents an unacceptable demand on conceivable ISRU systems if the entire ice cell volume must be filled before astronaut arrival.

The extremely long fill time can be counteracted by designing the ice cell configuration in a manner that allows for strategic, incremental filling. By filling half of the cells prior to astronaut arrival, then continuing to fill the remainder of the cells as the astronauts live in the habitat, the first astronaut crew to inhabit MIH may experience incrementally increasing radiation protection as the MIH is fully filled. Water volume may be further reduced by distributing ice volume to thicken the top of MIH and thin the sides, developing a new cell configuration to increase radiation protection, or reducing the habitation area.

3.3 Water Cell Design Configuration

The current MIH design includes walls with 2m thickness, but this is supplemented at the apex of the hemisphere by the water storage tanks used during filling and operation of MIH (Fig. 3). This configuration maximizes radiation shielding in areas where the crew spends more time. Note that reduced thickness of the MIH floor is acceptable because Mars' surface provides some radiation shielding. This distribution significantly reduces the overall volume of water required for shielding.

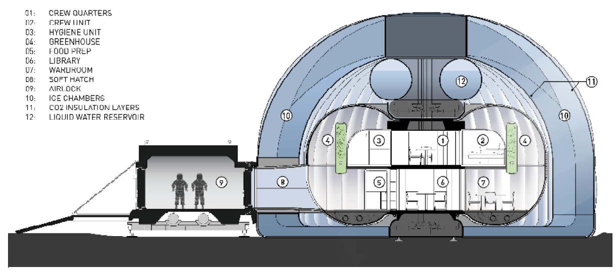

Figure 3. Ice Home Cutaway Section showing water reservoir above sleeping areas.

Further design development considered several iterations of water cell configurations designed to reduce water volume while maintaining radiation shielding effectiveness. Designs considered a configuration that would simplify fabrication, packaging, and deployment. Additional requirements included ease of filling/irrigation, responding to freeze and thaw cycles, providing structural integrity and redundancy, reducing material mass through surface area reduction, and increasing the capability for design scaling.

The final water cell configuration utilizes a series of radially organized vertical ice arches (Fig 4). The arch geometry reduces total ice cell volume while blocking the majority of incident GCR raypaths (Fig. 5) In addition to radiation shielding, the arches provide redundant structural support, utilize less overall surface material, and include small gaps that can be used to allow natural light into the habitat.

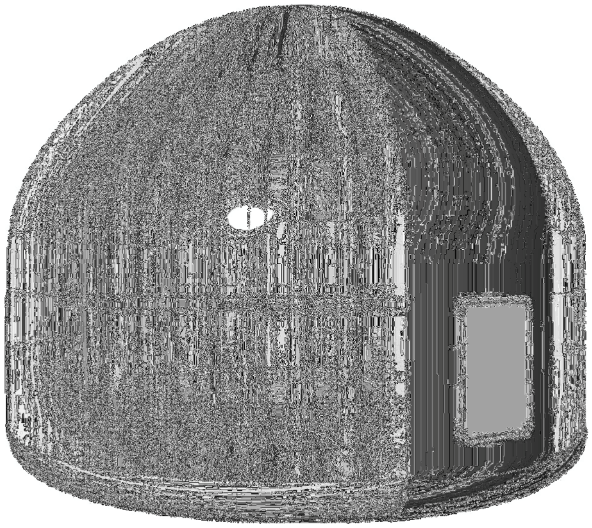

Figure 4. Vertical Slice Water Ice Cell Configuration

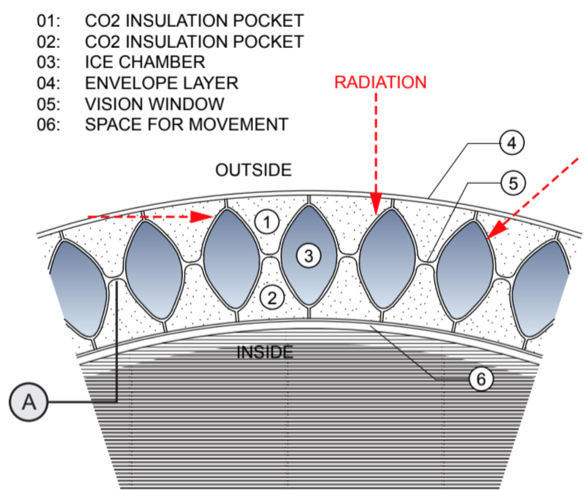

Figure 5. Planform view of MIH walls, showing ice arch configuration. Total ice volume is reduced while still blocking the pathway for a majority of incident GCR.

The radiation dose received by astronauts within the radial arch configuration shown in Fig. 5 was analyzed in the same manner as the ice sphere described in Section 2.3. Two targets were analyzed inside the ice home, the first in the center on the second level and the second on the lower level near one of the hatches. In this configuration, only 655 m^3 of ice is required to reduce the effective dose by 50% relative to an unshielded crew member (Table 3).

Table 3. Effective Dose Reduction Based on Water Cell Design

Shield Geometry	Effective Dose (mGy/Year)	Diff. over Unshielded Crew (%)
No Shield	178	Baseline
1m Water Sphere	107	-40
2m Water Sphere	75	-58
3m Water Sphere	50	-72
MIH Version 1 Target 1	118	-33
MIH Version 1 Target 2	130	-27
MIH Vertical Cell Target 1	**89**	**-50**
MIH Vertical Cell Target 2	**93**	**-48**

The volume of 655 m^3 is much more reasonably met by a conceivable ISRU system; a production rate of 0.5 m^3/day would require 1310 days to completely fill the MIH ice cells. Thus, the radial arch configuration achieves the radiation protection goal with an ice volume that can be obtained within a reasonable span of time.

5. Physical Testing: Water Ice Properties

During the 2016 Mars Ice Home feasibility study technical risks associated with filling an inflatable structure with water ice and freezing it in Mars environmental conditions had been identified. An understanding of the mechanical properties of ice formed at low pressure, as well as the effect of thermal and freeze/thaw cycles on materials used in MIH construction will prove to be crucial in risk mitigation. Over the 15-year design lifetime of MIH in the Exploration Zone architecture, three freeze thaw cycles may occur if the water in the MIH cells is used to produce fuel for the MAV. Such a long lifetime also implies significant exposure to ultraviolet light and thousands of diurnal temperature cycles.

Our initial tests focus on the properties of ice produced during freezing at low pressure. The MIH ice cells will be outside of the habitation area and thus will be a pressure less than one Earth Atmosphere. Since the pressure loads drive the material requirements, operating the water holding cells at lower pressures will reduce the thickness of the material and thus landed mass requirements. In order to reduce risk there is a need to verify that clear solid ice can be obtained by freezing water at the low pressures expected in the water holding cells.

The mechanical properties of the ice are influenced by the ice "microstructure" – that is, the size and shape of ice grains (crystals), as well as the porosity of the ice. Increased porosity may reduce the compressive strength of the ice, while crystal size affects the ice viscosity and, as a result, the resistance to creep (slow deformation) [4]. In general, larger grains produce ice with higher viscosity, which resists creep. Larger grains also result in fewer scattering surfaces within an MIH ice cell, thereby improving clarity of the ice (important in allowing natural light to enter the MIH volume). This study therefore examined porosity, ice grain size and clarity as a function of the ambient pressure in the prototype cells.

5.1 Water Composition

Water used in MIH is assumed to be "reasonably" pure, with a pH between 6 and 8, based on requirements imposed on ISRU systems that provide water for propellant generation.

Notional ISRU systems produce water from either ice-rich surface deposits or water-rich minerals, in both cases using distillation to release water from the source material. Commercially-available distilled water containing trace impurities (from other volatiles) is considered a comparable analogue, although there is currently great uncertainty in the specific impurity content of water produced by a Martian ISRU system. Potential impurities include CO_2, H_2S, HCl, SO_2, and CH_3Cl. The effects of impurities on MIH ice cells are primarily on the strength of the ice; bubbles due to exsolution of gasses may increase porosity and decrease strength, while concentrated acids along grain boundaries in the ice may accelerate creep. The effects of these impurities on the properties of the Ice Home water cells may impose requirements on water delivered by the ISRU system, or on design of the cells. However, given current uncertainties in the ISRU system to be used, the tests described below were conducted using deionized water.

5.1 Testing Objectives

Typical Martian atmospheric pressure is only 0.09 PSI (as opposed to Earth's 14.69 PSI). Although the final habitat design (and thus the pressure that the ice cells will be subject to) are not finalized, it is expected that the water holding cells will not require a differential pressure greater than 3 PSIG to maintain their shape when initially inflated. This pressure is typical of inflatable structures that do not have to carry significant loads. Conversely, a differential pressure less than 0.5 PSIG will be inadequate to maintain a good shape when filling is being performed.

5.2. Test Protocol

Low-pressure freezing was conducted in a custom-built apparatus in the Brown University Ice Lab (Fig. 6). The apparatus consists of a stainless steel low-pressure chamber connected to a vacuum pump, with a pressure manifold configurable to control both bag internal pressure and chamber pressure (Fig. 6). A needle valve in line with the vacuum pump allowed precise control of chamber or sample pressure.

Deionized water was degassed by boiling for several minutes prior to the filling tests. The water was cooled to approximately 10ºC prior to the filling test. This temperature was empirically determined to be high enough to prevent freezing within the apparatus' water lines during filling.

The test chamber was placed inside a commercial chest freezer at −15ºC and allowed to thermally equilibrate for several hours. Pressure within the Tedlar bag was reduced to the desired test set-point before the pressure in the chamber was lowered. The sample bag was then filled with the degassed water from a reservoir at 1 atm and allowed to freeze overnight. After at least 12 hours, the chamber was equalized with ambient air and the sample bag removed for microstructure analysis. Bags were frozen at <1 psi ambient pressure and at 5 psi ambient pressure

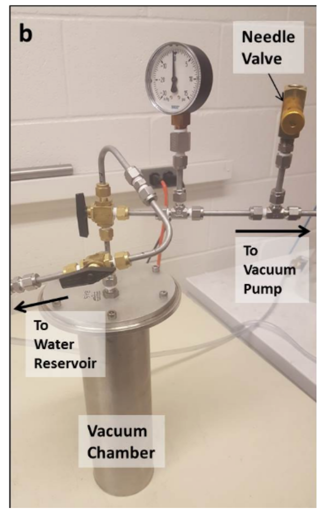

Figure 6. Apparatus for low-pressure filling and freezing tests. (a) P&ID of apparatus configuration. (b) Photograph of test chamber and pressure control manifold.

Ice microscopy was conducted within a chest freezer at −15ºC. Ice microstructures were evaluated using 2-4mm "thick sections" cut from the frozen bags using a band saw. Sections were cut from various regions of the frozen samples, including edges and center, to evaluate spatial variability of ice properties within the bags. Sections were cut both normal- and parallel to the uppermost surface of the water during freezing. After cutting, each section was sanded with 1200-grit sand paper to remove scratches prior to viewing. The samples were then placed between cross-polarized film on an LED light table and photographed. Fig 7 shows one example of these images.

Grain size and porosity were evaluated in sample imagery using the NIH software ImageJ. Grain size was measured by the line-intercept method, with a multiplicative factor of 1.5 applied to account for viewing geometry. Relative transmissivity of the thick sections was evaluated by measuring the absolute gray values (A measure of total brightness) of the specimens and comparing those values to the unimpeded output of the LED light table.

Further tests were conducted with trace amounts of dissolved CO_2 and HCl to determine the effect of impurities on ice.

5.3. Results

In all tests, a solid mass of ice was produced inside of the Tedlar bag. A small amount of "snow" was also found within the bags. All bags displayed a region of finer grains near the liquid/vapor interface inside of the bag. Much larger grains were observed within the bulk of the ice, although the difference in grain size between the two regions was more apparent in the bag frozen at <1 psi than in the bag frozen at 5 psi. The transition between grain sizes was sudden, rather than gradual. Despite the water having been degassed prior to freezing, numerous elongated bubbles were present in each sample. However, the overall porosity is very low.

The absolute gray value of the specimens did not vary significantly between tests, indicating that the grain size variations between specimens did not produce measurable differences in the transmissivity of ice at the thicknesses studied. The measurements are not particularly useful, however, because the observed grain size is larger than the thickness of the specimens. As a result, measurements are effectively of the transmissivity of single crystals of ice. Future evaluations of the transmissivity of MIH cells should utilize larger specimens.

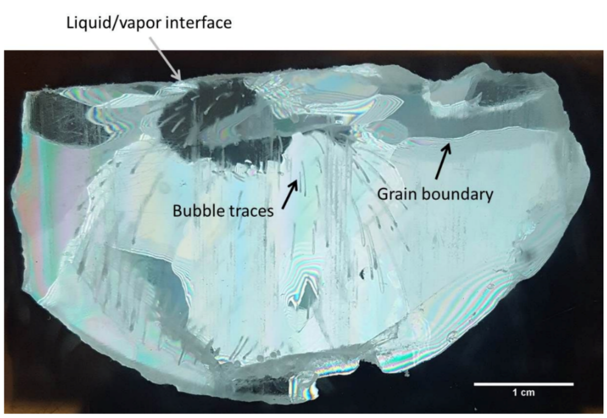

Figure 7. Cross-section along short axis of bag frozen at <1psi ambient pressure.

In the low pressure test (<1psi ambient), average grain size nearest the ice-vapor interface was 0.9cm, while in the lower portion of the specimen, average grain size was 2.4cm (Fig. 7). In higher pressure tests (5psi), grain sizes measured in range from 1.4-3.1cm, with less variation across the specimen.

5.4. Discussion

The general texture of the ice packets indicates that an initial "quench" crust forms at the liquid/vapor interface during filling at <1 psi ambient, with substantially smaller grains at the interface than the ice in the bulk of the cell. The specimen frozen at 5 psi ambient did not exhibit this dichotomy in grain size, indicating that higher pressure precludes rapid freezing of the surface layer.

The implication of these microstructures is two-fold. First, water introduced in relatively large batches into a very low-pressure MIH cell will have bimodal grain size, with regions of coarse grains overlain by regions of smaller grains. These fine-grained layers may serve as zones of weakness. If water is introduced to very low-pressure MIH cells in small batches, the final microstructure may be an accumulation of fine-grained layers, with an overall lower creep strength. Second, if water is introduced to a cell at higher pressure, the grain size throughout the cells will be more homogeneous.

It is important to note that in addition to the ambient pressure during freezing, several other factors such as the rate of cooling, direction of freezing, and annealing after freezing can all affect the final grain size in an ice aggregate. Thus, while these tests demonstrate that solid ice with low porosity can be obtained at very low pressures, the filling protocol for MIH cells can be adjusted to increase the grain size and improve the strength of the ice.

6. Design Development: Material Selection

In addition to the properties of the ice itself, the Ice Home design and Risk Reduction efforts focused on the properties of construction materials within the Ice Home system.

Basic material selection and design were based on existing NASA Langley Research Center soft goods inflatables developed for a number of years which include inner bladder and scuff layers, a structural restraint layer and insulation layers. The MIHRR effort focused on adapting this system for use with an outer layer of pressurized water cells and the necessary insulation.

A primary driver informing the adaption of traditional soft goods inflatables to MIH was the desire for translucency in materials, enabling ambient diurnal light from the surroundings to enter the structure. Significant effort went into the selection of materials that offer high strength with low creep, high durability to withstand the Martian environment, in addition to high light transmissivity.

6.1 Environmental Considerations

Environmental considerations for the 15-year operational lifetime of the MIH include:

- External abrasion by windblown dust
- External degradation by radiation, perchlorates, and atomic oxygen

- Internal abrasion by crew activities and water ice movement
- Internal outgassing into the crew area (in accordance to ASTM E595)
- Flexibility, creasing, and degradation at extremely low temperatures

It is anticipated that the large dimensions of the bladder layer for the habitation area along with the low permeability required will pose a significant manufacturing challenge.

Interior abrasion layers have been designed to be removable to allow access to the internal bladder layer in the event repair is needed.

6.2 Material Requirements

There are several considerations specific to the material selection of the primary water cell boundary.

6.2.1 Tensile Strength

Given the initial assumption is that the water cells will be pressurized to 6895 Pa (1.0 PSI), for constant pressure, the tension loads on the boundary layer will increase linearly with the diameter of the water holding cells. In addition, the cells will have added loads at the bottom of the cells due to the increased water pressure, which on Mars would be about 1/3 that on Earth for an equivalent depth. Given the above assumptions and the requirement for a Factor of Safety of 2, a minimum tensile strength for the primary water cell boundary layer would be in the range of 40 to 50 MPa. (Note that as a reference point DuPont Tedlar film has a tensile strength of 90 MPa).

6.2.2 Thermal Properties

Because the water cells will be inside a gas insulation layer, the primary heat loads will be from solar-induced heating on the upper surface of the water cells. To be conservative the *maximum* anticipated temperature during operations will be 90 degrees F (~32.2^{o}C) caused by the greenhouse conditions in the gas insulation cells.

It is expected the payload will have thermal control during transit to mitigate deep space temperature swings. While on Mars the outside temperature may drop to -100 degrees F. Although the water cells will be inside a gas insulation layer there is still potential that a loss of power will allow the material to be exposed to the *minimum* Martian temperature of -100 degrees F (-73.3^{o}C).

Thermal cycling is another important consideration. There are a little more than 5000 Martian days (AKA Sols) in the estimated 15 Earth-years of operations. Since Mars has a wider day/night temperature range than Earth, these diurnal cycles likewise inform requirements for material selection, even though the water ice cells will be insulated to some extent by the external layer of gas insulation.

6.2.3 Freeze Thaw Cycles

Because of the duration required to collect water, three full freeze/thaw cycles are anticipated during three crew rotations. Freeze/thaw cycles will be a critical factor in determining filling procedures. Cells cannot be overfilled given water expands as it freezes. Freezing rates, fill methods, and surface coatings are also critical to expansion rates and loads on the material.

6.2.4 Material Creep

At a relatively low average temperature (50 degrees F, for example) – the water cells will be filled with gas for up to two years before being filled with water ice. Given the configuration's likeness to greenhouse conditions and susceptibility to greenhouse effect, the temperature in the cells may get quite warm due to solar heating. It is important that the water boundary layer does not continuously stretch under load causing the water cells to slump.

6.2.4 Additional Requirements

Further requirements for the primary water cell boundary include:

- 90% light transmissivity for natural lighting for the crew
- Resistance to UV light
- Resistance to chemical leaching into water
- Resistance to abrasion while under compression
- Resistance to degradation at creases (when material is unfolded from storage)

6.3 Material Layers

Ice Home concepts include several layers, an inner bladders, a restraint layer, and an exterior shielding of water with insulation layers. Material makeup is adopted from similar inflatable structures, however translucent materials were selected and the water and insulation layers were added to support the habitat requirements.

Table 4. Freeze Thaw Cycle Summary

from exterior	Function	Function
1	Outer Cover	Beta Cloth
2	Insulation	Mylar
3	Radiation Protection / Water "Bag"	Mylar, Tedlar, or sim
4	Insulation	Mylar
5	Structure	Fiberglass Fabric
6	Air Bladder	HDPE
7	Scuff	Nomex

For the restraint layer, material experts selected high grade fiberglass webbing for its low creep properties, wide temperature range, high resistance to chemical and UV degradation, as well as its visible transmission properties.

Clear Mylar is considered for thermal air cells as it is a proven material used in space environments with high chemical resistance to UV degradation.

Clear Tedlar is considered for the water cell material. It too has exceptional UV resistance, very good durability in cold temperatures, high light transmissivity, and a higher strength than other materials like Teflon.

Though the outer water and insulation layers are indeed pressurized, they are pressurized at a much lower level than the habitation areas, and therefore will not necessitate the same restraint layer as required by the inner air bladder.

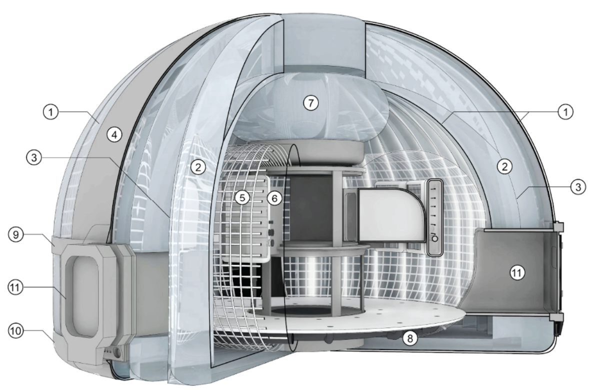

Figure 8. Ice Home Material Layers.

6.4 Insulation Options

Preliminary calculations indicate that a CO_2 insulation layer 13.2 cm thick would require ~5000 Watts of internal energy to keep the internal water cells liquid and the external ice cells frozen. This gas insulation layer also offers several important advantages for the MIH design. First it requires no launch mass since it is obtained from the Mars atmosphere. Second, it mitigates the impact of expansion and contraction of the pressurized habitation area on the ice layer when changes in pressure occur (due to temperature changes, air lock operation. etc.). Third, the thickness of the gas layer can be adjusted as needed to accommodate differing energy outputs within the habitat so that excess energy is not wasted for heating and cooling. In addition, the gas insulation layer is transparent to maximize light transmission.

Having an outer layer and an inner layer of CO_2 insulation cells allows for greater thermal control which is important in controlling the freezing rate of water in the water cells. A slow freezing rate provides ice with better structural and optical characteristics. An external gas insulation layer can be filled and emptied as needed to allow internal heat to melt the ice layer for filtering, replacement or transfer. By reducing the thickness of the internal gas insulation layer and increasing the thickness of the external gas insulation layer, operators would be able to control melting rates for highly efficient water use, acting as fuel for the Mars Ascent Vehicle (MAV), in addition to other potential uses.

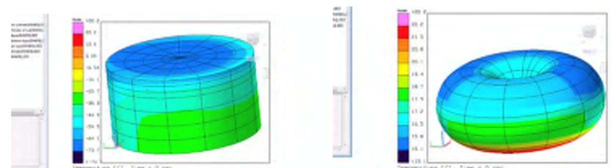

Figure 9. Basic thermal analysis using simple geometric models.

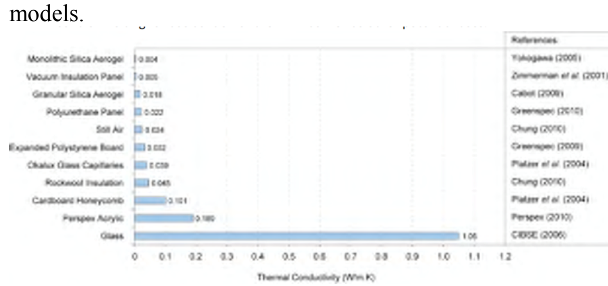

Figure 10. Comparison of Thermal Conductivity for various materials.

7. Physical Testing: Material Properties

Knowledge gained on the performance of a number of material candidates will be valuable for future refinements of the Ice Home design, and help current Mars mission architecture teams with material data that can be used for applications such as inflatable water storage tanks within ISRU systems, as an example.

7.1 Testing Objectives

The purpose of material testing was to identify the top water cell boundary layer material candidates and test material performance given the environmental and performative requirements defined above. Materials were selected and exposed to different conditions that might be seen in application including changes in temperature, the physical stress of water and ice, exposure to radiation, and resistance to abrasion.

7.2 Test Procedures Overview

The following materials were chosen based on their transparent properties and large continuous temperature ranges:

(1) Tedlar: Polyvinyl Fluoride (PVF) is used from -73 to 107C
(2) Teflon FEP: Polytetrafluoroethylene (PTFE) Fluorinated Ethylene Propylene is used from -268 to 204C

(3) Ethylene tetrafluoroethylene (ETFE) is used from -100 to 150C

Each of these materials were subjected to the following separate experimental studies to determine material degradation, failure, or durability:

(1) Material Durability During Freeze-Thaw Cycles
(2) Radiation Exposure
(3) Abrasion Resistance Under Compressive Loads

7.3 Freeze-Thaw Cycle Durability Test

To evaluate material durability, material bags were filled with water and exposed to several freeze-thaw cycles and performance was evaluated.

150X200mm heat-sealed bags were fitted with an injection fitting. The bags were filled using distilled water in thicknesses ranging from 0.13 to 0.35mm at 80-90% of their storage capacity. Filled bags were placed in a walk-in storage freezer (-24 to -17 C) for anywhere from 21 to 120 hours. These bags were then removed to thaw in room temperature (23.8 to 25 C) for 24 hours or more. Bags were exposed to multiple freeze-thaw cycles until failure (tears or leaks). Bags were tested as suspended or as lying flat on a surface. In tests where bags were placed on the surface, water froze from bottom up in contact with the surface.

Table 5. Freeze Thaw Cycle Summary

Material	Max Cycles Tested	Mass Decrease after max cycle	Avg. Decrease in Modulus (GPa)	Avg. Decrease in Ultimate Tensile Stress (MPa)
Tedlar	36	2%	18%	16%
Teflon	20	5%	10%	0%
ETFE	23	-	-	-

No major failures were a direct result of the freeze/thaw cycle. Failures were mostly located along seams and in corners and due to the expansion of water ice, indicating the need for sensors to detect the fill level of a water cell to reduce the risk of overfilling. Furthermore, there were no apparent changes in the tensile properties of the materials due to thermal cycles, with the exception of Tedlar in which case tensile strength decreased in one orientation. The bags did however, lose weight after some time and took in more air indicating a certain amount of stretching of materials and material reduction.

7.4 Radiation Exposure Test

A film of each material was exposed to a neutron radiation source for 51 days receiving a total of 16,547.72 mrem, and then tested for weakness or effect on its tensile properties. (Note that a Mars 180-day transit mission exposure is closer to 30,000 mrem.) There was minimum effect on tensile strength due to radiation exposure.

7.6 Abrasion Resistance Test

Materials strips were taped to rubber wheels and abraded against a rotating disc on a Qualistest GT-7012-T Taber Type Abrasion tester. Abrasion testing showed that the materials had good abrasion resistance. This is measured in percent light transmittance which showed little change. Both a frozen and unfrozen sample set was tested.

7.3 Results

Based on these initial results, Clear Tedlar is currently the leading water cell material candidate for its extensive temperature range, superior performance in freeze-thaw cycles, and light transmissivity. Further testing of these materials is required in relationship to the final water cell design.

8. Conclusions

The Mars Ice Home Risk Reduction effort brought the possibility of using in-situ water ice as a habitat material closer to reality. Design development led to further clarification in mission requirements, formal design properties, material requirements, and procedural considerations for ISRU derived water ice in extreme environments. Follow-up studies include a sub-scale demo demonstrating a combined effort of water ice, material, and design trades. Material testing of the MIH materials has already been selected for on-flight testing on the International Space Station.

As more news comes out on the potential of water on Mars, the possibility of using in-situ water ice as a habitat material is becoming an increasingly realistic and preferred choice for human habitation.

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